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DAMAGE PROPAGATION AND THERMOGRAPHY IN DISCONTINUOUS CARBON FIBER COMPOSITE (DCFC) UNDER TENSILE (FATIGUE) LOADING

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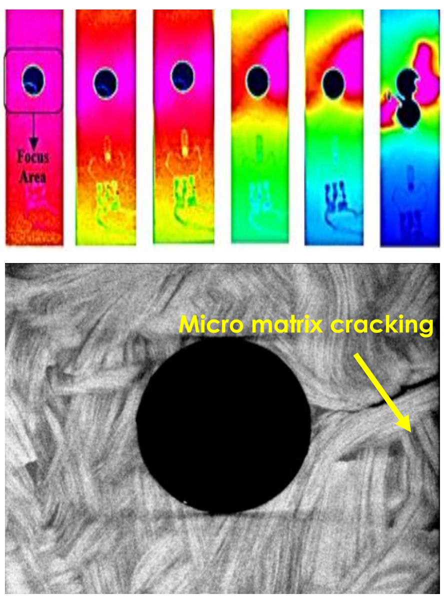
Graphical abstract



Abstract

The discontinuous carbon fiber composite (DCFC) has a different damage behaviour due to non homogenuous sub structure. Consequently, monitoring and diagnosis of DCFC damage mechanisms require the application of a contactless method in real-time operation, i.e., non destructive method of thermography. The aim of this study is to investigate the damage propagation of DCFC material under tensile (fatigue) condition with non destructive testing (NDT) thermography method. Under fatigue testing, temperature evolutions were monitored by an Infra-Red (IR) camera. The results show that damage propagation and thermal response indicated the similar behaviour which consists of three stages. At the beginning, low temperature increased until ≈ 10% of fatigue life due to the initial damage. The initial damage propagated and the temperature reached the stable thermal state due to the saturation in the damage appearance of micro cracking of matrix and chip until ≈ 80% of fatigue life. At the last ≈ 20% of fatigue life, damage continued to propagate and provoked the occurrence of macro damage that induced the final failure indicated by highest peak of temperature. The analysis from the experiment results concluded that thermal response relates with the damage propagation of DCFC under fatigue loading.

Keywords: Thermography, DCFC, damage, tensile, fatigue loading

1.0 INTRODUCTION

Discontinuous carbon fiber composite (DCFC) is prepeg-based discontinuous of randomly distribution of carbon chip-reinforced polymer composite, as known as Quantum Lytex 4149 and HexMC under various manufaturer and brands [1-2]. The main advantage of this type of material is its good suitability to be molded in complex geometries with lower manufacturing costs and at higher rates that justify their adoption to reduce overall part acquisition costs [3-4]. Several studies about mechanical and damage behaviour of DCFC were performed by previous authors [5-10]. They concluded that the failure of DCFC is the combination of two failure modes: cracking caused separation along the surface that perpendicular to the chip axis and delamination caused separation along the thickness that parallel to the chip length under static loading.

Under fatigue, DCFC as a polymer composite material has a complex and different phenomenon since several factors contribute to the damage of material, such as: non homogenuous sub structure, insensitive to circular notches, highly modulus variation

[11-14]. Consequently, monitoring and diagnosis of these different forms of damage mechanisms require the application of a contactless method in real-time operation, i.e non destructive method. A thermography technique has been used to study the evolution of temperature on the specimen surface of composite material under fatigue loading and can characterise the fatigue and damage behaviour due to the degradation by fatigue loading [15-20].

Recently, Bale *et al*. [21], studied about thermal analysis and damage evolutions of DCFC to determine the high cycle fatigue strength (HCFS) under fatigue loading. The results indicated that thermography and energy dissipation approaches can be used to determine HCFS of DCFC material, which is much more time consuming. This study presented the propagation of damage behaviour and thermography method of DCFC under tension-tension fatigue loading experiments.

2.0 METHODOLOGY

The open hole tension (OHT) specimen test is 60 % of random discontinuous (chip form) carbon fiber volume as the reinforcement and epoxy matrix. Chip dimensions are 50 mm length and 8 mm width where fabricated into composite material under compression molding. The test was carried out on INSTRON Machine 8501 100 kN, equipped with mechanic grips of 20 kN max capacity. Local strain was measured using single strain gage with a gage length of 5 mm. Temperature evolutions during the cyclic tests were monitored by an Infra-Red (IR) camera. Figure 1 below shows the schematic diagram of experimental set up.

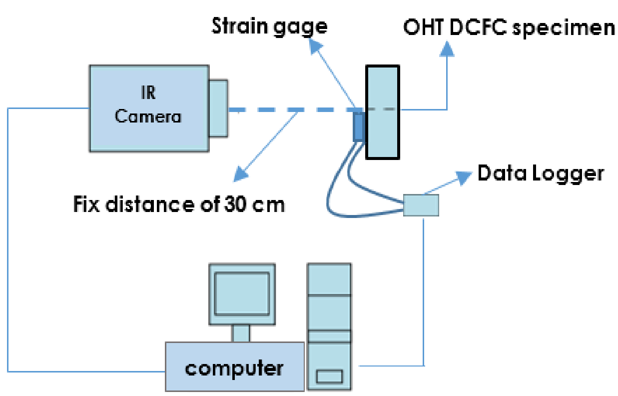
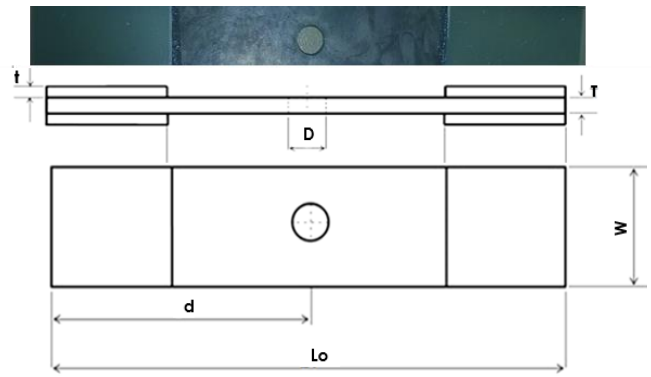


Figure 1 Schematic diagram of experimental set up

The fatigue tests were performed under load control, at a stress ratio, R, equal to 0.1, i.e., tension tension loading and constant 3 Hz of frequency. An IR camera was placed in front of the specimen with fix distance, i.e., 30 cm. The test specimen is rectangular shape with an open hole condition, as seen in Figure 2.



Lo: 200 mm; T: 4 mm; W: 25 mm t: 2 mm; d: 100 mm; D: 10 mm

Figure 2 DCFC specimen

3.0 RESULTS AND DISCUSSION

3.1 Stiffness Degradation and Damage Propagation

The fatigue tests conducted with different of load level, i.e., 60 % of ultimate tensile strength (UTS) and 75 % UTS. Figure 3 shows the stiffness degradation (E/Eo) as a function of fatigue life (Nf). The stitffness degradation were in the range between 1 and 0.

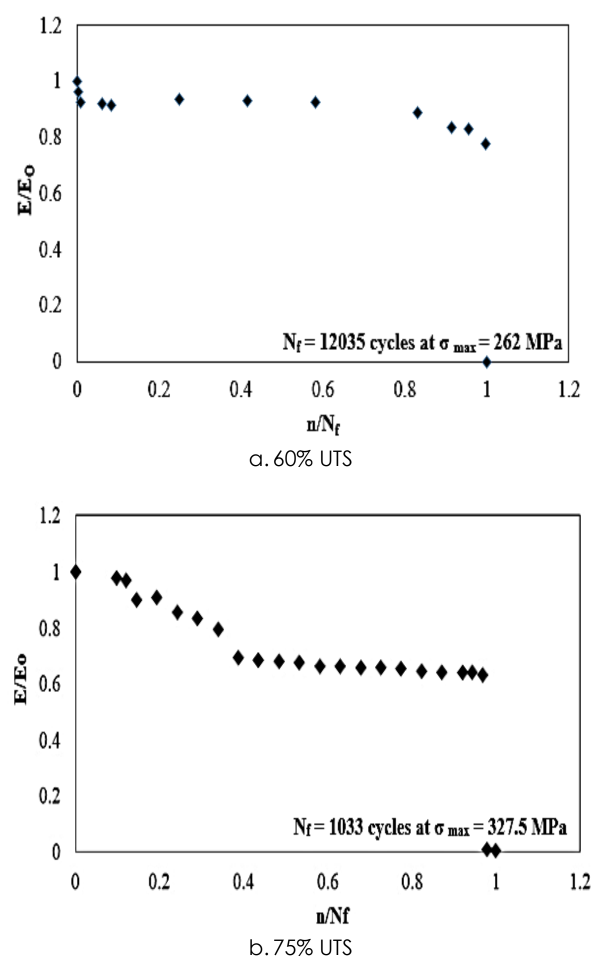
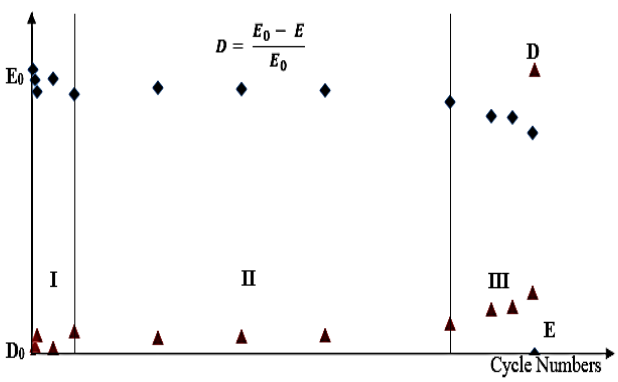


Figure 3 Stiffness degradation of DCFC

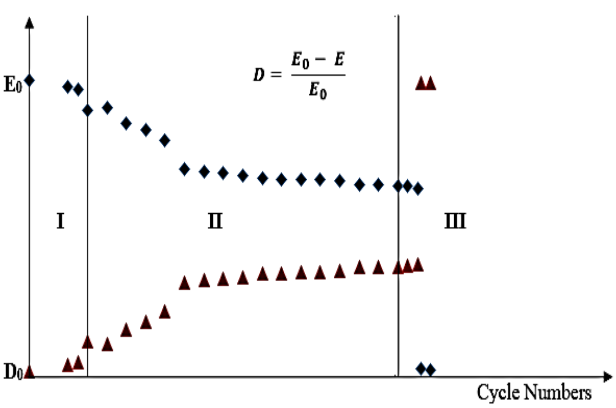
From Figure 3, under different load level, specimens failed at different number of fatigue life (Nf) where 60% of UTS generates Nf of 12035 cycles and load level of 75 % of UTS has a shorter fatigue life of 1033 cycles. it is noted that DCFC specimens experience the change in modulus or stiffness as a function of fatigue cycles. The Stiffness degradation curve or the decrease trend in material modulus has been commonly used to express the state of cumulative damage D in polymer composite material as a function of loading cycles [14], where defined as:

$$D = 1 - \frac{E}{E_0} \quad (1)$$

where E and E_0 are the residual and initial modulus, respectively. Figure 4 shows the cumulative damage and stiffness degradation. According to Equation (1), the accumulate damage will be in the range between 0 and 1.



a. 60% UTS



b. 75% UTS

Figure 4 Cummulative damage versus stiffness degradation of DCFC

In general, under fatigue loading, the first small drop of stiffness is associated with the presence of initial micro matrix cracking damage mechanism in micro scale. Then, the stiffness propagates into gradual decrease as also the damage seems to increase and develop into others mechanisms, such as interfacial matrix/fiber debonding and delamination. The final stage of damage propagation leads to a decline of stiffness with an increasing amount of damage mechanisms, such as fiber breakage and delamination growth [22-24]. The ilustration of stiffness degradation and damage propagation of fiber composite can be seen in Figure 5.

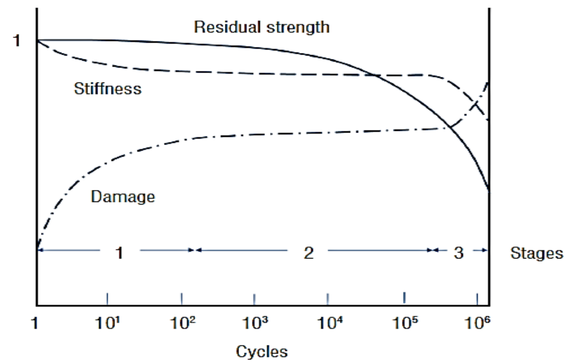


Figure 5 The three characteristic stages of fatigue damage in composites [25]

For DCFC specimen, under fatigue loading, it shows similar behaviour compared to fiber composite. In both D versus E/Eo curves show the same behaviour which consists of three stages:

- The initial area (stage I) shows an initial rapid decrease trend of stiffness along with an increase of damage propagation rapidly. This stage takes 10 % of stiffness reduction and presence of initial micro damage growth of matrix cracking during the first period of fatigue life.
- An intermediate area (stage II) shows a gradual decrease trend and forms into an approximately linear fashion with respect to 70-80 % of second fatigue life period. In this stage, a stiffness reduction of 5-15 % occurs due to the stable propagation of chip/matrix debonding and chip cracking.
- The Final area (stage III) forms a rapid stiffness reduction of 5-10 % during the 10-20 % with the respect to the cycles numbers. In the final stage, chip breakage take places and which caused separation along the thickness and for the last 2-5 % of fatigue life, a final catastrophic failure occurs as a consequence of sudden increase of damage propagation. The boundary between region II and III is the so called fatigue limit [26].

Figure 6 shows the microcrack of matrix during the first period of the fatigue life as an initial cause of specimen's failure.

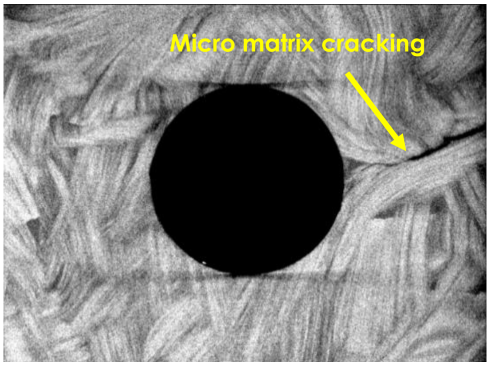


Figure 6 CT scan image of micro matrix cracking

3.2 Thermal Analysis based on Thermography Observation

The basic idea of thermography is to apply infrared frequency range of electromagnetic radiation emitted by object under research to obtain information concerning its selected physical properties or processes taking place within this object. The camera thermograpy will absorbs the IR energy emitted by the object and it transforms the amount of infrared energy into the temperature then represented in the form of thermographic images. The ilustration of principle of measurement by themography as shown schematically in Figure 7.

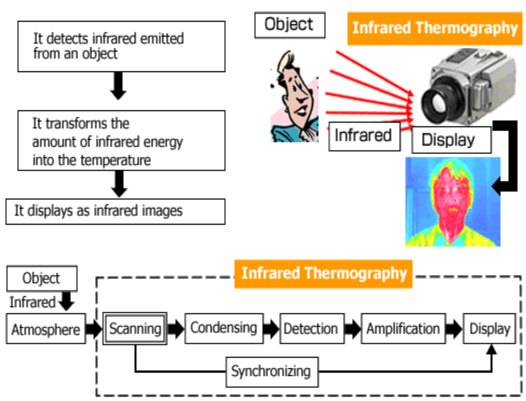


Figure 7 The principle of thermography [27]

It is well known that, thermography can fulfill the need of a non contact technique and real time inspection of damage detection under dynamic loading conditions [28-34] due to the transformation of damage in an irreversible way into heat [35]. An ilustration of thermal evolution during a fatigue test can be seen in Figure 8.

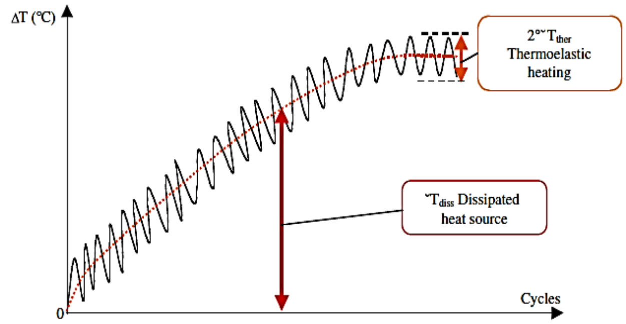


Figure 8 Thermal evolution during a fatigue test [15]

The aim of this study is to have a relationship between temperature evolution and damage propagation. Figure 9 shows the temperature change for certain cycles until failure, respectively. The focus area is localised around the hole.

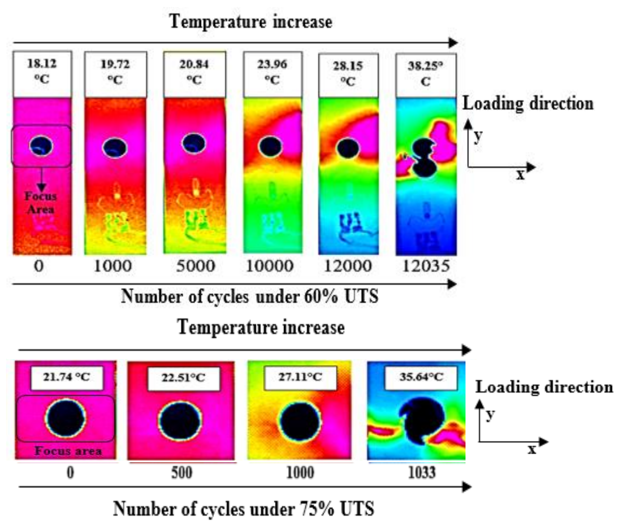
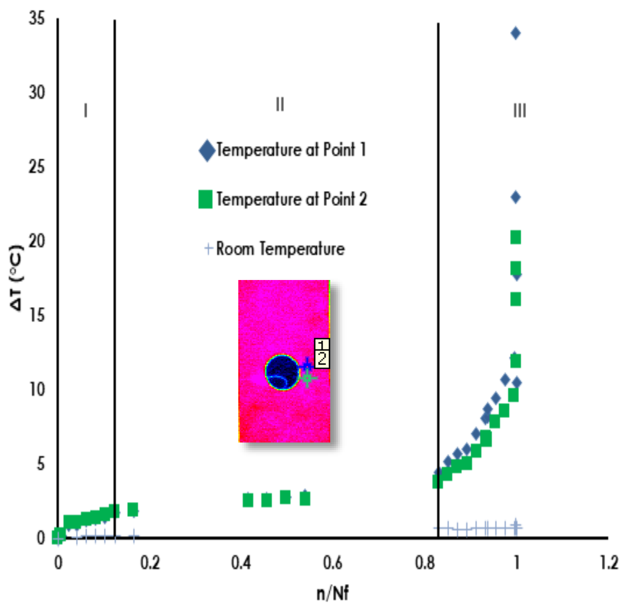
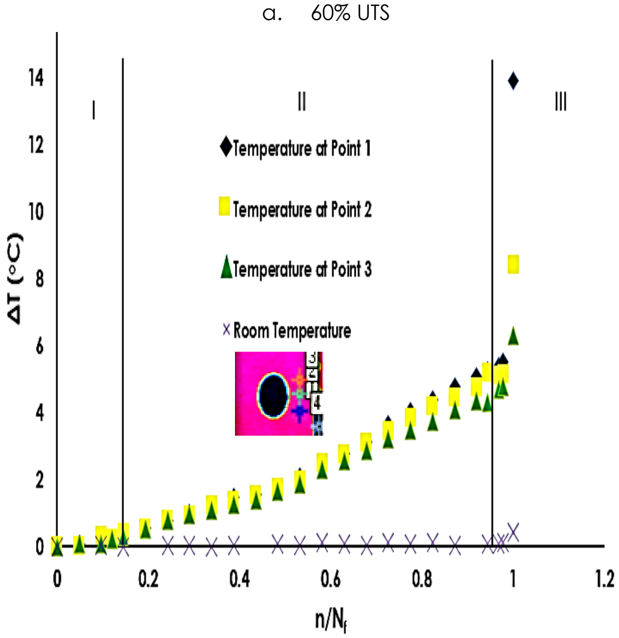


Figure 9 Temperature images of DCFC under fatigue loading

The focus area, which the damage area at the edge of the hole, is shown in Figure 9 for the 60% UTS and 75% UTS specimen. The temperature shows a similar slow increase until it reaches at N_f around 10000 cycles for 60% UTS and 1000 cycles for 75% UTS. A significant increase of temperature occurs at the end of fatigue life for both specimens and reaches ΔT ≈ 20°C for 60% UTS and ΔT ≈ 14°C for 75% UTS. All temperature formation during the fatigue test can be seen in Figure 10



a. 60% UTS



b. 75% UTS

Figure 10 Thermal evolution of DCFC under fatigue loading

When damage occurs, it represents the energy which gradually released. The energy that has been absorbed is sufficient to create micro-crack, enlarging the pre-existent ones, and create new inner and interfacial debonding and chip cracks then leads to final failure. The heat generated from the energy release then detected by the IR camera that showed an increase in temperature in the area of damage. It shows temperature increase behaviour at ΔT ≈ 1-3 °C until ≈ 10% of fatigue life due to the initial damage. The initial damage propagates and the temperature reaches the stable thermal state (an example of a slope of 0.0004°C/cycle from 1200 to around 10000 cycles for 60% UTS) due to the saturation in the damage [15]. Each peak of temperature indicates different type of damage mechanisms. We found that temperature reaches at ΔT ≈ 1-5 °C is directly associate with the appearance of micro cracking of matrix and chip. After that, damage continues to propagate and temperature starts to show a higher increase until reaches at ΔT ≈ 12°C. The ΔT ≈ 6-8°C for 60% UTS and ΔT ≈ 4-5°C for 75% UTS is related with the appearance of interfacial damage. The higher temperature of interfacial damage is in fact due to absorb more energy of damage. From the temperature evolution during test, the presence of macro damage indicate the area of final failure which is exist and concentrate in the region of focus area around the hole. In sum, initial macro damage provokes the occurrence of catastrophic or final failure of the specimen that induce the highest peak of temperature at ΔT ≈ 20-34 °C for 60% UTS and ΔT ≈ 13-14 °C for 75% UTS suddenly. Based on the temperature evolution of DCFC above under fatigue test, an approximate of temperature behaviour of DCFC until fatigue limit can be approached in a form of an empirical relationship, which is expressed as:

$$\Delta T = m.Nf \quad (2)$$

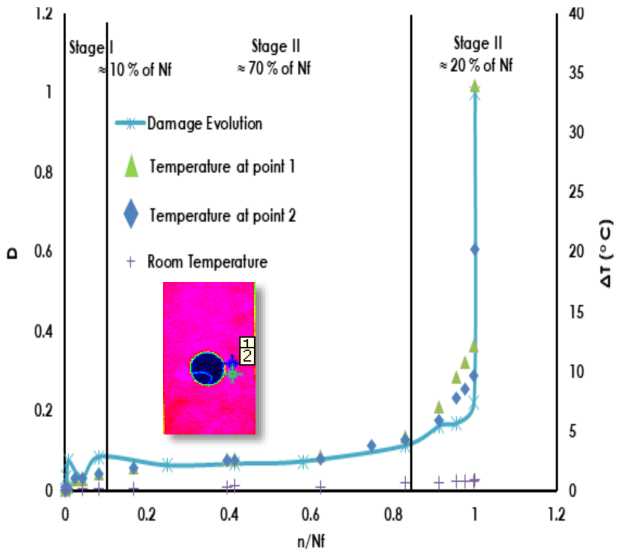
where:
ΔT = temperature evolution (°C)
m = temperature slope (°C/cycle)
Nf = Number of fatigue life (cycle)

Table 1 shows the equation of ΔT of DCFC during the fatigue loading for each load level.

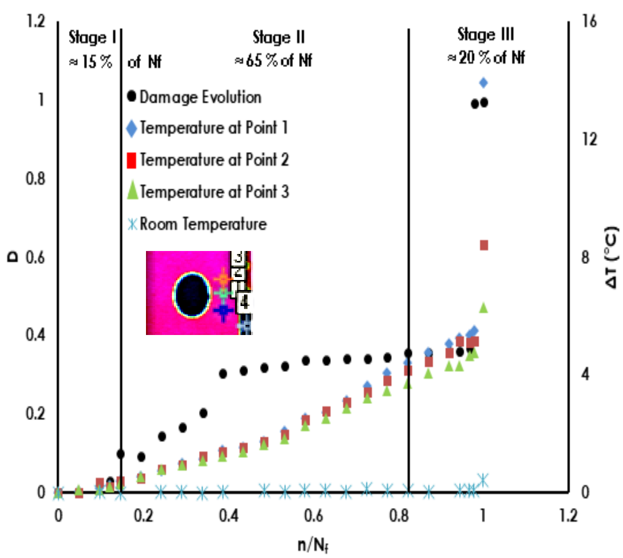
Table 1 The equation of ΔT evolution of DCFC

Stage	**60 % of UTS**
I	ΔT = 0.0033 (°C/cylce) x Nf (cycles)
II	ΔT = 0.0004 (°C/cylces) x Nf (cycles)
Stage	75 % of UTS
I	ΔT = 0.008 (°C/cylces) x Nf (cycles)
II	ΔT = 0.005 (°C/cylces) x Nf (cycles)

The comparison between the thermal evolution and the damage propagation can be seen in Figure 11.



a. 60% UTS



b. 75% UTS

Figure 11 Comparison between the temperature evolution and the damage propagation of DCFC under fatigue loading

From Figure 11, temperature evolution and damage propagation show the same 3 (three) increase phases characterised by low phase, slow-gradual phase, and high-sudden phase. Therefore, it can be noted that the temperature behaviour (ΔT response) of DCFC under fatigue loading can be used as one of damage parameter and not only stiffness degradation which has been used in conventional method. This confirms the results from previous studies [15, 18-19, 21], which conclude that thermal dissipation relates to the damage evolution and can effectively estimates the damage behaviour of carbon fiber composite material.

4.0 CONCLUSION

This study presents experimental results of damage propagation and temperature evolution on discontinuous carbon fiber composite (DCFC) under tensile (fatigue) loading. The results confirm that thermal response of ΔT on specimen surface can be effectively used to identify the damage propagation of DCFC. Damage propagation and temperature evolution of DCFC form an increasing phase consisting of low phase due to initial micro damage growth of matrix cracking, slow-gradual phase caused by the stable propagation of chip/matrix debonding and chip cracking, and high-sudden phase as a consequence of final failure dominated by chip breakage. Therefore, thermal response is highly potential parameter to be explored in relation to composite material damage from various dynamic test conditions in the future.

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