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Modelling the fatigue behaviour of composites honeycomb materials (aluminium/aramide fibre core) using four-point bending tests

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ABSTRACT

Composite Sandwich Materials are being increasingly used in high-performance structural applications because of their high stiffness and low weight characteristics. Presently, the long-term performance of such structures, especially under fatigue loading, is not enough studied. The aim of this paper is to address such fatigue behaviour by using a fatigue model verified by experimentation. The fatigue model is based on the fatigue modulus concept (degradation of stiffness) which is proposed for core-dominated behaviour and for two directions cells (L and W). Two non-linear cumulative damage models (L and W) derived from the chosen stiffness degradation equation, are examined in context with the linear Miner's damage summation and compared with available experimental results.

1. Introduction

The use of sandwich structure continues to increase rapidly due to the wide fields of their application, for instance: satellites, aircraft, ships, automobiles, rail cars, wind energy systems, and bridge construction to mention only a few. The sandwich composites are multi-layered materials made by bonding stiff, high strength skins facings to low density core material (Fig. 1). The main benefits of using the sandwich concept in structural components are the high stiffness and low weight ratios. In order to use these materials in different applications, the knowledge of their static and fatigue behaviours [1] are required and a better understanding of the various failure mechanisms under static and fatigue loadings conditions is necessary and highly desirable.

From phenomenological point of view, fatigue damage can be evaluated, in the global sense by stiffness, residual strength, dissipated energy or other mechanical properties [2–6]. Fatigue modulus concept for fatigue life prediction of composite materials is proposed by Hwang and Han [7]. It is suggested that the changes in stiffness might be an appropriate measure of fatigue damage. Many investigators have examined the effectiveness of the stiffness degradation in composite materials as a measure of accumulated damage [8]. To test the change in Young's modulus of material, the damage development of composite materials can be described by stiffness degradation of materials in fatigue behaviour investigation [9]. As residual strength, stiffness and life are affected by fatigue damage, only residual stiffness can be monitored non-destructively [10]. Residual strength decreases slowly with the increase of the number of cycles until a stage close to the end of life of the specimen, where it begins to change rapidly until complete destruction [11]. On the contrary, stiffness exhibits greater changes during fatigue specifically at the early stage of fatigue life of specimen [12]. Much important work on residual stiffness has been done by Reifsnider et al. [13]. The residual stiffness as a parameter to describe the degradation behaviour and to predict the fatigue life is selected by Wu et al. [14]. There is an interesting feature in stiffness degradation approach that only limited amount of data is needed for obtaining reasonable results [15]. Kin [16] reported that the reduction of bending strength of foam cored sandwich specimen is caused by the stiffness reduction of foam due to ageing of polyurethane foam during fatigue cycles. Shenoi [17] investigated the static and flexural fatigue characteristics of foam core polymer composite sandwich beams. Failure modes relate to both core shear and skin failure. Jen and Chang [18] analysed the four-point bending fatigue strengths of aluminium honeycomb sandwich beams with cores of various relative densities. In their study, the debonding of the adhesive between the face sheet and the core was identified to be the major failure mode. Kulkarni et al. [19] observed the fatigue failure of foam core sandwich composites under flexural loading. The crack propagation rate was used to predict the

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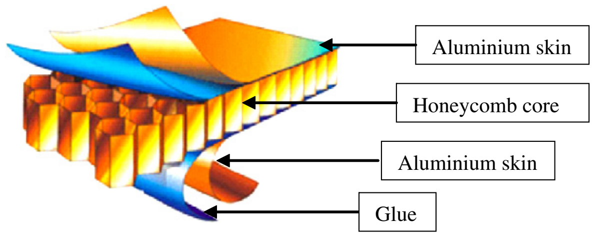

Fig. 1. Description of the honeycomb sandwich structure.

fatigue life. Azouaoui et al. [20] investigated the evaluation of impact fatigue damage in glass/epoxy composite laminate. The fatigue characteristic of two cellular foam core materials is tested by Burman and Zenkert [21]. The bending fatigue behaviour of pure epoxy and 3D woven sandwich composites is studied by Judawisastra et al. [22]. Panel with aramide fibre core were selected. The results of the stiffness degradation correlated well with the mechanical properties of the sandwich panel. The purpose of this study is to develop analytical models describing the flexural behaviour of honeycomb composite core (aramide fibre) sandwich under cyclic fatigue. The stiffness degradation approach allows the assessment of the fatigue damage. Two non-linear cumulative damage models for (L and W) oriented cells derived from the chosen stiffness degradation equations are examined assuming linear Miner's damage summation. Predicted results are compared to the available experimental results. It is worth it to note that the proposed models are not compared with other existing works, since there is no similar investigation in the literature with the considered material (Sandwich with aluminium skins and Nomex core with the same core geometry, dimension and density).

2. Fatigue modelling

2.1. General

Fatigue damage in composites and other related materials has often been modelled by using the reduction in strength or stiffness. With strength-degradation approaches, the residual strength is determined from a static test after fatigue cycling, so that a series of tests are required to determine a single strength degradation curve. The Strength Life Equal Rank Assumption (SLERA) is often assumed, which states that the rank in static strength is equal to the rank in fatigue life. This assumption appears to be valid for a wide range of fibre-reinforced plastics where the scatter in fatigue data is primarily due to variations in static strength, provided that the failure mode does not change [23]. A statistical distribution of strengths determined from static tests of undamaged specimens until failure is often used to relate the static scatter to the scatter of residual strengths in fatigue [23–25]. Stiffness degradation methods have the advantage of being able to allow measurement of effective stiffness during cycling without destruction of the specimen, so that a stiffness degradation curve can be obtained from a single test. Smaller numbers of specimens are required and average results can be used rather than the use of a full statistical analysis. However, stiffness can be defined in different ways. Usually, it is taken as a modulus term where the reduction in stiffness can be measured from the linear portions of stress/strain graphs at different cycle numbers. Yang et al. [26] assumed that the degradation rate is a power-law function of the number of load cycles. This approach is mainly suitable for fibre-dominated response where the stress/strain curve is linear. Hwang and Han [27] introduced a model based on the fatigue modulus concept, an approach particularly suitable for resin-dominated behaviour. During fatigue cycling, the stress/strain curve changes, causing a reduction of fatigue modulus. The fatigue modulus at a specific load cycle, n, is represented on the stress/strain curve by a line drawn from the origin to the resultant strain at the applied stress level. The rate of decrease of fatigue modulus can be related to an empirical power-law function of the form An^C. The theoretical decrease in modulus from an initial static value can be expressed as:

$$G_f(n) = G_0 - An^C \tag{1}$$

where $G_f(n)$ and G_0 are the transient fatigue modulus and instantaneous static modulus, respectively, and A and C are material constants to be determined from experimental study. This is achieved by converting the experimental deflection response into fatigue modulus term (see Section 4). Assuming a normal distribution, the constants are determined by using curve fitting techniques.

Clark et al. [28] modified this model because it is applied to the secondary region of the fatigue modulus response, i.e. $n \geqslant n_{if}$. Therefore the cycle number, n, must be replaced by $(n - n_{if})$. After closer examination of the secondary region of the experimental deflection response, the power-law function shown in Eq. (1) was deemed to be less satisfactory than an exponential function. Thus Equation was modified and expressed as:

$$\left.\begin{array}{lll} G_f(n) = G_0 & \text{where} & n \leqslant n_{if} \\ G_f(n) = G_0 - Ae^{(n-n_{if})C} & \text{where} & n \geqslant n_{if} \end{array}\right\} \tag{2}$$

where n_{if} is the number of cycles to initiate damage.

The equation used by Clark et al. [28] to predict the number of cycles at failure for different applied stress level, r was given by:

$$N_f = n_{if} + \frac{\ln[B(1-r)]}{C} \tag{3}$$

where $B = \frac{G_0}{A}$, r is equal to the ratio of applied stress to ultimate static stress, $\left(r = \frac{\tau_a}{\tau_u}\right)$, and N_f is the number of cycles at failure.

2.2. Cumulative damage model

2.2.1. General damage model

At a constant frequency and environmental condition, fatigue damage, D accumulates from an initial damage state, usually equal to zero, at zero cycles to a final failure value, usually equal to unity.

For constant loading

$$\left.\begin{array}{lll} D = 0 & \text{where} & n = 0 \\ D = 1 & \text{where} & n = N_f \end{array}\right\} \tag{4}$$

2.2.2. Cumulative damage equations

Different forms of the cumulative damage parameter, D, can be chosen depending on the degree of linearity of the degradation response. Two models are investigated. The first model is linear, based on "number of cycles", whilst the second a model based on changes of "modulus". Damage is assumed to initiate when fatigue damage is first observed, i.e. at $n = n_{if}$. At $n = N_f$ the damage is equal to one. For the purpose of all the cumulative damage models investigated it is assumed that:

$$\left.\begin{array}{lll} D(n) = 0 & \text{where} & n \leqslant n_{if} \\ D(n) = 1 & \text{where} & n_{if} \leqslant n \leqslant N_f \end{array}\right\} \tag{5}$$

(A) Model I: The most basic linear cumulative damage model is that proposed by Miner [29] which was originally derived from energy considerations. It states that the amount of damage at a given number of cycles is the ratio of the current cycle number to the number of cycles to cause fatigue failure. In this case, the damage model occurs after the initiation of damage and can be expressed as: