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# The strength prediction of adhesive single lap joints exposed to long term loading in a hostile environment

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ABSTRACT

This work is concerned with investigating the residual static strength of adhesively bonded joints after long-term exposure to a combined mechanical-hygro-thermal environment. Associated experimental data are also reported. The degradation process of the joints was modelled using a fully-coupled approach, with the moisture concentration affecting the stress distribution and the stress state affecting the moisture diffusion analyses simultaneously. A bilinear cohesive zone model was then used to implement the progressive damage FE analysis of the quasi-statically loaded joints following the ageing phase. This model is degraded using the damage factors (creep strain and moisture uptake) accumulated over the ageing process and calibrated against the experimental results from static tests on the bulk adhesive. Predicted and experimentally-measured quasi-static responses for the aged adhesive joints were found to be in good agreement.



## 1. Introduction

Adhesives have been widely used in the automotive, aerospace and construction industries to replace the conventional joining techniques [1]. The lack of accurate strength prediction of adhesively bonded joints exposed to a long-term hot-humid environment inhibits a more wide-spread application of adhesive bonding. A reliable strength prediction model is essential to reduce the amount of expensive and time-consuming durability testing at the design stage [2–6].

The diffusion of water ingress in adhesives has been modelled extensively by Fick's second law [7–9]. The deleterious effect of water on the integrity of adhesive joints has been investigated by Gledhill and Kinloch [10]. The measured strength of their joints, saturated in distilled water, decreased considerably and higher immersion temperatures led to more rapid degradation. It is worth noting that no further degradation was observed after saturation. Brewis et al. [11] found that plasticisation occurred in the adhesive they studied which, in the form of the single lap joint, was exposed in a hot-humid environment for up to 2500 h.

The residual stress in adhesive joints caused by adhesive swelling and the mismatched thermal expansion coefficients may relax due to creep. Thus it is important to determine the viscoelastic properties of the adhesive to provide reliable prediction of the adhesive behaviour during long-term degradation. Peretz and Weitsman [12] presented creep tests on FM73 bulk adhesive to investigate the viscoelastic characteristics at elevated temperatures. A temperature range of 30–60 °C was considered and the results showed that it is essential to include thermal and viscous effects in the characterisation scheme. Jurf and Vinson [13] studied the effect of moisture on the viscoelastic shear properties of FM73M and FM300M and found that moisture can enhance the creep rate significantly.

Crocombe [14] studied the environmental degradation of the static strength of adhesively bonded structures assuming both interfacial and cohesive failures based on experiments and FEM simulations of joints bonded by FM1000 adhesive and immersed in water. Sugiman et al. [15,16] modelled the moisture diffusion process in the adhesive layer of adhesively bonded joints under both static and fatigue loading and immersed in deionised water for up to 2 years based on experimental bulk adhesive data. The joint strength and fatigue resistance were found to be degraded by moisture ingress after long term immersion. A similar trend was found when investigating the effects of cyclic thermal loading on adhesive single lap joints by Hu et al. [17]. Results revealed that a cyclic temperature environment decreased joint strength significantly initially and the degradation rate decreased as exposure time increased.

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Progressive environmental damage has been used to predict the residual strength of degraded adhesive joints using a continuum damage model [5,18] or a cohesive zone model (CZM) [4,19–21]. However, fully-coupled situations where stress and moisture uptake occur simultaneously have not been modelled. In this work, prior to numerical simulation, experimental work was carried out to measure: (a) the stress dependency of moisture uptake in the bulk adhesive; (b) the moisture dependent creep compliance of the bulk adhesive; (c) the stress-strain curves of the bulk adhesive degraded by creep and by moisture and (d) the residual strength of degraded adhesively bonded single lap joint (SLJ) specimens. Numerical modelling was then performed in two steps (1) to characterise the long-term ageing process in adhesively bonded joints under combined thermal–hygro-mechanical loading conditions using a fully-coupled methodology and (2) to simulate the quasi-static tensile residual strength of the aged adhesive joints employing a CZM model which used a bilinear traction-separation law.

## 2. Experimental methods

### 2.1. Specimen manufacturing

Experimental studies have been carried out on both bulk adhesive specimens and aluminium single lap joints bonded with FM73 (Cytec®, New Jersey, USA) film adhesive with a nominal thickness of 0.18 mm. A plate of bulk adhesive has been made by stacking and curing nine layers of FM73 film and then machining into dogbone specimens with overall length, gauge length and gauge width of 65 mm, 30 mm and 5 mm respectively. The thickness of the bulk specimens was maintained at 1 mm using steel spacers. The film was cured at 120 °C for 1 h as recommended by the manufacturer [22]. Further details related to the manufacturing process can be found elsewhere [15,23,24].

Two 2024-T3 aluminium adherends (45 mm in length, 4.7 mm in thickness and 3 mm in width) bonded with FM73 adhesive constitute the single lap joints (10 mm overlap length and 0.2 mm adhesive layer thickness) investigated in this work. Surface preparation was applied to the aluminium substrate by Airbus before being bonded, first using chromic acid etching (CAE) followed by phosphoric acid anodising (PAA) and then by applying the corrosion inhibiting primer BR127. The detailed specification for the actual treatments are not available but typical specifications are available in the literature [25,26] for CAE and PAA respectively. The joint manufacturing was carried out in an environmentally controlled room to avoid excessive dust particles. The two aluminium substrates were bonded together in a spring-loaded jig and a pressure of 0.3 MPa was applied to the overlap area. To maintain an adhesive thickness of 0.2 mm, steel spacers with thickness of 4.9 mm were used. The curing procedure was the same as for the bulk adhesive described above.

### 2.2. Bulk adhesive ageing

To investigate the moisture diffusion, creep and thermal and swelling expansion behaviour in the bulk adhesive, the bulk specimens were immersed (some loaded and some unloaded) in deionised water at 50 °C for 6 months. A spring-loaded rig, shown schematically in Fig. 1, was designed to provide the required loading levels (both unloaded and at 25% of the static failure load) for the bulk specimens. The length of the spring was periodically re-adjusted during the loading period to provide essentially a constant load on the specimen.

The weight of the specimens was measured periodically over a period of time until saturation was achieved. This method is known as the gravimetric method and was used to obtain the coefficients of moisture diffusion and equilibrium moisture uptake. Further details of this method can be found elsewhere [27]. At the same time as the weighing procedure, the swelling of the bulk adhesive (assumed to be isotropic) was determined by measuring the specimen thickness using a micrometer [26,28].

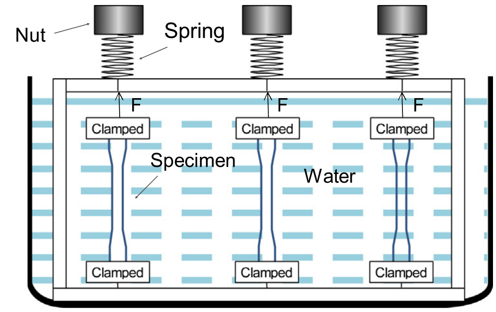


**Fig. 1.** Loading jigs for the bulk adhesive degradation test.

The CTEs of FM73 adhesive and aluminium alloy 2024-T3 were required to determine the thermal stresses induced in cooling from the curing temperature of 120 °C. The CTE for aluminium alloy (Al) 2024-T3 can be found elsewhere to be 2.36E-5 $°C^{-1}$ [29]. This material was used as a reference material when determining the CTE of the adhesive. Strain gauges were bonded on both the aluminium and the adhesive and were placed in an oven to measure the strain variation with increased temperature. The relationship between the CTEs for the adhesive and the reference material (Al 2024-T3) can be deduced from Eq. (1) [30].

$$\alpha_A - \alpha_R = \frac{(\varepsilon_{T/O/(G/S)} - \varepsilon_{T/O/(G/R)})}{\Delta T} \quad (1)$$

here, $\alpha_A$ and $\alpha_R$ are CTEs for the adhesive and reference materials, $\varepsilon_{T/O/(G/S)}$ and $\varepsilon_{T/O/(G/R)}$ are the strain outputs for adhesive and reference materials and $\Delta T$ is the temperature change from the initial reference temperature to the current value.

Measurement of the extension of the bulk adhesive, strained in the spring loaded frame (Fig. 1) provided the creep behaviour of the bulk adhesive at 25% of the unaged static failure load tested at room temperature (RT). These specimens were initially dry when immersed and loaded and absorbed increasing amounts of water as the test progressed. Thus they change from a dry to a saturated specimen. The creep data obtained from these tests were supplemented with previous creep data on specimens that were dry and specimens that were pre-saturated before loading. These data were available for a range of load levels. A power-law creep model was used in the subsequent simulation procedure as expressed in Eq. (2) [31].

$$\dot{\varepsilon} = Aq^n t^m \quad (2)$$

here, $\dot{\varepsilon}$ represents the creep strain rate, $q$ is the von Mises equivalent stress, $t$ is the time and $A$, $n$ and $m$ are coefficients based on a fitting procedure to the experimental data.

### 2.3. Single lap joint ageing

The SLJs were constrained in spring-loaded jigs and immersed in deionised water at 50 °C under different loading levels (12.0% and 17.5% of the dry joint strength tested at RT) to investigate the effect of stress on the joint ageing response. The joint extension caused by creep was determined by periodic measurement of the displacement of the pre-compressed spring.