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A generalised damage model for constant amplitude fatigue loading of adhesively bonded joints

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ABSTRACT

The fatigue resistance of adhesively bonded joints is an important aspect of reliable structural design in many sectors. In this paper, the effect of load ratio on the fatigue behaviour of adhesively bonded joints was investigated using both experimental and numerical approaches. Single lap joints were tested under cyclic loading at different load ratios and load levels to characterise their response. A numerical model that accounts for the load ratio effect in constant amplitude fatigue loading was developed to predict the response of these bonded joints. The progressive damage of the adhesive material was modelled using a cohesive zone approach with a bi-linear traction-separation response. Damage initiation and propagation phases were monitored using the backface-strain and in-situ video-microscopy techniques. The load ratio effect on the fatigue behaviour of adhesively bonded joints was successfully predicted using a strain-based fatigue damage model. The numerical results were found to be in good agreement with the experimentally observed fatigue damage evolution and failure life.

1. Introduction

Adhesively bonded structural joints have been widely employed in various industries because of their advantages over the classical mechanical fastening methods. Such advantages include better fatigue resistance, eliminating fretting fatigue, reduction in structural weight, better sealing and vibration-damping properties and reductions in manufacturing costs. Although adhesively bonded structural joints benefit from relatively higher fatigue strength in comparison with other mechanical fastening techniques, fatigue damage is still one of the major causes of failure. Moreover, fatigue testing is often costly and time-consuming whilst predictive numerical models can reduce time and cost, and effectively help engineers to minimise the experimental effort required to attain a reliable structural design.

Constant amplitude fatigue loading is characterised by three load parameters: (a) maximum fatigue load, (b) load ratio (R, the ratio of minimum to maximum fatigue load) and (c) frequency. The effect of these fatigue load parameters depends on the type of adhesive system and the joint configuration being used. Although extensive work has been undertaken in investigating the effect of fatigue loading characteristics on the fatigue behaviour of metals, relatively few studies have been dedicated to the fatigue of polymeric adhesive systems. The effect of load ratio has been found to be significant in the fatigue response of polymeric materials [1–3]. It was observed that increasing the load ratio for a constant maximum fatigue load increased the fatigue life [2–4] and, conversely, for a constant load range, an increased load ratio has a deleterious influence on the fatigue response [1]. However, the effect of frequency on adhesively bonded joints was found to be less important [1,4]. Therefore, in many cases, the maximum fatigue load and the load ratio determine the fatigue response of adhesively bonded joints.

Underhill and DuQuesnay [4] studied the influence of surface pre-treatment and load ratio on the fatigue behaviour of adhesively bonded joints. They showed that in poorly bonded joints, the maximum fatigue load governed the fatigue behaviour whilst the load ratio had little influence. This was because as soon as the maximum load is applied the weak bond becomes totally damaged, leading to joint failure. Conversely, with good bonding, because of the strong connection between the substrate and the adhesive, total failure did not occur as soon as the maximum load was applied and other fatigue loading characteristics, such as load ratio affected the fatigue response.

The fatigue damage response of adhesively bonded joints has been modelled by several researchers [5–7] using finite element modelling. In these models, the adhesive material properties were degraded based on a fatigue damage variable to simulate the deleterious effect of fatigue. Solana et al. [6] and Shenoy et al. [5] reduced the elastic and plastic properties of the adhesive bond line based on a damage variable. Khoramishad et al. [7] utilised a cohesive zone model to simulate the progressive damage in the

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adhesive bond line and degraded the cohesive zone properties to model fatigue damage. Then, Katnam et al. [8] extended this fatigue model in a preliminary attempt to incorporate the load ratio effect. However, they did not take the sensitivity of the adhesive system to the variation of the load ratio into consideration and hence their model could only be used for a limited range of adhesive systems.

In this paper, the effects of load ratio and maximum fatigue load on the fatigue response of adhesively bonded joints were studied experimentally and numerically. Single lap joints were tested under fatigue loading at different load ratios and maximum load levels. A numerical model that accounts for the load ratio effect was developed and validated against the experimental results to predict the fatigue response of adhesively bonded joints.

2. Experimental work

Single lap joints (SLJ) were manufactured and tested under static and fatigue loading. In these joints, aluminium 2024-T3 substrates were bonded with FM 73 M OST toughened epoxy film adhesive. The substrates were pre-treated prior to bonding. This pre-treatment consisted of a chromic acid etch (CAE) and phosphoric acid anodise (PAA) followed by the application of BR 127 corrosion inhibiting primer to maximise environmental resistance and bonding durability. The joints were cured at 120 °C and under ~0.28 MPa pressure for 60 min. The dimensional details of the SLJ are shown in Fig. 1. The overlap length, the width and the thickness of the bond line were 30, 12.5 and 0.2 mm, respectively.

The SLJs were tested under static and fatigue loading and two strain gauges were attached to the substrates at 1 mm inside the overlap (see Fig. 1). These backface strain gauges provided an independent measure of damage propagation that was used to validate the models developed. The strain gauges used in this research were FLA-1-23 (Techni Measure, UK) with 1 mm gauge length and a resistance of 120 Ω. The surface beneath the gauges was prepared before attaching the gauges using an abrasive paper (grade 240) and M-prep conditioner A (a water based acidic surface cleaner) from Vishay followed by neutralising with M-prep neutraliser 5 A (a water based Alkaline surface cleaner) from Vishay measurement group and cotton wool buds. Then, the gauges were bonded on the prepared area using a cyanoacrylate adhesive.

The static strengths were measured by performing six static tests and an average value of 10.34 kN with a standard deviation of 0.22 kN was obtained. Fatigue tests were conducted at different load levels based on the average static strength and at load ratios of R=0.1 and 0.5. The load-life curves obtained from the fatigue tests for R=0.1 and 0.5 are shown in Fig. 2.

The maximum fatigue load, P_{max}, of the SLJ bonded with the adhesive FM 73 M OST, normalised by the static failure load, P_s, is plotted against the fatigue life for R=0.1 and 0.5 and compared with the load-life curves obtained for SLJ bonded with the adhesive AV119 [1]. It is evident from Fig. 2 that the fatigue

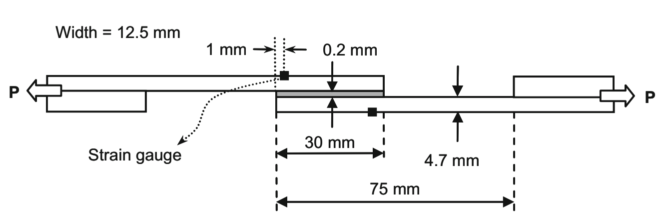

Fig. 1. The dimensional details of the single lap joint and the location of the attached strain gauges.

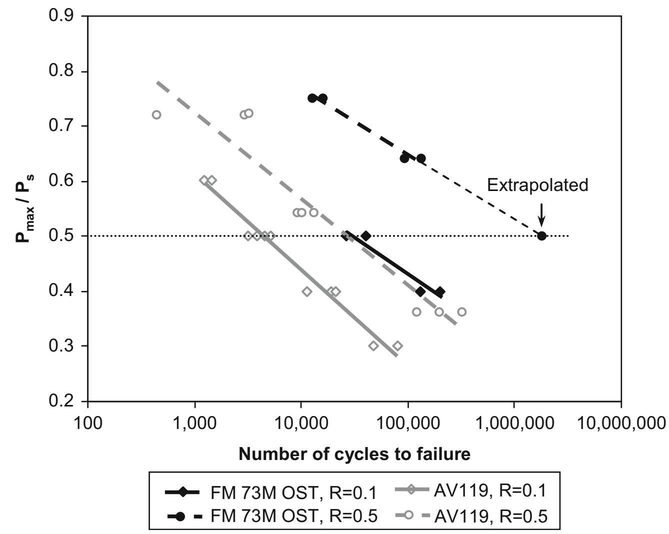

Fig. 2. Experimental load-life fatigue data for the SLJ bonded with adhesives FM 73 M OST and AV119 [1] for R=0.1 and 0.5.

responses of the single lap joints were dependent on the load ratio. However, the degree of dependency can vary with different adhesive systems. A horizontal line on Fig. 2 can be used to find the fatigue life obtained for a certain maximum fatigue load and different load ratios. For instance, by maintaining $P_{max}=0.5P_s$ and increasing the load ratio from 0.1 to 0.5, the fatigue life of the SLJ bonded with the adhesive AV119 increased by a factor of 5, while for the adhesive FM 73 M OST the life increased by a factor of over 50. This indicates a higher dependency of the adhesive FM 73 M OST in comparison with the adhesive AV119 to the load ratio. The extrapolated load-life data point was used for the adhesive FM 73 M OST at R=0.5 and $P_{max}=0.5P_s$ for calculating the increase in fatigue life resulting from changing the load ratio from 0.1 to 0.5 (see Fig. 2).

Typical fracture surfaces for fatigue tested FM 73 M OST SLJ are shown in Fig. 3. It can be seen that the failure was cohesive, running either fully within the adhesive layer or close to the interface. It can be seen that with lower maximum fatigue loads, the region of near-interfacial failure increased. This is possibly because as the damage evolution is slower in the low load case there is a longer time for localised damage to take place during the longer cyclic life. It should be noted that in Fig. 3 only half of the failure surfaces are shown.

Fatigue damage in adhesively bonded joints can be monitored using different techniques, e.g. backface strain, in-situ video microscopy, specimen sectioning, SEM and residual strength techniques. In this study, the backface strain technique was used to monitor the fatigue damage in the adhesive bond line. In the backface strain technique, which is a non-destructive method, strain gauges are bonded on the backface of the substrate, near a site of anticipated damage and, while the test is running, the strain variation is recorded. This variation of strain can be linked to the onset and growth of the damage. This is because damage initiation and propagation directly influence the deformation of the substrates and consequently cause variations in the strain. The backface strain technique was initially employed by Abe and Satoh [9] to study crack initiation and propagation in welded structures. Later, other authors [6,10–16] applied this technique to adhesively bonded joints. Numerical analyses were carried out to find the optimum position of the strain gauge. In this work, one strain gauge was attached 1 mm inside the overlap on both sides of the substrates (See Fig. 1). Fig. 4 shows the backface strain variations for SLJ under fatigue loading at load ratios of 0.5 and 0.1