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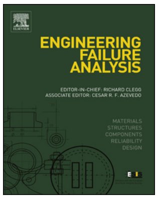

On the lifetime prediction of rolling lobe air springs

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ABSTRACT

In this paper, the fatigue life of rolling lobe air springs made from cord-rubber composites is investigated with particular focus on the crack nucleation approach. Commonly used test specimens like the simple tension test specimen or the dumbbell specimen fail in the fatigue analysis of rolling lobe air springs because the fatigue characteristic of the cord-rubber interface is represented insufficiently. Therefore a new cord-rubber specimen is developed. The fatigue characteristic of the new specimen is discussed and Wöhler curves for two different predictors based on Cauchy stress and configurational stress are determined. Using FEA with a two-scale model of the air spring, the cycles-to-failure with respect to piston diameter and different inner pressures are determined and compared to test results taken from the literature. The results from the literature were derived at elevated temperature. Therefore, the Arrhenius approach is used to take into account different temperatures. In addition the crack growth approach using the cracking energy density is applied. The results show an improvement in the prediction of rolling lobe air springs fatigue life with respect to the crack initiation plane orientation and the cycles-to-failure using the new specimen. Compared to the crack nucleation approach, the crack growth approach seems to slightly overpredict the fatigue lives.

1. Introduction

The widespread use of cord-rubber composites leads to a considerable interest in the fatigue characteristic of such so-called soft composites. The difference to common composites is the huge gap between the secant stiffness of the matrix material compared to the cord material. The stiffness of the reinforcing components can be 10.000 times the stiffness of the matrix material [1]. Cord-rubber composites are used in air springs which will be the subject of the present paper. An air spring consists of an upper flange and a piston as vehicle interfaces. Both are connected by a bellow filled with compressed air. The bellow forms a rolling lobe on the piston. During service, the rolling lobe rolls downward on the piston and the inner pressure increases for a compression stroke and vice versa for a rebound stroke. Cord-rubber composites are made of multifilament yarns twisted to cords which are embedded in a rubber matrix. Due to their composition, cord-rubber composites are characterized by a high tensile stiffness and flexibility to shear loading and bending. Because of the material inhomogeneity and anisotropic properties, damage and failure processes are quite complex. Examples of failures in cord-rubber composites are: crack propagation in the rubber between different cords or between the cords in the same layer (inter-ply cracks), fibre-matrix debonding around one single cord ("socketing") and at a crossing point of two cords. More rarely failures are for example a loss in adhesion between the cord and rubber matrix, or a simple brake of a cord. The analysis of

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materials fatigue life may be divided into two approaches [2]. The crack growth approach (CGA) and the crack nucleation approach (CNA).

The CGA considers the stored energy surrounding pre-existing flaws in the material and was first applied to rubber by Rivlin and Thomas [3]. The elastic energy available for the crack to grow (the so-called tearing energy) is the negative partial derivative (while the specimen is held at constant length) of the elastically stored energy over the fracture surface. Applying the Paris-Erdogan equation by using the tearing energy as the stress-intensity factor, the end of life is calculated by integration with respect to the crack length. Breidenbach and Lake [4] extend the energetic approach presented by Rivlin and Thomas to crack growth in cord-rubber laminates. The specimens consist of a sheet of rubber containing two layers of symmetrically arranged and equally spaced cords bonded to the rubber matrix with exposed ends. Subjected to repeated tensile deformations with fixed strain amplitudes and deformation allowed to return to zero for each cycle, they observed inter-ply crack growth or roughly cylindrical cracks around individual cords. A criterion for the transition of the two observed failure modes is obtained, while inter-ply cracks seems to be the major failure mode. Gent [5] examined the failure by pull out of one single cord or an array of cords partly embedded in an elastomeric block. Based on this work, other authors widen out the tearing energy approach for cord-rubber composites using different types of specimens. Huang and Yeoh [6] examined the crack initiation in specimens with cords embedded and ending in rubber sheets. They suggest, that penny shaped cracks initiate at the end of the cords and propagate through the composite. Basic premise of their theory is that the rate of propagation of the cracks is governed by the usual crack growth characteristics of rubber. This seems reasonable for cracks in the rubber matrix but not for cracks around the cords in the interface region. Lee et al. [7,8] performed tests on angle-plied composite specimens which represents the carcass of aircraft tires at different deformation levels, frequencies and carbon black loadings of the matrix compound. Subjected to high interply shear strain, they found out, that there is a threshold for the onset of fibre-matrix debonding.

The effect of minimum cyclic stress is examined by Ku et al. [9]. The effect of cord reinforcement for radial tires is examined by Song et al. [10] and Lee et al. [11]. Different cord reinforcements show almost the same Wöhler curve characteristics for the same rubber matrix, cord angle, cord volume and ply lay-up, which reflects the matrix-dominated failure modes in cord-rubber composites. However Lake [12] examined a discrepancy of the damage growth rate of cord-rubber composites with the crack propagation characteristics of elastomers. The discrepancy was attributed to the departures of real cracks in the composite laminates from ideal shape assumed in fracture mechanics theory.

The CNA deals with the initiation of cracks at flaws in the material. A flaw could be for example a filler agglomerate. A detailed study on the initiation of crack in elastomer is given in Santier et al. [13] and Huneau et al. [14]. The CNA was first applied to rubber by Cadwell [15]. It is assumed, that the fatigue life can be determined from the history of stress and strain in the material. For every material point an appropriate damage parameter or predictor is determined. With characteristic tests on the product or on a specimen the end of life time can be plotted against the predictor, gaining the so-called Wöhler curve [16]. The critical value of the predictor is defined as the end of life value. Using numerical analysis and a linear damage accumulation [17], the end of life of a product under simple loading conditions can be calculated.

For multiaxial stresses and non-proportional loadings, the application of both approaches is still not fully understood. In the CGA, the tearing energy can not be assumed to be proportional to the strain energy density. In [18,19] Mars introduces the cracking energy density, which represents the part of the strain energy available for crack growth on a specific plane. In the case of the CNA, the application of the commonly used predictors failed for non-proportional loadings. Flamm et al. [20] presents a methodology for the CNA using Haigh-diagramm data [21] for multiaxial loading conditions. Other approaches for dealing with multiaxial loadings in rubber can be found in [13,22–24] for example. As stated by other authors the CNA inherit the advantage to predict the spatial distribution of the fatigue life for the ideal part, and can therefore be used during the product development process [25].

In [26] a method to calculate fatigue life of air springs with respect to the cord angle is presented based on the CNA. The method uses a smeared material description (rebar formulation) of the bellow and is in good agreement with accelerated test data [27]. Unfortunately the use of a Wöhler curve for the specific air-spring system is needed. An approach based on continuum damage mechanics for the cord-rubber interface can be found in [28,29].

The problem in applying the CNA to cord-rubber composites based on common specimens is the inability of the existing specimens to cover the fatigue characteristic of the cord-rubber interface. In case of tires the ending cord or the ending cord layers can be the place of crack initiation while in air springs, no ending cords are in the deformed regions. For these types of cord-rubber articles the paper presents a new specimen to examine the fatigue characteristic more in detail. After a description of the numerical procedure and the approaches to predict the cycles-to-failure, Wöhler curves are determined using the new specimen. Tests are performed at room temperature. The cycles-to-failure of rolling lobe air springs are determined and the improvements due to the new specimen are demonstrated by a comparison to experimental results taken from [30]. For the evaluation, the CGA using the cracking energy density is applied as well.

2. Cord-rubber specimen

The inability of conventional specimens, used in the CNA like dumbbell specimens or simple tension test specimens (STTS) to cover the fatigue characteristic of the cord-rubber interface is the motivation for the new specimen, called the cord-rubber specimen (CRS, see Fig. 1). The aim is to improve the numerical fatigue analysis of air springs based on finite element analysis (FEA) and fatigue tests on specimens, to shorten the development process. Under the assumption of a reliable production of the air spring, the usual failure is a crack in the rubber between the cords, where the local stresses reach their maximum. For rolling lobe air spring the area of the bellow with the most throughputs of the rolling lobe is the critical region. The local stresses in the rubber matrix result