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Characterisation of the tensile fatigue behaviour of RTM-laminates by isocyclic stress–strain-diagrams

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Abstract

In this work a new evaluation method for the characterisation of the fatigue behaviour of carbon/epoxy laminates, manufactured in the resin transfer molding (RTM) process, is introduced. Fatigue data are represented in isocyclic stress–strain diagrams by plotting associated pairs of stress and strain values for each 10^xth cycle. Isocyclic stress–strain curves are comparable to isochronous stress–strain curves for static tests. These curves represent a material law encompassing reversible visco-elastic effects as well as irreversible damage accumulation and can be used in the design of cyclically loaded components to predict their endurance limits. This paper concentrates on the characterisation of laminates made from compacted fabric packages using binder and sewing techniques and infused with RTM epoxy resins.

Keywords: Cyclic stress–strain curve; Fatigue test methods; Polymer matrix composites

1. Introduction

Because of its excellent weight-saving and load-bearing capacity, applications of fibre-reinforced composites have rapidly increased during the past three decades, especially in aircraft and spacecraft areas, which have typical weight-sensitive structures [1]. Manufacturing processes related to liquid resin molding continue to receive significant interest for aerospace applications. Liquid resin infusion methodologies, such as resin transfer molding (RTM) have been introduced in recent years as alternative technologies to conventional prepreg processes. In addition to a significant cost reduction potential the RTM process offers several advantages like the fabrication of hollow shapes and complex integrated structures, an excellent dimensional control with tight tolerances and good surface finish and the use of 3D-wovens, stitched assemblies and braids as reinforcement types. However, in general the impregnation of the various reinforcement types requires low viscosity resin systems which in the cured state tend to be rather brittle. On the other hand, using tougher resin formulations of higher viscosity may lead to poor impregnation and voids.

To date, the adoption of the RTM process for the manufacture of aerospace primary structures is ongoing and highly toughened RTM resin are on the market [2]. Different preform compaction methods, as binder or sewing techniques are under development in order to achieve the required fibre volume fraction. Distortion of dry fabric can be prevented by applying different compaction methods as well.

Material qualification for aerospace applications is expensive and time consuming and frequently contributes to delays in the application of new materials. It is thus imperative to develop new evaluation methods to speed up durability testing if composites are to find further applications in structural aerospace parts.

In aircraft applications fatigue properties are an integral part of material comparison and selection but they are also important for component design. Fatigue is a very critical loading mode for laminates, because under cyclic loads

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failure occurs by the initiation and growth of a crack (delamination) at loads far away from the strength of the material. Generally, conventional "Wöhler" curves or *S*–*N* (S = stress amplitude or stress maximum, N = load cycle number) curves or hysteresis measurements are used to characterise the behaviour of laminates under cyclic loads [3–12].

The generation of "Wöhler" curves or *S*–*N*-curves is very time-consuming and a large number of test specimens is needed; nevertheless, they only allow failure criteria for cyclically loaded components to be inferred and therefore enable the definition of allowable stresses as a function of the number of load cycles. The number of cycles to failure measured, however, gives no information about possible structural changes in the material. Moreover, the periods of crack initiation and growth can generally not be differentiated.

Hysteresis measurements are usually evaluated as a stiffness decrease and a change in the damping behaviour as a function of load cycle number. The goal is to detect structural changes in a material and thus to establish load limits; nevertheless, although the elongation is measured, no deformation analysis is usually carried out.

Therefore we propose in this work the characterisation of such changes using isocyclic stress–strain diagrams (ICSS diagrams) [10]. Analogous to the isochronous stress–strain diagrams that are widely used in plastics engineering, ICSS diagrams correlate stress (σ), strain (ε) and load cycle number (N) in an isocyclic way and represent a material law, from which the design engineer can obtain the elastic (E) modulus as a function of load cycle number and load as well as estimations of allowable stresses. Within this study, the influence of different preform compaction methods and resins on the fatigue behaviour of laminates manufactured in the RTM technique was described with the help of ICSS diagrams.

2. Experimental

2.1. Materials and test-specimen production

Six different RTM laminates were manufactured from eight layers of carbon fabric. Five laminates were infused with the epoxy resin RTM6™ (Hexcel Composites, Dagneux, F):

- An uncompacted laminate with the woven carbon fabric HTA-5H-6k-370 (Hexcel Composites, Dagneux, F).
- A compacted laminate with the binder-coated fabric G0926 D 1304 INJ E01 2F™ (Hexcel Composites, Dagneux, F); this binder-coated fabric was consolidated in a heating press at 100 °C for 20 min.
- Three polyester-stitched laminates (woven carbon fabric HTA-5H-6k-370, stitching yarn LT 220™ (Gütermann, Gutach, G)). Stitching was performed in parallel rows at ±45° to the direction of the woven roving plies. The distance between each row and the next was 20 mm and the stitch length was 4 mm. Preforms were produced with eight, four or two layers stitched together in one step. In order to investigate the influence of stitch density, the preforms were built up using different packages. To obtain the final thickness of the RTM test panels, one preform was made from a single 8-layer package, a second preform from 2 packages of 4 layers each and finally a third preform made from 4 packages with 2 layers each.

One laminate was made by infusing the hybrid fabric PRIFORM™ 6k HTA-5H-370-ST-T1 with the epoxy resin CYCOM™ 977-20RTM to give the new toughened RTM system developed by Cytec Engineered Materials (CEM, Wrexham, GB).

Laminates were injected in a 500 × 500 × 3 mm matched mould using a RTM piston equipment manufactured by ISOJET (Lyon, F). Rectangular specimens in the dimension of 250 × 15 mm for monotonic tensile testing and 250 × 25 mm for tensile fatigue testing were cut out from the RTM panels. The test specimens from the stitched panels were cut so that the loading direction was at ±45° to the direction of the stitching during testing.

The internal designations for the uncompacted Hexcel Composites material and the binder-coated material were INJW and INJBC1, respectively. The stitched formulations were named INJST1 × 8, INJST2 × 4 and INJST4 × 2 according to the single packages. The designation for the material from CEM was PRIW. In Table 1 the investigated laminates are summarised.

2.2. Monotonic tensile and tensile fatigue testing

Monotonic tensile and tensile fatigue testing were conducted using a computer-controlled MTS 810 servo-hydraulic testing machine (MTS System Corp., Berlin, G) with servo-hydraulic wedge grips that were especially designed for testing without applying any tabs to the test specimens. The tests were carried out in a laboratory environment of 23 °C and 50% relative humidity. Monotonic tensile tests were conducted at a cross-head speed of 1 mm/min with rectangular test specimens (250 × 15 mm). The *E*-modulus of each sample was determined according to the relevant standard EN2561 (calculated between 10% and 50% of failure load).

All tensile fatigue tests were performed under load control at a frequency of 10 Hz and a stress ratio of $R = 0.1$ (min. stress/max. stress) with rectangular test specimens (250 × 25 mm). The different stress levels selected were 35%, 60%, 70% and 75% of the tensile strength of the individual laminates. At each stress level 3 test specimens were tested and average values of the generated results were taken for data presentation. In order to limit the duration of the tests, the number of cycles was restricted to a maximum number of 10^6 cycles.

All the measured stresses in the tensile and tensile fatigue tests were normalised to a fibre volume fraction of 57%.