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Aspect of Fatigue Analysis of Composite Materials: A Review

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ABSTRACT

This paper reviewed the aspect of fatigue approaches and analysis in a fibre reinforced composite materials which have been done by researchers worldwide. The aim of this review is to provide a better picture on analytical approaches that are presently available for predicting fatigue life in composite materials. This review also proposes a new interpretation of available theories and identifies area in fatigue of natural fibre reinforced composite materials. Thus, it was concluded there are still very limited studies on fatigue analysis of natural fibre reinforced composite materials, especially using non-destructive technique (NDT) methods and a new mathematical modelling on fatigue should be formulated.

Keywords: Fatigue life, composite materials, non-destructive technique

INTRODUCTION

Fatigue life of the classical engineering materials is difficult to predict, and not even surprisingly for composite materials. Predicting fatigue life for homogeneous materials was done in the past three decade but from a review of the limited research done and developed on natural fibre reinforced composite. Previously, a vast majority of the fatigue studies focused on synthetic fibre/resin system (Harris, 2003). Research on the fatigue properties of natural fibre composites is a new field and these have become a focus for many engineers and scientists. In composites, fatigue damage and failure mechanism commonly occurs is more complex compared to homogenous materials such as metal. There are four basic failure occurs in the composites under cyclic loading which are matrix cracking, interfacial debonding, delamination and fibre breakage (Wu & Yau, 2009).

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A long time ago, a man produced materials used which were widely in building and in many structure but later the materials had changes in the composites. Nowadays, due to the increased interest in the potential of natural fibre composites for applications in primary structures such as automotive parts and buildings, a fundamental study of their fatigue properties is essential (Towo & Ansell, 2008). Recently, scientists and researchers have discussed and worked on natural fibre in composites such as Kenaf, sugar palm, coconut, coir, jute, sisal, bamboo, wood, pineapple and banana. There are many reasons for using natural fibre as a filler or reinforcement in composites compared to glass fibres, and these include low density, biodegradable and recyclable, high strength and stiffness good fibre adhesion and environmental consciousness (Sapuan *et al*., 2006). Thus, the following section will elaborate on the aspect of the composites analysis of fatigue to better understand the integrity of this new material under dynamic loading.

PREDICTING FATIGUE LIFE

Fatigue can be defined as a failure under a repeated or varying load. These failures have two domains of cyclic or stressing and straining in different mechanisms of low-cycle fatigue and high-cycle fatigue (Wu & Yau, 2009).

Fatigue failure process involves two distinct phases in the rubber. The first phase is a period during which cracks nucleate in regions that were initially invisible or free of observable cracks. The period during which nucleated cracks grow to the point of failure is the second phase of the fatigue failure process. It will be seen that in the second phase, nucleation, growth and final failure may be rationalized in terms of the fracture mechanical behaviour of rubber (Mars & Fatemi, 2002).

Normally, three methods are used to predict life including total life by plotting stress-life (S-N) curve, crack initiation strain-life (E-N) and crack growth. Meanwhile, there are two approaches used for predicting the models for rubber. The first approach focuses on predicting crack nucleation life, given the history of quantities that are defined at a material point, in the sense of continuum mechanics. Stress and strain are examples of such quantities. The second approach, based on the ideas from fracture mechanics, focuses on predicting the growth of a particular crack, given the initial geometry and energy release rate history of the crack (Mars & Fatemi, 2002).

Predicting fatigue life in composite materials is more complicated as compared to metal. This is because in the composite materials, failure does not occur by the propagation of a single macroscopic crack. The micro-structural mechanisms of damage accumulation, including fibre breakage and matrix cracking debonding, transverse-ply cracking, and delamination, occur independently sometimes and interactively at times, and the predominance of one or the other may strongly affect both materials variables and testing conditions. Fig.1 shows the degradation of composites strength until failure occurs (Harris, 2003).

Many experiments have been done by the researchers to predict fatigue analysis by using the derived empirical S–N curves between stress and fatigue life. Fig.2 shows a typical S-N graph, where straight lines indicate endurance limit region. These relationships have been suggested for use in design in numerous industries such as aerospace, automotive and construction. The

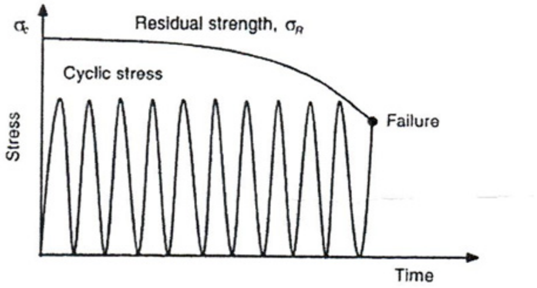

Fig.1: The degradation of composites strength until failure occurs (Harris, 2003)

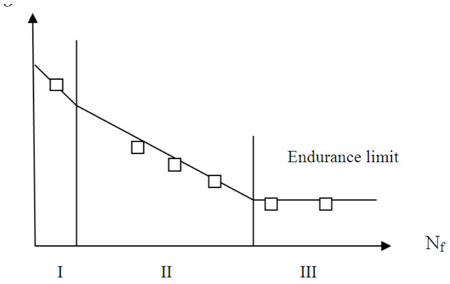

Fig.2: A typical S-N graph where straight lines indicate endurance limit region (Harris, 2003)

linear and non-linear S–N curves have been proposed (Yang, 1978; Nicholas, 2000). It also uses a non-linear curve between strains to predict the fatigue life of the composite materials (Reifsnider *et al*., 2000). It also discusses on a linear relationship between the maximum stress S and the logarithm of N, while the number of load cycles to fatigue failure is widely used to fit the experimental data, as follows:

$$S = m \log N = b \tag{1}$$

where m and b are parameters dependent on material properties. By predicting fatigue life under constant cyclic loading, fatigue damage can be evaluated after a given number of cycles. Composite is assumed to fail in the phase when accumulated damage exceeds the critical level of damage (Clark *et al*., 1999).

In a study on the flexural behaviour of sandwich composite materials under cycling loading, El Mahi *et al.* (2004) utilized Wohler Curve (S-N Curve) to obtain the comparison between the experimental result and analytical results. It was reported that a good agreement had been found between these two analyses. The approach was based on the interpolation by empirical function, in which the parameters were obtained from the experimental results using the stiffness concept. It was also reported that this approach is able to predict the fatigue life and the evolution of damage according to the loading level, which will reduce the number of experiments. In their work on the derivation of the model for fatigue life criteria, the failure occurs to residual strength degradation method. The failures were caused by the degradation of residual strength to the applied stress.

Another approach that has been used by several authors is strain failure criterion which considers the final failure of the composite materials that occurs at the stage of resultant strain that reaches the ultimate static strain (D'amore *et al*., 1999; Clark *et al*., 1999). The other method used to predict fatigue life, done by Salvia *et al*. (1997), is stiffness reduction or degradation which needs another failure condition rather than the total failure of the specimen such as predefined critical number of cycles representing certain damage state. The critical number of the cycles was obtained when a given stiffness loss (predefined) was reached, and then the critical cycle numbers and stiffness reduction were associated.

MODELLING FATIGUE IN COMPOSITES

Damage Accumulation

Damage evolution mechanism is one of the important focuses and also a foundation to predict fatigue life. The mechanical properties of the composite materials show progressive degradation with the increasing of the number of cyclic loading. Two quantitative relations, obtained from a study on a fatigue damage model of composite, are defined by the stiffness degradation rule in the loading direction. The proposed model is as follows:

$$D(n) = \frac{E_0 - E(n)}{E_0 - E_f} = 1 - \left(1 - (\frac{n}{N})^B\right)^A \tag{2}$$

Where E_0 is the initial Young's modulus, E_f is the failure Young's modulus, $E(n)$ is Young's modulus of the material subjected to *n*th cycling loading, *n* is the cycle, *N* is the fatigue life, A and B are model parameters, *D(n)* is the fatigue damage which equals 0 when n=0 and equals 1 when n=N (Wu & Yau, 2009).

Shen *et al*. (1993), in predicting of fatigue life of Boron/Aluminium composite, worked on a technique involving the iteration of damage accumulation and internal stress redistribution. As pointed by Shen *et al*. (1993), damage accumulation can be determined by applying the fatigue damage evolution law and the redistribution of stress. The characteristics of damage growth in the composite materials have been studied and compared with those of the damage growth in homogeneous materials.

The study on the fatigue damage of composite materials of characteristic of damage accumulation in composites materials was done in 2002 by Mao and Mahadevan, who reported that the concept of damage accumulation might be used as a more suitable approach to predict the fatigue life of the structures of composite materials. However, fatigue damage cannot be measured directly. Therefore, for quantitative evaluation of fatigue damage, Young's modulus or the stiffness of composite materials is often used to evaluate the fatigue damage due to cyclic loading. Fig.3 shows a schematic comparison of damage accumulation in the composite materials and homogeneous materials as a function of fatigue cycle ratio. Fig.3 is plotted in terms of damage index versus cycle ratio, where the damage index is defined as Eq. (3):

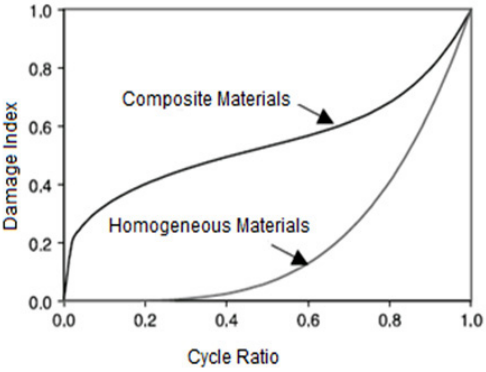

Fig.3: Sketched fatigue damage accumulation (Mao & Mahadevan, 2002)

$$D_1 = 1 - \frac{E}{E_0} \tag{3}$$

where D_1 is accumulated fatigue damage, E is the Young's modulus of the damaged material and E_0 is Young's modulus of undamaged material. The cycle ratio is the number of cycles at a given instant divided by the fatigue life.

Mao and Mahadevan (2002) presented a new damage accumulation model to describe the degradations of composite materials. This model accurately explains the rapid damage growth during both the early and final stages of life. The proposed function is of the following form:

$$D = q\left(\frac{n}{N}\right)^{m_1} + (1-q)\left(\frac{n}{N}\right)^{m_2} \tag{4}$$

where D is the normalized accumulated damage; q, m_1 *and* m_2 are material dependent parameters; n is the number of applied loading cycles, and N is the fatigue life at the corresponding applied load level. The parameters for Eq. (4) are defined as:

$$q = \frac{A\left(\frac{N_0}{N}\right)^{\alpha}}{1-(1-A)\left(\frac{N_0}{N}\right)^{\alpha}} \tag{5}$$

$$m_1 = \left(\frac{N_o}{N}\right)^{\beta} \tag{6}$$

$$m_2 = \left(\frac{N}{N_0}\right)^{\gamma} \tag{7}$$

where N_0 is the reference fatigue life. The parameters α, β and γ are material dependent constants. These parameters can be obtained with fatigue experimental data. Once the damage indices are obtained during the fatigue tests, regression analysis can be carried out to obtain the parameters q, m_1 and m_2. Then, the parameters α, β and γ can be calculated using Eqs. (5) – (7).

Crack Nucleation Approaches

Fatemi *et al*. (2002) stated that there are two approaches used in the models for predicting fatigue life in rubber. The first one focuses on predicting crack nucleation life, given the history of quantities that are defined at a material point, in the sense of continuum mechanics. Stress and strain are examples of such quantities. The other approach, based on the ideas from fracture mechanics, focuses on predicting the growth of a particular crack, given the initial geometry and energy release rate history of the crack.

Crack Growth Approaches

Fatigue crack growth approach has been used to analyze fatigue in composites (see Salvia *et al*., 1997; Fatemi *et al*., 2002; Dawis & Bradstreet, 1970; Savastano Jr., 2009; Woo *et al*., 2008). It was started to be used and applied widely since 1960s and the cracks were claimed to be related to damage. In the experimental study of resistance-curve behaviour and fatigue crack, the crack growth was observed to have occurred in three stages, namely, an initial decelerated growth, a steady-state growth and the final catastropic crack growth (Savastano Jr., 2009). Nowadays, this concept was applied with sophisticated tool and a technique available that can measure a very small crack up to 1µm (Fatemi & Yang, 1998). Southen and Thomas (1978) applied fracture mechanic approach based on fatigue crack growth to develop a model for abrasive wear of rubber. Stevenson, (1987) also stated that compressive loading must be considered carefully in any analysis of fatigue growth.

Savastano Jr. (2009) presented the results of an experimental study on resistance-curve behaviour and fatigue crack growth in cementitious matrices reinforced with eco-friendly natural fibre obtained from agricultural by-products. He used blast furnace slag cement (BFS) reinforced with pulped fibres of sisal, banana and bleached eucalyptus pulp and ordinary Portland cement (OPC), which was reinforced with bleached eucalyptus pulp. Meanwhile, single-edge notched specimen was used to analyze fatigue crack growth and fracture resistance (R-curve). Then, the analysis of crack/microstructure interaction was done by using the NDT method via scanning electron microscopy (SEM) and X-ray spectroscopy (EDS). As pointed in this study, fatigue crack growth occurs in three stages, which are initial decelerated growth, a steady-state growth, and a final catastrophic crack growth. The crack growth diagram was plotted and the results of Sisal BFS, Banana BFS, Eucalyptus BFS and Eucalyptus OPC are shown in Fig.4a to Fig.4d, respectively.

The fatigue life of banana and sisal fibre reinforced composite mostly occurred in the second stage of steady state crack growth (Fig.4a and Fig.4b). The fatigue crack growth rates of Eucalyptus reinforced composites are faster as compared to the sisal and banana reinforced composites (Fig.4c and Fig.4d). The results of the crack/microstructure interactions revealed

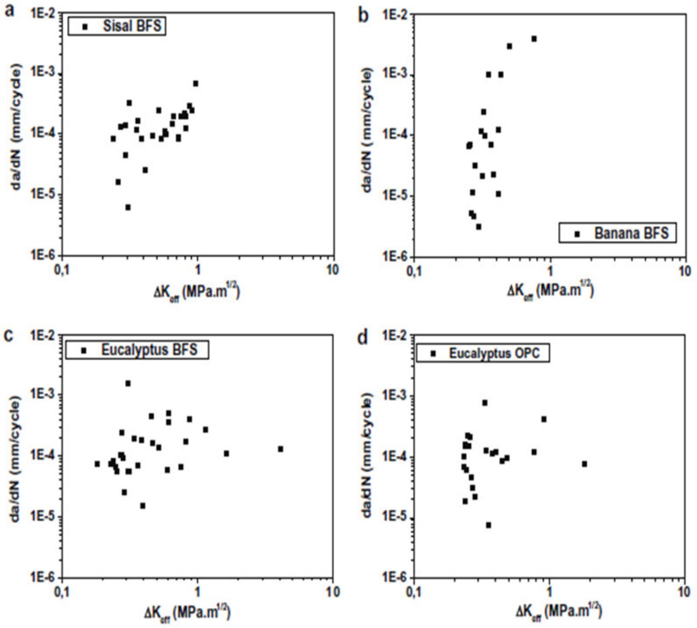

Fig.4: Fatigue crack growth rate of diagram (a) Sisal BFS, (b) Banana BFS, (c) Eucalyptus BFS, and (d) Eucalyptus OPC (Savastano Jr *et al*., 2009)

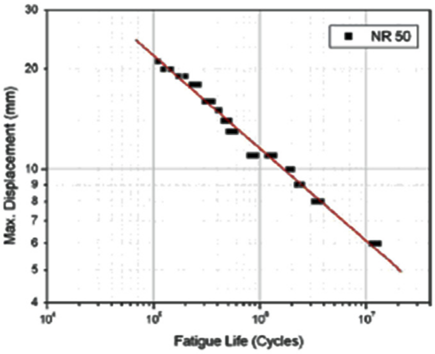

Fig.5: Fatigue life of rubber materials at maximum displacement (Woo *et al*., 2008).

that fatigue crack growth in composites occurred by matrix cracking, crack deflection around fibres and crack-bridging by uncracked fibres and ligaments (Savastano Jr., 2009).

Woo *et al.* (2008) studied on the material properties and fatigue life of natural rubber component. The fatigue lifetime prediction methodology by using the incorporating of finite element (using Green-Lagrange strain) analysis and fatigue damage parameters has been proposed. Meanwhile, fatigue damage parameters were obtained from the fatigue test and Green-Lagrange (G-L) strain determined at the critical location. A single function of G-L strain was then used to represent the equation for predicting fatigue life. Fatigue test was performed using a 3D dumbbell specimen and roll front component in ambient temperature under the stroke controlled condition with a sine waveform of 5 Hz and the mean displacement is 0-10mm at a displacement range is -11 to 21mm. Fig.5 shows the relationship between the maximum displacement with fatigue life. This shows that fatigue life decreases as the maximum tension displacement increases. In this study, the fatigue lives of the 3D specimens are represented by the maximum G-L strain parameter, $N_{f,}$ as performed in Eq. (8):

$$N_f = 495,450\left[\varepsilon_{\text{G-L}}\right]^{-1.324} \tag{8}$$

Toubal *et al.* (2006) worked on woven laminates composite of fabric (HR 285/G803), with high strength carbon fibre and the matrix is epoxy resin. This composite has been used in manufacturing aeronautical structures. The fatigue test was carried out under tension-tension load and analysis of temperature on external surface involving thermal concept or thermal imaging technique using infra-red camera applied in this research. This study intended to relate the damage evolution and heat dissipation in composites. An analytical model based on the cumulative damage has also been proposed to predict damage evolution. Roylance (2001) stated that a cumulative damage model is often hypothesized when the cyclic load level varies during the fatigue process. They are considered to be two main approaches for cumulative damage such as Miner's rule and the other is that of residual strength. Miner's rule can be written as Eq. (9):

$$\sum \frac{n_i}{N_i} = 1 \tag{9}$$

where n_i is the number of cycles applied at a load corresponding to a lifetime of *Ni*, and for residual strength $\sigma_{R,}$ Broutman and Sahu (1972) stated Eq. (10) as follows:

$$\sigma_R = \sigma_S - \sum_i \left(\sigma_S - \sigma_i\right)\frac{n_i}{N_i} \tag{10}$$

where σ_S is the instantaneous tensile static strength as measured on the virgin material before any fatigue damage is induced as $\sigma_{S=}\sigma_i$ (with σ_i being the maximum stress in the cycle). In another example, Granda *et al*. (2008) reported from their prediction of fatigue damage of an automotive axle, which was subjected to variable loading observations that there was a localized damage process which resulted from a cumulative damage. Marin (1962) proposed a cumulative damage based on the consideration of the relations between damage as a function of cycle ratio and changes in the S-N curve due to damage accumulation.

Cumulative damage, as a function of loading cycles, is described in Fig.6. It was determined that *D* is cumulative damage, *N* is the three numbers of loading cycles and N_f is the number of cycles to failure. Cumulative damage was determined by using Equation (11):

$$D = 1 - \frac{E}{E_0} \tag{11}$$

where *E* is the residual modulus and E_0 is the initial modulus (Toubal *et al*., 2006).

Toubal *et al.* (2006) used Eq. (4) proposed by Mao and Mahadevan (2002) to determine the analytical model of accumulation damage and the values of *q,* m_1 *and* m_2 are given in Table 1 and plotted in Fig.7 to Fig.8, respectively.

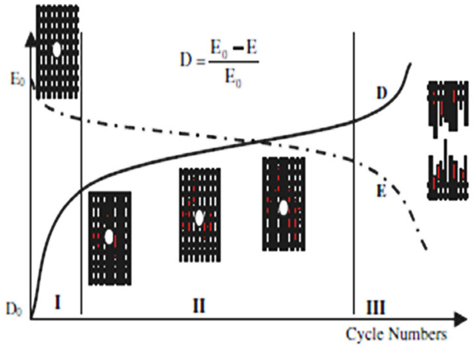

Fig.6: Evolution of the modulus of elasticity E and damage D according to the number of cycle (Toubal *et al*., 2006)

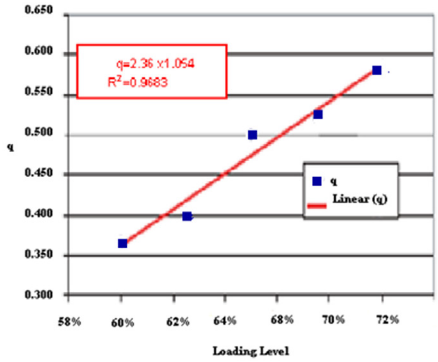

Fig.7: Evolution of q according to load (Toubal *et al*., 2006).

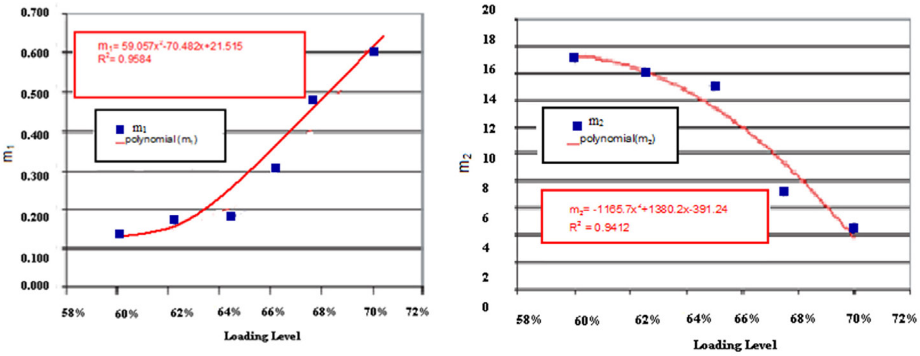

Fig.8: Evolution of m_1 and m_2 according to load (Toubal *et al*., 2006).

Table 1: The values of q, m_1 and m_2, Toubal *et al.* (2006)

Loading of load (%)	q	m_1	m_2
70	0.585	0.600	4.50
67.5	0.520	0.460	7.20
65	0.500	0.180	10
62.5	0.400	0.142	14
60	0.365	0.135	15

Fig.9 shows a comparison of the evolution of the damage for different loads by analytical means using Eq. (4), as proposed by Mao and Mahadevan (2002) and the experimental approaches. Fig.10 shows an image of the thermal distribution on the surface of the examined specimens provided by an infrared camera. It shows that the hot zone is localized at the centre of the specimens. The correlation between the increase of temperature and the damage evolution in the composites was done by using this thermography and experimental data. Fig.11a, Fig.11b, and Fig.11c show a comparison between the change of temperature and the damage at different loadings.

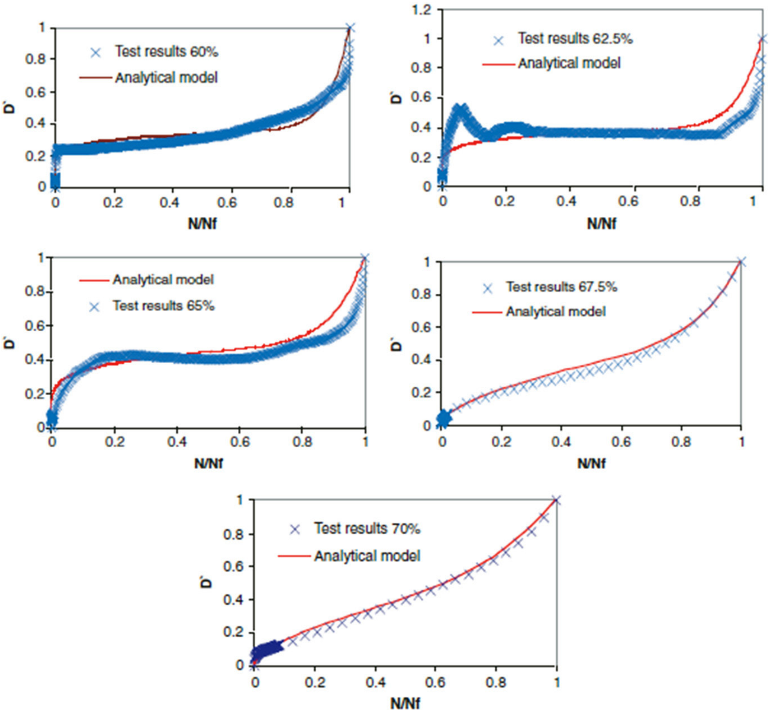

Fig.9: A comparison of the evolution of the damage by experimental and analytical (Toubal *et al*., 2006).

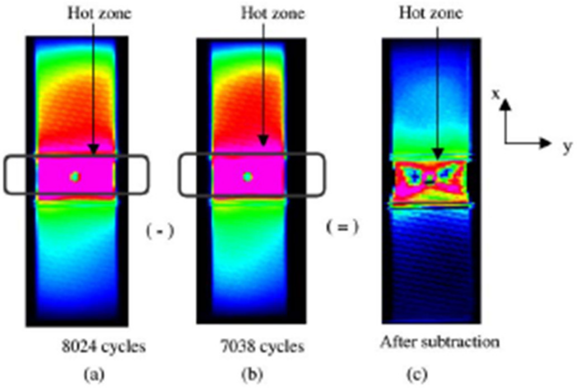

Fig.10: Various cartographics of temperature for various cycles (Toubal *et al*., 2006)

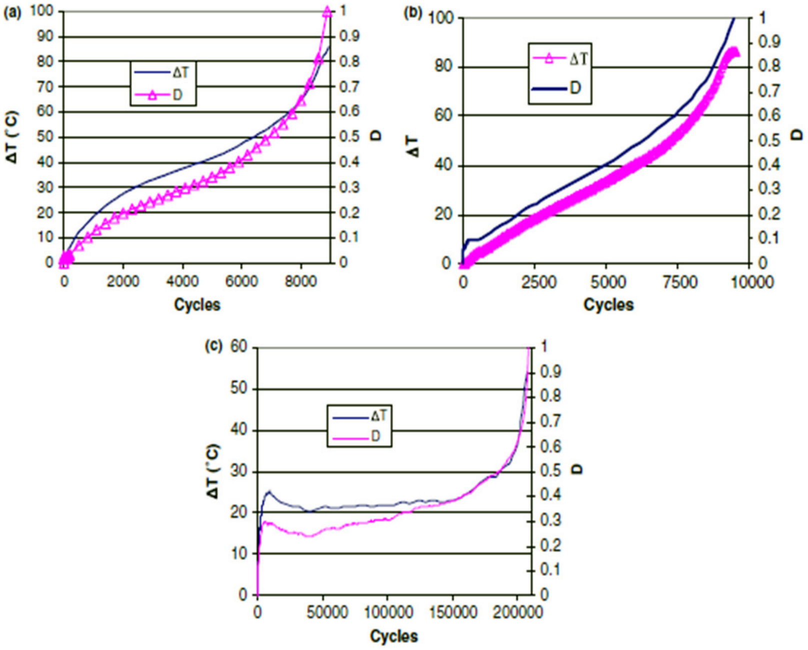

Fig.11: A comparison between the change of the temperature and the damage; (a) 70%loading, (b) 67.5% loading, and (c) 60% loading (Toubal *et al*., 2006).

Non-destructive Technique (NDT)

Non-destructive technique (NDT) is used for a group or a single part of an instrumental which does not damage or disturb (permanently) the object. NDT for testing and evaluating are the concepts and terms that have been used by the scientists or researchers for only the past 50-60 years (Boogard, 1994). The terms 'technique' and 'method' have been cautiously applied as follows*: method* will be used for the description of a discipline such as ultrasonic inspection, while pulse-echo or through-transmission is qualified as a *technique*. The principal objective of a non-destructive examination (NDE) is to provide the inspector with quantitative as well as qualitative information (Coffey, 1983). Non-destructive testing (NDT) is particularly relevant to the inspection of large and expensive components. The aerospace, food, nuclear and offshore industries are only a few examples of industries which employ a wide range of the NDT techniques. The most commonly used NDT methods in industry include visual inspection, liquid penetrant inspection, magnetic particle inspection, eddy current testing, alternating current potential drop, alternating current field measurement, ultrasonic testing, radiography and thermography. These NDT techniques can be used for the detection of unwanted discontinuities and separations in a material (flaws), structural assessment of a component (microstructure and matrix structure), metrology and dimensional purposes (thickness measurement, checking of displacement and alignment), determination of the physical properties of a material (electrical, magnetic or mechanical properties, as well as the detection of foreign bodies in food (Gros, 1996). In addition, NDT also provides information about product's properties such as composition and chemical analysis, stress and dynamics response, signature analysis and abnormal sources of heat (Giorleo & Meola, 2002).

CONCLUSION

Most of the presented studies conducted on predicting fatigue life of the composites materials or the proposed models have used synthetic fibre. There are still limited works done on predicting the fatigue life of natural fibre reinforced composites materials. Based on the review, the following are concluded:

1. Generally, it was found that many fatigue analyses had been done in composites materials but studies carried out on composites materials reinforced by natural fibres are rather limited.
2. As observed in the present results, most of the researchers obviously intended to use a non-destructive technique (NDT) in their work.

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