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Fatigue life and backface strain predictions in adhesively bonded joints

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ABSTRACT

Fatigue is a very important factor in any adhesively bonded structure subject to service loads. Prediction of fatigue life using finite element analysis (FEA) techniques is very complicated due to the complex nature of fatigue damage. This paper presents experimental data obtained by testing single lap joints (SLJs) in constant amplitude fatigue at a range of load levels and associated fatigue damage modelling. Six strain gauges (SGs) placed along the overlap were used to monitor fatigue initiation and propagation within the adhesive layer. An elasto-plastic damage model was developed that was capable of predicting the experimentally observed backface strain patterns and fatigue life at different fatigue loads. It was implemented in the finite element code ABAQUS and used a user defined subroutine to calculate the damage, and the resultant degradation in adhesive Young's modulus and yield stress.

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1. Introduction

Fatigue loading is a common cause of failure in structures. Although much fatigue testing of adhesively bonded joints has been undertaken comparatively little work has been addressed at simulating the fatigue damage process. This paper addresses this important area. Several experimental and modelling approaches to detect and monitor damage initiation in adhesively bonded structures have been assessed. Recent work has included the use of the backface strain technique and video-microscopy.

Quaresimin et al. [1] tested SLJs of varying overlap length in fatigue at different stress levels and conditions. The damage was monitored using video-microscopy and a crack length of 0.3 mm was arbitrarily fixed as a threshold value for crack initiation. This damage was defined as a crack nucleation phase during which the adhesive whitened and crazed. This phase lasted between 20% and 70% of the fatigue life depending on the stress level and overlap.

On the other hand Xu et al. [2] observed the damage initiation as a process of microcrack formation. A series of microcracks appeared ahead of the tip and then merged into a major crack. This pattern was also seen by Apalak and Engin [3] in static joint testing. Dessureault and Spelt [4] also investigated this phenomenon in fatigue. Crack initiation and propagation characteristics generally varied depending on the applied mode of loading, in mode I a similar microcrack formation process was observed.

Ishii et al. [5] and Zeng and Sun [6] also used video-microscopy to monitor fatigue damage in adhesive joints. Both used a different definition for crack initiation to Quaresimin et al. [1] Ishii et al. defined initiation as when the crack passed over the tip of the substrate corner contained in the fillet whilst Zeng and Sun used the first visible crack appearance.

A more complete method was applied by Cheuk et al. [7]. They tested double lap joints and used both video-microscopy and SGs. They identified 2 different crack initiation scenarios; along the vertical interface on the end of the substrate and through the fillet.

The use of the backface strain technique in bonded joints was first assessed by Zhang et al. [8]. Their research with SLJ's concluded that crack initiation can be detected by the switch in the direction of the backface strain change. However, Crocombe et al. [9] investigated the technique in more detail and showed that the backface strain response was highly dependent on its location. The research concluded that ideally the SG position should be inside the overlap because here it will produce the largest change in backface strain with damage.

Lefevre and Dillard [10] employed the backface strain technique to determine the number of cycles necessary for an interfacial crack to appear in an epoxy-aluminium epoxy wedge. The data from tests were used to develop a damage initiation map. Imanaka et al. [11] adopted a similar approach with adhesively bonded butt joints. The damage was evaluated as a change in the rigidity of the adhesive layer which was measured by two SGs connecting the upper and lower substrates across the adhesive layer.

The modelling approaches to fatigue also vary. Crocombe et al. [9] are amongst those who sought to correlate the fatigue performance against the stress field in the adhesive. Crocombe and Richardson [12] tested four different bonded joints

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configurations made with the same material, AV119 epoxy adhesive and steel. The effect of the mean load was investigated by performing fatigue tests at different load ratios. The results showed that the load-life data could be matched by using a Goodman type approach.

Some authors have used the stress singularities. Lefevre and Dillard [10] defined crack initiation based on these stress singularities and developed a fatigue initiation map. Ishii et al. [5] also used the stress singularity to evaluate the fatigue strength of various lap joints. The fatigue strength was defined as an endurance limit, which depended on the apparent values of the stress intensity factor and of the stress singularity.

Imanaka et al. [11] developed a continuum damage model, which was coupled with a kinetic law of damage evolution. The normalised apparent Young's modulus was very important in measuring the damage characteristics because it corresponded with the decrease of effective cross-sectional area due to the formation and growth of voids and microcracks. A damage variable D was used to characterise this reduction in cross-sectional area. When the experimental and numerical results were compared there was a good match.

Barrandon [13] explored the possibilities of a linear damage model based on the adhesive von Mises stress. The Young modulus decreased with the increasing damage. He was then able to successfully simulate the measured experimental backface strain scenarios. Crocombe et al. [9] also developed and matched these backface strain scenarios. However, they relied on inserting cracks in the adhesive layer. A 3D model of an epoxy-aluminium SLJ was developed. Crack growth was simulated by decoupling nodes on the interface between the adhesive and the substrate. This approach gave good results when fitting the experimental backface strain data. Finally, Quaresimin [1] proposed a damage model based on two phases, nucleation and propagation. In the first a generalised stress intensity factor was used, while in the second a derivative of the Paris law was applied.

This current work continues from the work reported earlier [14], where SLJs were tested and six SGs were used across the overlap width, to detect and monitor fatigue initiation. Now the SGs have been placed at three different positions along the overlap, which allows a more thorough monitoring of damage progression. An elasto-plastic damage model has been developed, capable of predicting and matching backface strain patterns and fatigue life at different loads.

2. The experimental tests

The SLJ dimensions are shown in Table 1. The fatigue tests were conducted using an Instron 8511 fatigue machine in constant amplitude fatigue at 5 Hz with maximum fatigue loads of 50%, 40% and 30% of the static shear strength (τ_S) and with a load ratio $R=0.1$. Static tests to failure were performed to assess the SLJs reliability in terms of strength. The static strength of the tested joints was very similar, 17 kN. The variation was less than 0.5 kN, thus reliability of the specimens was very good.

Table 1
Single lap joint characteristics.

Type	Specification
Aluminium	2024-T6
Substrate length	115 mm
Substrate thickness	3.24 mm
Adhesive	FM-73M
Overlap	30 mm
Adhesive thickness	0.2 mm
Width	25 mm

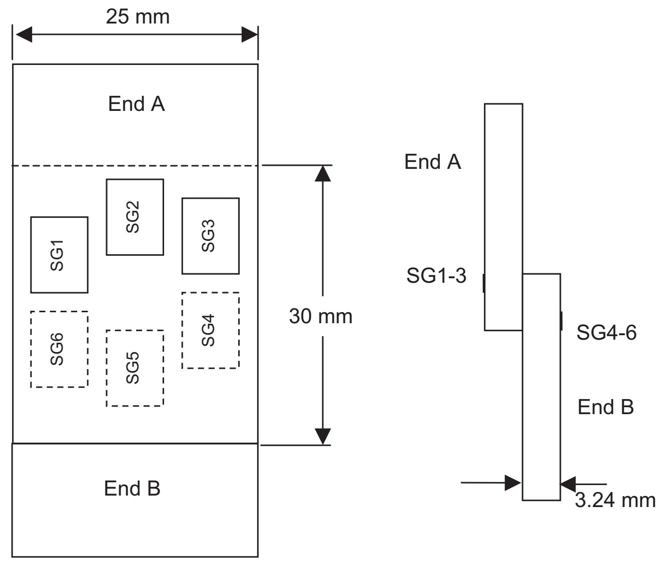

Fig. 1. SG positions in adhesive overlap (not to scale).

Table 2
Experimental fatigue load-life data.

Maximum fatigue load/static failure strength	Life (cycles)
0.5	10 442, 10 100, 34 253
0.4	60 500, 59 995
0.3	420 000

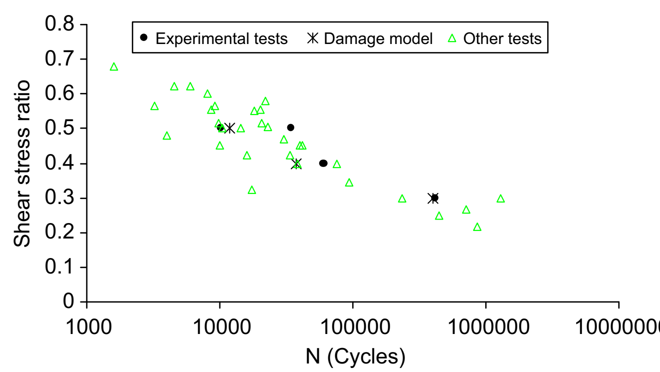

Fig. 2. Fatigue load-life experimental data and comparison with calibrated damage model predictions.

Six strain gauges were placed on the SLJs overlap. The gauges used were self-temperature compensated EA-13-060LZ-120 uniaxial SGs with a gauge length of 1.5 mm. The SG positions with respect to the overlap can be seen in Fig. 1. SG1-3 were placed at end A and SG4-6 at end B. SG2 and 5 were placed 1 mm inside the overlap; SG3 and 6 were placed 3 mm inside the overlap; SG1 and 4 were placed 5 mm inside the overlap (Fig. 1). The change in voltage was amplified and recorded using in-house data-logging software measuring maximum and minimum voltage values, and snap shots of the complete voltage change of all 6 SGs. The data were then converted into strain.

A total of 6 specimens were tested in fatigue and the load-life data are shown in Table 2 and plotted in Fig. 2, along with data

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