FATIGUE DAMAGE EVOLUTION IN LAMINATE COMPOSITES WITH BALSA WOOD

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The damage evolution mechanism is one of the most important issues in fatigue behaviour investigation of composite materials, also, it serves as basis for predicting the fatigue life of composite structures for engineering applications. In this paper, the fatigue damage in laminate composites with seven plies of melamine and balsa wood, $\left[0_m^1, 90_b^1, 0_b^2, \overline{90}_b^2\right]_S$, was evaluated, based on a phenomenological fatigue damage model defined by material stiffness degradation. The results were expressed in terms of fatigue damage parameter as a function of normalized fatigue life, for different stress levels.

Keywords: fatigue damage, stiffness degradation, composite laminate, normalization fatigue life

INTRODUCTION

Wood is the most ancient, but still the most widely used structural material in the world. Today, the world production of wood is roughly the same as that of iron and steel; with about 10^9 tonnes per year, this production finds many uses. Balsa wood is generally characterized by low density, good heat and sound insulation, being therefore preferred for insulation, cushioning, models, cores for sandwich panels, panels and doors for inner design of railway vehicles. The mechanical properties of balsa wood, like those of cellular solids, depend primarily on the properties of the cell wall, on the relative density and shape of the cells. If a sample of wood is cut at a sufficient distance from the centre of the tree, three orthogonal planes of symmetry may be observed: the radial, the tangential and the axial one (Fig. 1). Stiffness and strength are the highest in axial direction, that is parallel to the trunk of the tree, comparatively with the radial and tangential directions. All these differences are related to the structure of wood. At a mm scale, balsa wood is a cellular solid: cell walls, often with the shape of hexagonal prisms, enclose the pore space (Fig. 2).

The present paper describes a fatigue damage evolution procedure for laminate composites with plies of balsa wood with different fibre orientations.

The fatigue damage and failure mechanism of composites is more complex than that of metals, and four basic failure types will occur in composites under cyclic loading, namely, matrix cracking, interfacial debonding, delamination and fibre breaking.

Based on experimental investigations, in recent decades, many damage models,[1–6] defined by strength degradation, stiffness degradation and energy dissipation of composites, have been employed to describe the damage development of materials. The understanding of damage evolution mechanisms developed from linear to nonlinear models. Under cyclic stress or strain, irreversible structural changes will occur in micro local field in composite materials, leading to the fatigue damage of composites. With increasing the number of loading cycles, the change will also increase and the damage will cumulate synchronously. The accumulation of damage leads to a change in the macroscopic mechanical properties of the composites, such as degradation of strength or stiffness of the material. Starting from experimental investigations, Reifsnider[1] concluded that fatigue damage evolution is nonlinear in composite materials. During the initial period of fatigue life, many non-interactive cracks occur in the matrix. When matrix crack density reaches saturation, fibre failure, interfacial debonding and delamination occur in the composites. Damage will rapidly develop, causing the "sudden death" of the material at the end of fatigue life, as shown in Figure 3.

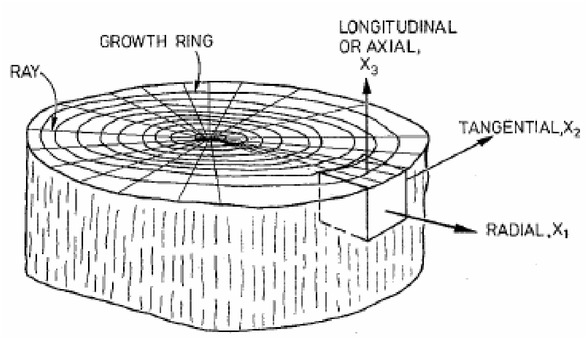


Figure 1: Section through a tree trunk showing axial, radial and tangential directions[18]

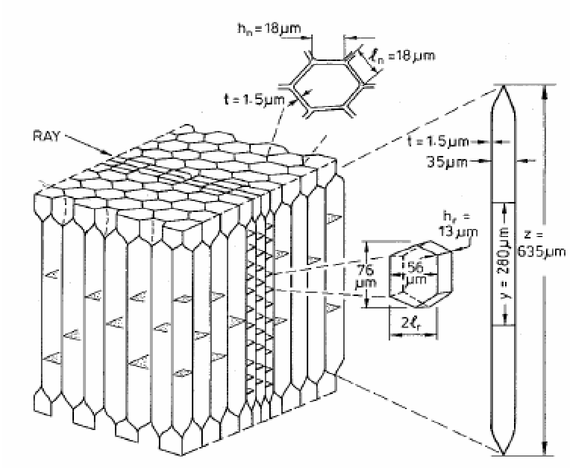


Figure 2: Cellular structure of balsa wood[18]

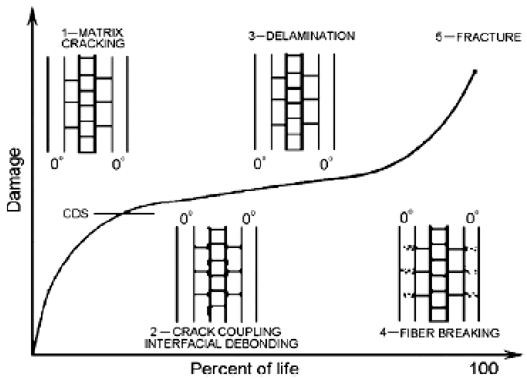


Figure 3: Fatigue damage evolution in laminate composites[1]

To test the change produced in Young's modulus of the materials during fatigue behaviour investigations, the damage development of composite materials was described by stiffness degradation of the materials. Based on this technique, known as saving both experimental time and costs, many nonlinear damage evolution models[6] were presented. The models defined by stiffness degradation of laminate composites have been widely investigated – both theoretically and experimentally – as they fairly describe the damage progress in the initial or/and middle period of fatigue life.

EXPERIMENTAL

An experimental study on fatigue damage evolution in composite laminate has been performed. Fatigue damage is expressed by material stiffness degradation. Damage mechanics provides an effective approach for the measurement of damage, *D*, accounting for the damaged area on a given plan, A_d, in terms of the original area, A_0, in a material with a uniform distribution of cracks,[6] so that:

$$D = \frac{A_d}{A_0} \tag{1}$$

Applying Hook's law for stress substituton, damage definition can be related to the initial elastic modulus, E_0, and to the fatigue modulus, E_N, after N cycles:

$$D = 1 - \frac{E_N}{E_0} \tag{2}$$

Decrease in modulus, shown to correspond to an increased crack density, can be used as an indicator for uniform damage in composites. Eq. (2) is equivalent with the following relationship:

$$D = 1 - \frac{\varepsilon_0}{\varepsilon_n} \tag{3}$$

where: ε_n is strain accumulation after N cycles, corresponding to the applied stress level, and ε_0 is the strain registered at the static tensile test, corresponding to the same stress level.

Table 1
Lay of plies in laminate composites

$$\left[0_m^1, 90_b^1, 0_b^2, \overline{90}_b^2\right]_S$$

Melamine	0°	1 mm thickness
Balsa wood	90°	1 mm thickness
Balsa wood	0°	2 mm thickness
Balsa wood	90°	2 mm thickness
Balsa wood	0°	2 mm thickness
Balsa wood	90°	1 mm thickness
Melamine	0°	1 mm thickness

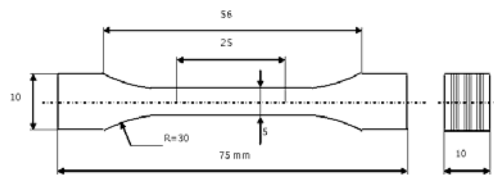


Figure 4: Specimen used for static and cyclic tensile tests

This procedure was applied for laminate composites with seven plies of melamine and balsa wood, described in Figure 4 and Table 1, subjected to static and cyclic tensile tests at different stress levels. A Walter-Bai model servo-hydraulic testing machine was used to perform all static and cyclic tests. The testing frequency was 2 Hz, a sinusoidal waveform being used for cyclic tests. The tests were carried on at room temperature. The strains were measured using an MFL-extensometer.

Cyclic tests were conducted for the applied stress levels, corresponding to 80, 60, 50, 40 and 30% of the ultimate tensile strength, σ_{ult}, at R = 0.08.

RESULTS AND DISCUSSION

The results of static tensile tests of the laminate composites under analysis are listed in Table 2.

The fatigue results were expressed in terms of cyclic stress – strain (Fig. 5), and damage parameter, D – as a function of the normalization fatigue life, n/N (Fig. 6).

Simultaneously, for all applied stress levels, the number of cycles up to failure of the first layer of the laminate composite was recorded, and the σ_{maxapp}–N fatigue curve was determined in log-log coordinates (Fig. 7).

The fatigue curve shows that the variation between the maximum applied stress, σ_{maxapp}, and fatigue life, N, is given by the following equation:

$$\sigma_{\max app} = 37.145 \cdot N^{-0.076} \tag{4}$$

Solving equation (4) leads to:

$$N = e^{\frac{3.616 - \ln \sigma_{\max app}}{0.076}} \tag{5}$$

Based on the damage evolution curves (Fig. 6) for 40, 50 and 80% from σ_{ult}, it was found out that the variation between the damage parameter, D, and normalization fatigue life, n/N, is given by equation (6), where *A* and *B* are constants depending on the maximum stress applied.

$$D = A \cdot \ln\left(\frac{n}{N}\right) + B \tag{6}$$

By graphically representing constants A and B as a function of the applied stress level, corresponding to 40, 50 and 80% of σ_{ult}, the following equations resulted:

$$\mathbf{A} = -0.0002 \cdot \sigma^2_{\mathbf{max\ app}} + 0.0106 \cdot \sigma_{\mathbf{max\ app}} - 0.0874 \tag{7}$$

$$\mathbf{B} = -0.0008 \cdot \sigma^2_{\mathbf{max\ app}} + 0.0494 \cdot \sigma_{\mathbf{max\ app}} - 0.3629 \tag{8}$$

By introducing relations (5), (7) and (8) in (6), a procedure that can predict damage evolution at any applied stress levels was proposed.

This procedure was used to determine the damage evolution curve for 40 and 50% of σ_{ult}, the results being compared with the experimentally obtained data (Fig. 8). A good agreement was established between the experimental and the predicted values of fatigue damage.

Table 2
Results of tensile tests of composite laminate $\left[0_m^1, 90_b^1, 0_b^2, \overline{90}_b^2\right]_S$

Specimen No.	h [mm]	b [mm]	A [mm^2]	L_0 [mm]	F_{max} [N]	E_x [MPa]
1	10	5.1	51	25	1584	4500
2	10	5	50	25	1713	4437.5
3	10	5.1	51	25	1744	4272.72
4	10	5.1	51	25	1758	4555.55
Averages					1699.8	4441.44

h – thickness of specimens; b – width of specimens; A – cross-section of laminate composite specimens; L_0 – calibrated length; F_{max} – maximum value of force recorded at tensile tests; E_x – longitudinal Young's modulus of laminate composite

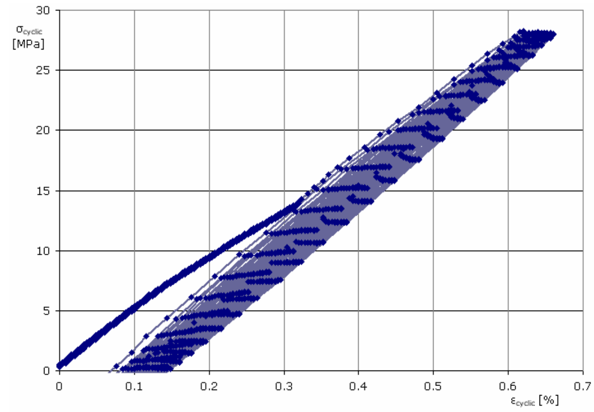


Figure 5: Cyclic stress – strain for applied stress level, corresponding to 80% of σ_{ult}

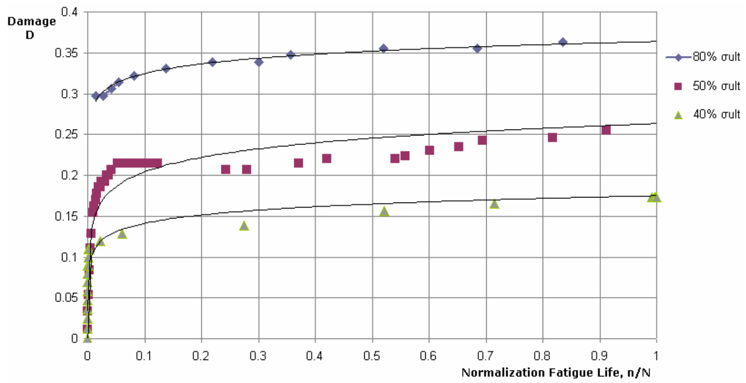


Figure 6: Evolution curve of fatigue damage parameter, D, for 3 applied stress levels

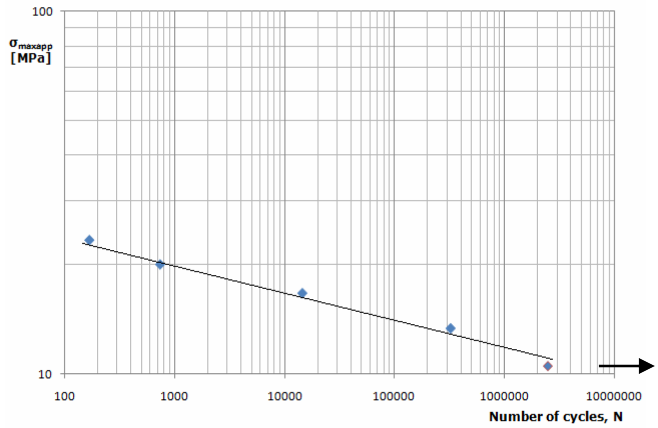


Figure 7: Fatigue curve of tested laminate composite, in log-log coordinates

Macro and micro structural analysis of fracture surfaces

For a complete evaluation of the fatigue damage mechanism of the laminate composites here under investigation, macro and micro structural analysis of the fracture surfaces was performed. To this end, an Olympus SZXT stereo microscope and a SEM microscope type FEI Inspect S were employed. Microscopic observations showed that fracture was initiated in balsa wood layers oriented at 90° on loading direction.

Figure 9 a and b evidences the presence of cracks and pores in balsa wood layers oriented at 90° on loading direction, causing a rapid accumulation of damage in stage I.

SEM analysis indicates a brittle fracture of the melamine layer; in the balsa wood layers oriented transversally (90°) to the loading direction, cracks may be observed on the fibre walls, providing information on fracture – cell-wall breaking mechanism (Fig. 10 a and b).

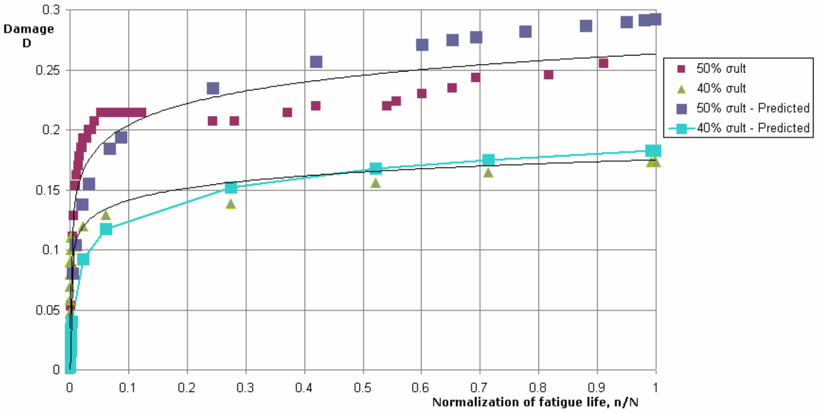
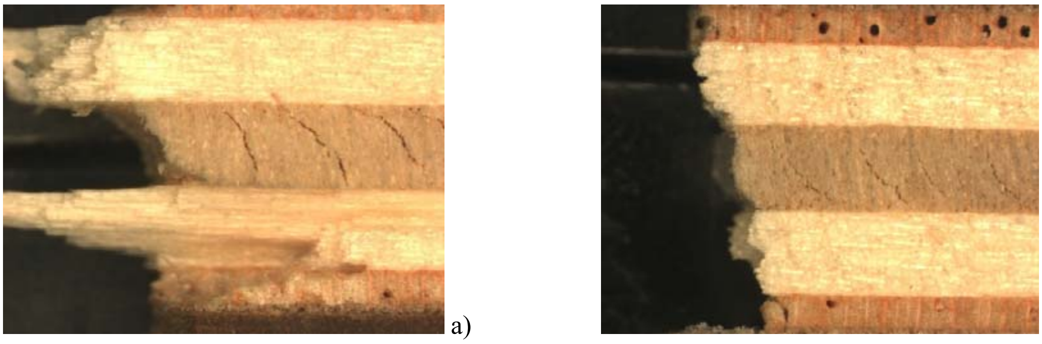
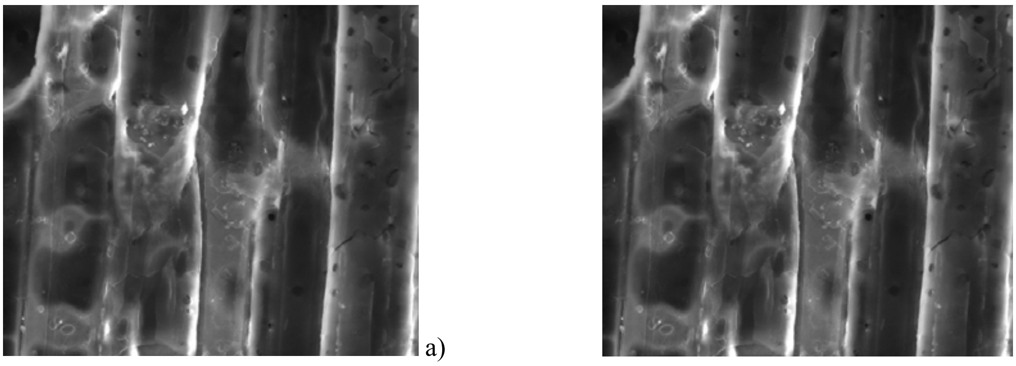


Figure 8: Comparison of predicted and experimental fatigue damage evolution curves for 40 and 50% of σ_{ult}



a) b)

Figure 9: Cracks and pores in balsa wood layers, oriented at 90° on loading direction; a, b – macro structural observations



a) b)

Figure 10: Cell-wall breaking mechanism; a, b – SEM observations

CONCLUSIONS

Based on the stiffness degradation rule of composite materials under fatigue loading, a damage procedure is presented. The accumulation of damage in laminate composites $\left[0^1_m, 90^1_b, 0^2_b, \overline{90}^2_b\right]_S$ can be described by a simple two-stage model. Initially, in stage I, fatigue damage increases rapidly, developing into a steady-state stage II damage accumulation for the remaining life. The fatigue damage parameter is capable of describing damage evolution throughout the whole life cycle, and can be applied to predict fatigue life.

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