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Technical note

Damage initiation in polymer matrix composites under high-cycle fatigue loading – A question of definition or a material property?

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ABSTRACT

Damage initiation in composites under high-cycle fatigue loading is often defined by the presence of a crack of detectable size. This article is intended to assess if damage initiation under cyclic loading can also be described in a more physical way. In order to achieve this, SN-curves for fatigue damage initiation are normalized by dividing the maximum stress per load cycle by the static strength. By presenting normalized fatigue damage initiation data, the influence of specimen geometry, test setup and fiber type can be eliminated. The normalized presentation of the experimental data suggests that fatigue damage initiation in composites subjected to high-cycle fatigue loading may indeed be a material property of the resin which can be described by a normalized SN-curve.

1. Introduction

Since the 1960s fiber reinforced composites have been introduced into the aerospace industry. Failure due to fatigue has for a long time not considered a major design driver for airframe structural applications due to the low strain allowables imposed by mitigation rules for the consequences of impact damage [1]. Composites have now been introduced into rotating components such as fan blades in jet engines or helicopter rotor blades. As these components exhibit a large number of cycles (>10^7) during their life, fatigue becomes an issue that the designers have to treat explicitly. Even though there are many competing damage mechanisms in composite materials, fatigue life of polymer matrix composites, similar to metallic structures, can be divided into two main phases: A damage initiation phase and a damage propagation phase [2,3]. Nowadays, the damage propagation phase is well understood and can be described by the Paris law [4] relating the crack growth rate to the applied energy release rate. Therefore damage propagation is a material property which can be described using physically based models. The damage initiation phase on the other hand has not been studied intensively. Instead, damage initiation has always been described in a more phenomenological way without strong physical justification. An engineering definition for fatigue damage initiation is "the time required forming a crack of detectable size" [5]. This poses the question: what is detectable? Damage in composite materials is usually not detectable with visual methods. Non-Destructive Test (NDT) methods such as X-rays, C-scans or acoustic emission allow monitoring of damage initiation and growth [6]. Depending on the measurement equipment used the detectable crack size can vary from a few tenths of a millimeter [2] to a few millimeters [7]. This led to Fricke and Müller-Schmerl's definition of a "technical crack length" for initiation of l_{ini} = 3 mm [8]. There have only been a few attempts to identifying the onset of delamination under fatigue loading on a physical basis rather than the phenomenological approaches described above. Hiel et al. [9] performed fatigue tests on elliptical specimens made from T300/934 carbon/epoxy. Under both quasi-static and fatigue loading these specimens failed by sudden mode I delamination. On the global time scale, the propagation phase was so short that the moment of failure can be seen as the onset of delamination. Wisnom and Jones [10] manufactured humpback bridge specimens from E-Glass/913 and subjected them to cyclic bending loading. The geometry used is sketched in Fig. 1.

For both, specimens with cut plies, acting as crack starters, and without cut-plies, the specimens failed in similar fashion to the elliptical specimens tested by Hiel et al. [9]. Expectedly, the cut-ply specimens failed at lower load levels than the pristine specimens as shown in Fig. 2a). However, Wisnom and Jones noted that if the fatigue strength data (SN-curve) was normalized with the quasi-static strength, the fatigue life curves for the cut-ply specimens and the pristine specimens collapse into a single master-curve as shown in Fig. 2b).

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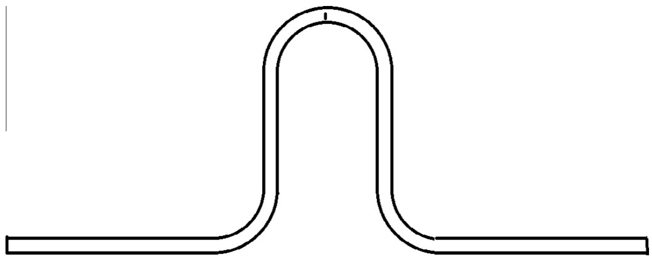

Fig. 1. Humpback bridge specimen.

This is a first indicator that the initiation of mode I delamination under fatigue loading is a material property. The purpose of this article is therefore to analyze additional data from the literature to investigate if damage initiation is indeed a material property or if the classical phenomenological definition of damage initiation is sufficient.

2. Material and literature data

For this study, literature data on aerospace grade resin HexPly® 8552 is analyzed. HexPly® 8552 is an amine cured, toughened epoxy resin system. The system is supplied in form of prepreg material with unidirectional or woven carbon or glass fibers.

O'Brien et al. [11] studied the initiation damage in IM7/8552 carbon/epoxy and S2/8552 glass/epoxy specimens under transverse tension fatigue induced by cyclic bending of thick 90° laminates. For both materials, static and cyclic bending tests were performed in three-point and four-point bending configurations. Under bending, a crack initiates at the tensile surface and propagates very quickly toward the top surface. On the general timescale the propagation phase is very short. One can therefore assume that initiation happened at the same time as the sample broke into two pieces. This is of particular importance as this allows a straightforward analysis of fatigue damage initiation without the need for considering a long damage propagation phase.

The glass/epoxy tests were performed on 24 ply UD beams with an average thickness of 5.56 mm, width of 6.35 mm (∼1/4″) and length of 57.2 mm (∼2.25″). The span between the support rollers was 50.8 mm (∼2″). The span between the loading rollers for the four-point bending test was 25.4 mm (∼1″).

The carbon/epoxy tests were performed on 40 ply UD beams and 24 ply UD beams for three-point bending and four-point bending tests, respectively. The specimens for the three-point bending test were of thickness 4.93 mm, width 6.35 mm, and length 57.2 mm long. The four-point bending specimens were cut twice as wide to increase the failure load and decrease the deflection at failure. The specimens were tested in the same configuration as the glass/epoxy specimens. The test setups are shown in Fig. 3.

Table 1 summarizes the different test configurations and the associated static failure strengths.

As expected the static failure strength is highly influenced by material type (e.g. type of fiber), specimen geometry (e.g. composite thickness) and test configuration (e.g. 3 PB or 4 PB). O'Brien et al. [11] used the same test configurations to determine transverse tension fatigue life. Cyclic three-point and four point bending tests on glass/epoxy were carried out for the stress ratio $R = 0.1$ and maximum cyclic stresses in the rage of 77–92 MPa. Cyclic three-point bending tests on carbon/epoxy were carried out for $R = 0.1$ and maximum cyclic stresses ranging from 72.7 MPa to 84.9 MPa. Cyclic four-point bending tests on carbon/epoxy were carried out for $R = 0.1$ and maximum cyclic stresses in the range of 64.7 – 78.6 MPa. Fig. 4 shows four SN-curves extracted from the data presented by O'Brien et al. [11]. Solid diamonds indicate four-point bending tests performed on IM7/8552 carbon/epoxy, solid squares indicate four-point bending tests performed on S2/8552 glass/epoxy, hollow diamonds indicate three-point bending tests performed on IM7/8552 carbon/epoxy, hollow squares indicate three-point bending tests performed on S2/8552 glass/epoxy. In this classical maximum stress based presentation of the data, there is no obvious connection between data taken from different test setups or fiber types. In addition to the quasi-static strength, fatigue damage initiation seems to be dependent on extrinsic parameters such as test setup and specimen geometry. Additionally, the type of fiber used (IM7 carbon fiber or S2 glass fiber) has a strong influence on the SN-curve.

3. Further discussion of data

Following Wisnom and Jones [10], the data were then processed further by normalizing the maximum stresses per load cycle with the static strength. The underlying idea of this normalization is the elimination of the aforementioned extrinsic effects (e.g. specimen geometry and test setup). Fig. 5 compares normalized three-point bending data for S2/8552 glass epoxy (squares) and IM7/8552 carbon/epoxy (diamonds). The normalized data points seem to collapse into a master-curve indicating that for three-point bending configuration there is no influence of the fiber type. Fig. 6 compares normalized four-point bending data for S2/8552 glass epoxy (squares) and IM7/8552 carbon/epoxy (diamonds). Again, the normalized data points seem to collapse into a master-curve. Consequently, for the four-point bending configuration there is also no influence of the fiber. Similar observations were made by Kawai [12] as well as Quaresimin and Carraro [13] for resin dominated failure in off-axis tension and tension–torsion

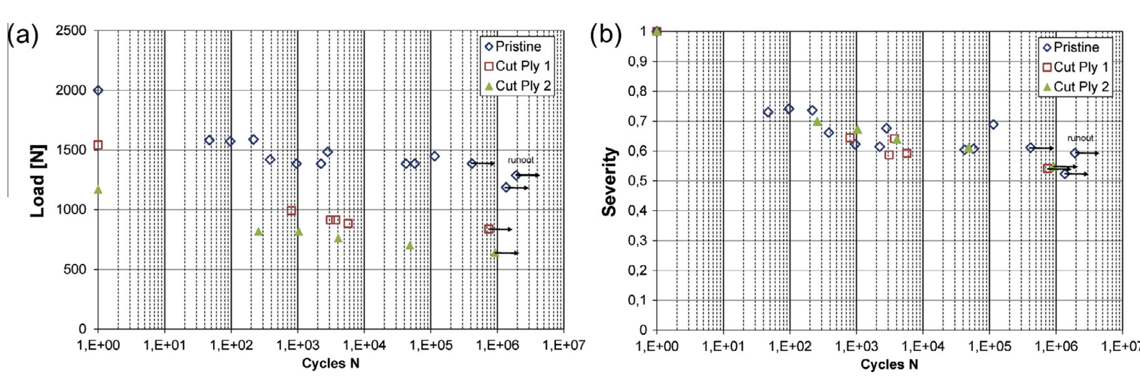

Fig. 2. Summary of mean fatigue life data extracted from [10].