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Fatigue lifetime prediction of adhesively bonded joints: An investigation of the influence of material model and multiaxiality

V.C. Beber[a,b,*], P.H.E. Fernandes[a], B. Schneider[a], M. Brede[a], B. Mayer[a,b]

[a] Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM), Wiener Straße 12, D-28359 Bremen, Germany
[b] Universität Bremen, Fachbereich Produktionstechnik – Maschinenbau & Verfahrenstechnik, Badgasteiner Straße 1, D-28359 Bremen, Germany

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ABSTRACT

In the present work the influence of material model and multiaxiality on the fatigue lifetime predictions of scarf and single-lap joints under uniaxial tension-tension cyclic loading is investigated. Lifetime predictions, from 10^3 to 10^6 cycles, were performed using a stress-life approach taking into account for the effect of multiaxiality by means of hydrostatic pressure (p) and von Mises stress (q). These stresses were calculated employing 2D-FEA with linear-elastic and elastoplastic (von Mises and Drucker-Prager) material models. Effective stresses were obtained using the theory of critical distances. Findings showed that material model affected significantly the multiaxiality distribution of the single lap joint (SLJ), especially at singularity regions. For scarf joints, this effect was noticeable for higher stresses. With the exception of the SLJ, by excluding the singularity regions close to the free edges, the value of multiaxiality was nearly constant and decreased with increasing bondline angles (higher shear effects). With regards to lifetime predictions, overall accuracy for the scarf joint was higher than for the SLJ. Linear-elastic material models provided satisfactory accuracy for the scarf joint, but not for the SLJ. Elastoplastic material models were able to improve predictions and to provide suitable accuracy for both joint configurations.

1. Introduction

1.1. Background

The increasing use of lightweight structures in energy production, automotive, aerospace, railway and ship industries has promoted the employment of materials such as composites (*e.g.* CFRP, GFRP), light metals (*e.g.* aluminium, titanium), ceramics, timber and others [1]. Hence, with the need of joining such dissimilar materials, adhesively bonded joints are widening their application as a manufacturing technology. Specially, due to attributes including continuous load distribution, joint flexibility and corrosion resistance [1]. In order to expand the use of bonded joints for structural purposes, it is important to continuously improve safety and reliability under fatigue conditions. Essentially, fatigue is one of the main causes of engineering failure and components can be exposed to cyclic loads from several sources, such as vibration, transmission of power, compression/decompression and accidental loads [2].

Fatigue life is considerably reduced by stress concentrations, which arise from geometrical features (*e.g.* holes, corners, edges) that are built-in characteristics on the project of components. These stress concentrations might: (i) induce plastic deformations in the adhesive layer despite nominal stresses being still within the elastic range, and (ii) generate locally a multiaxial state of stress even under uniaxial loading [3]. It is known that multiaxiality may affect the mechanical properties and the nucleation/growth of voids in polymeric materials [4]. Regarding fatigue of adhesively bonded joints under multiaxial stress conditions, Imanaka et al. proposed a method combining fatigue testing and numerical modelling for single and double-lap joints [5]. They concluded that fatigue limits are governed by the maximum principal stress except in the presence of negative hydrostatic pressure.

Among the several approaches available for modelling the fatigue of bonded joints, the stress-life approach is particularly useful for predicting the fatigue life of a component by correlating the number of cycles to failure (N) to the applied stress amplitude (σ_a) [2]. This relationship is normally represented by an SN curve obtained from experimental testing. The calculation of stress in the adhesive layer can be done using analytical methods, such as Volkersen, Goland-Reissner and might also include the effect of non-linear-elastic behaviour as described by Hart-Smith and Bigwood-Crocombe [6]. However, with the increasing complexity of joints and the evolution of computational processing power, the Finite Element Analysis (FEA) has become the

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[*] Corresponding author at: Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung (IFAM), Wiener Straße 12, D-28359 Bremen, Germany.
E-mail address: vinicius.carrillo.beber@ifam.fraunhofer.de (V.C. Beber).

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most employed technique for stress analysis [7]. Abdel-Wahab et al. [8] used 2D and 3D FEA of butt, cleavage and scarf joints, to investigate which joint would be the most suitable for controlling the multiaxiality in the adhesive layer. They found scarf joints to be most adequate for this application due to the nearly constant value of the multiaxiality along the bondline and the simpler relationship between bondline angle and multiaxiality. In the case of highly inhomogeneous stress distributions (*e.g.* singularities, notches), an averaging method is often necessary to determine the effective stress to be used in the stress-life approach. The Theory of Critical Distances (TCD), originally proposed in the works of Neuber [9] and Peterson [10] and brought back in the recent years by Taylor [11], has been well established as an averaging method for the assessment of fracture in both quasi-static and fatigue loading in a wide range of materials. Susmel presented a summary of the use of the TCD for fatigue applications in the medium/high cycle range of notched components and under multiaxial fatigue [12]. In the case of quasi-static loading of adhesives, Crocombe [13] applied a stress criterion based on an averaging method in order to predict the failure load of single-lap joints (SLJ) obtaining good predictions for ductile adhesives. More recently, Khoromishad et al. [14] employed a critical distance concept to successfully predict the effect of overlap length and substrate thickness for SLJ's. For the fatigue of adhesives, Schneider et al. [15] used the maximum principal stress to predict lifetime of scarf, thick adherend and SLJ's at different temperatures using a linear-elastic material model. They concluded that the homogeneity of stress distributions in the adhesive layer has a direct influence on the accuracy of lifetime predictions. Beber et al. [16] extended this analysis including elastoplastic material models. They were able to improve the quality of predictions, especially for SLJ's. As mentioned earlier, the hydrostatic pressure can influence directly the fatigue limit of adhesives. In order to address it, the *p-q* diagram was successfully used to predict the lifetime of several types of adhesive joints in a wide range of temperatures in joint projects comprising several German institutions [17,18]. Nevertheless, one of the remaining challenges in the application of the stress-life approach is the validity of transferring results between SN curves of different joint geometries (even with similar adhesives), which require a proper choice of equivalent stress [1,2]. Moreover, there are limited studies on adhesives considering the combination of effects of non-linear-elastic material behaviour and multiaxiality under fatigue conditions.

1.2. Objectives

In the present work the influence of material model and multiaxiality on the fatigue lifetime predictions of scarf and single-lap joints under uniaxial tension-tension cyclic loading is investigated. Lifetime predictions, from 10^3 to 10^6 cycles, were performed using a stress-life approach employing *p-q* diagrams constructed from reference SN curves found in the literature. The objectives of the present investigation are:

(a) to analyse the influence of material model behaviour on the multiaxiality distributions along the adhesive layer;
(b) to assess the accuracy of lifetime predictions with regards to material model and multiaxiality;
(c) to conduct a parametric analysis on the sensitivity of the proposed prediction approach to different critical distances;
(d) to evaluate whether the critical distance is a only a material parameter or if it is also dependent on the joint geometry.

Multiaxiality was defined in terms of the pressure (p) and the equivalent von Mises stress (q). Stresses were calculated employing 2D-FEA with linear-elastic and elastoplastic (von Mises and Drucker-Prager) material models. Effective stresses were obtained using the theory of critical distances.

2. Material and methods

2.1. Material model

In the current work a hot curing one-component toughened epoxy adhesive was investigated. This adhesive is designed for automotive applications, particularly due to its enhanced fracture toughness [4]. In order to model its behaviour, the simplest approach is to use a linear-elastic model governed by Hooke's law, in which stress and strain are correlated by the Young's modulus. One of the advantages of this model is the possibility of faster simulations times. However, in the case of adhesives a non-linear behaviour is often to be expected, especially in the low cycle fatigue (LCF) range and/or in the presence of stress concentrations. As mentioned in the introduction, elastoplasticity was one of the first ways to address the non-linear behaviour of adhesives [6]. Moreover, it is recognized from the literature that hydrostatic pressure plays a role in the mechanism of yielding of adhesives [1]. Therefore, the von Mises yielding criterion can be modified to account for the effects of hydrostatic pressure. With regards to toughened epoxies, the Drucker-Prager yield criterion is well accepted for this purpose [19].

Three different material models were employed in the present analysis: (i) linear-elastic, (ii) von Mises plasticity (pressure independent) and (iii) linear Drucker-Prager (pressure dependent). The linear-elastic model was defined by the Young's modulus (E) and Poisson's ratio (ν). Pressure (p) and von Mises equivalent stress (q) can be calculated from the principal stresses (σ_1, σ_2, σ_3) as follows:

$$p = -\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{1}$$

$$q = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]} \tag{2}$$

In the von Mises criterion (VM), the yield surface (f_{VM}) is defined by *Eq.* (3) in terms of yield stress (σ_y) and q:

$$f_{VM} = q - \sigma_y = 0 \tag{3}$$

A hardening curve is necessary to describe the elastoplastic behaviour of the material after yielding. For the adhesive under investigation, this data was obtained in the literature and it is shown in Fig. 1a. Pressure dependence was modelled using a linear Drucker-Prager (DP) criterion. In this case, the yield surface (f_{DP}) is described by *Eq.* (4):

$$f_{DP} = q - p\tan(\beta) - \sigma_y = 0 \tag{4}$$

Here β is a property of the material known as the friction angle which is a function of the ratio between yielding stress at tension and compression. The influence of pressure (p) on the yielding surfaces of von Mises (VM) and linear Drucker-Prager (DP) material model is illustrated in Fig. 1b.

The dilation angle (ψ) describes the evolution of the plastic strain ($d\varepsilon^{pl}$) according to a plastic flow law. If an assumption of associated flow is used; the dilation angle (ψ) is equal to the friction angle (β). Garcia et al. [19] presented a complete investigation on the material definition for the Drucker-Prager model. For the FEA, the aforementioned material data at room temperature was obtained from the literature with: $E = 1571.9$ MPa; $\nu = 0.4$; $\sigma_y = 15.1$ MPa [16] and $\beta = \psi = 35°$ [20]. Since adherends were made of construction steel, which is much stiffer than the adhesive, a linear-elastic material model was used with $E_s = 210{,}000$ MPa and $\nu_s = 0.3$ [15].

2.2. Finite element analysis

A 2D-FEA under plane strain conditions was carried out in order to calculate the stress distributions along the adhesive layer. Several studies validated the use of 2D models for the analysis of bonded joints. It allows a faster analysis and a mesh refinement at regions with stress