

Damage Initiation and Fatigue Behavior of Carbon-Fiber Composite Disk Springs

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ABSTRACT

The disk spring offers the potential of significant weight savings when designed with continuous fiber reinforced composite materials. The internal stresses in a disk spring are ideally suited for composite material application due to their superior resistance to in-plane and bending stresses. In this study, a composite laminate disk spring is designed, analyzed and fabricated to take advantage of the low specific strength and weight and high damage tolerance of composite laminates. The design of the disk composite spring considers effects of the laminate stacking sequence and the geometric variables on the disk spring's mechanical performance. A continuum damage finite element analysis approach is used to understand the damage initiation and evolution as a function of applied load. Experimental analysis and a progressive damage analysis based on virtual crack closure technique are performed to evaluate the damage tolerance of the disk spring under fatigue loadings. Results show how a methodology can be used to study the crack propagation in carbon fiber disk springs.

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INTRODUCTION

In order to meet the current objectives of automakers and their suppliers to dramatically enhance the fuel efficiency in vehicles, fiber reinforced polymer composites have been proposed for several applications. Fiber reinforced composites offer the possibility for significant weight reductions due to their exceptional strength-to-weight ratios in addition to their design flexibility. However, laminated composite materials suffer from weak out of plane properties and their design requires careful consideration of these out-of-plane stresses and how they can propagate into the material. One potential light weight application which is the focus of this study is the light-weight of springs which are commonly used in many industrial applications. Of particular interest in this study is the behavior of fiber reinforced composite disk springs. Various researchers have considered composite springs of different types. For example, elliptical springs comprising layers of composite materials arranged in non-uniform longitudinal dimensions at different ratios can be used to obtain various spring rates [1, 2, 3]. Circular rings made of composite can also provide spring like behavior [4, 5]. Sulcated composite materials have also been proposed to create high-energy, compact storage springs[6, 7]. A sulcated spring consists of an elongated strip of composite materials arranged in a zig-zag fashion acting as a flexible spring element. The effect of hybridization on hybrid disc springs with standard cross-section has been investigated by Karakaya[8]. The optimum hybrid disc spring was determined according to cost and maximum loading capacity. Leaf springs have also been produced from fiber reinforced composites[9,

10]. In addition, some research has focused on the behavior of helical composite springs [11, 12]. Torsional loadings during compression loadings can lead to delamination and matrix cracking in composite springs. Coil springs using carbon fiber have also been investigated for weight reduction purposes [13, 14]. However, the challenge in these is in controlling the interlaminar stresses produced during compression of the springs.

In this study we focus our work on the behavior of composite disk springs. Disk springs, also known as Belleville, coned, conical, or cupped springs are essential washer type elements having a frustoconical shape which gives the washer element its spring characteristic. Stacking these disk springs in parallel or series combinations can lead to desirable spring characteristics controlling such behaviors as stacking height, load capacity and deflection. Parallel stacking can yield to increased hysteresis which may be desirable in energy dissipation applications. Fiber reinforced composites are an excellent material for disk spring application due to the mechanics of deformation in disk spring elements being primarily in flexure. This flexure behavior is favorable in contrast with the large interlaminar stress conditions produced when spiral springs are used that tend to drive higher interlaminar stresses driving delaminations. In this study the damage tolerance capability of the composite disk springs have been investigated under low cyclic fatigue loadings using experiments and progressive damage analysis based on the VCCT approach.



ANALYTICAL MODEL

The behavior of metallic disk spring needs to account for the material anisotropy in the composite. The original formulas for the load and deflection of metallic disk springs [15] need to be modified to capture the behavior of a specially orthotropic such as the woven carbon fiber fabric used. Consider the behavior in the disk springs as primarily a flexure response, the composite laminate bending moduli and Poisson ratio can be determined by:

$$E_x^b = \frac{12(D_{11}D_{22} - D_{12}^2)}{t^3 D_{22}} \quad (1)$$

$$E_y^b = \frac{12(D_{11}D_{22} - D_{12}^2)}{t^3 D_{11}} \quad (2)$$

$$G_{xy}^b = \frac{12(D_{66})}{t^3} \quad (3)$$

$$\nu_{xy}^b = \frac{D_{12}}{D_{22}} \quad (4)$$

where the D_{11} , D_{12} , D_{22} and D_{66} are coefficients from the bending stiffness matrix obtained from the classical lamination plate theory. The modulus in Eq. 1 is modified to account for the average modulus for the disk spring. In composite laminates and specifically orthotropic laminates, the elastic modulus, E will vary depending on the angle, θ , away from the primary axis :

$$E(\theta) = \left[\frac{m(\theta)^2}{E_x^b} (m(\theta)^2 - n(\theta)^2 \nu_{xy}^b) + \frac{n(\theta)^2}{E_y^b} (n(\theta)^2 - m(\theta)^2 \nu_{yx}^b) + \frac{m(\theta)^2 n(\theta)^2}{G_{xy}^b} \right]^{-1} \quad (5)$$

To account for the modulus variations, the effective average modulus for the disk spring, E_{ds} , is found by integrating Eq. 5 around the spring boundary to obtain :

$$E_{ds} = \frac{1}{2\pi} \int_0^{2\pi} E(\theta) d\theta \quad (6)$$

The modified equations for the load versus deflection of the composite disk spring of a specially orthotropic composite can be expressed as [16]:

$$P = \frac{E_{ds} \delta}{(1-\nu^2) M a^2} \left[\left(h - \delta \right) \left(h - \frac{\delta}{2} \right) t + t^3 \right] \quad (7)$$

where P is the axial load, δ is the axial deflection, ν is the Poisson's ratio, h is the free height of the disk, t is the thickness, a is the outer radius of the disk. In this equation, the constant M is a function of α , the ratio of the outer to inner radius, ($\alpha = a/b$):

$$M = \frac{6[(\alpha-1)/\alpha]^2}{\pi \ln \alpha} \quad (8)$$

MODELING OF FATIGUE BEHAVIOR

The finite element method is used to study the stress and strain distributions together with a coupled fatigue analysis of the composite spring disk. These simulations are performed in explicit dynamics finite element analysis with built-in initial cracks at the most probable locations in between layers. The finite element approach is previously evaluated by authors [17, 18]. A 3D brick element is used which allows for specification of the transverse shear effects in the out of plane direction of each ply. Fatigue simulations were then performed using the Direct Cyclic Fatigue (DCF) algorithm at predefined interface cracks located at the inner and outer diameters and at the center of the disk. The low-cycle fatigue criterion has been specified with the virtual crack closure technique (VCCT) to predict the crack growth at the interface. VCCT has been used to predict the propagation of delamination flaws in composite materials [19, 20]. The fracture criterion can be defined as the fraction of the equivalent strain energy release rate, G_{equiv} , at the node of crack onset to the equivalent critical strain energy release rate, $G_{Critical}$

$$e_{VCCT} = \frac{G_{equiv}}{G_{Critical}} \quad (9)$$

A value of 1.0 represents a crack growth increment. Mixed-mode, $G_{Critical}$ has been computed by the Benzeggah-Kenane formula [21]:

$$G_C = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{shear}}{G_T} \right)^\eta \quad (10)$$

Where G_{Ic} is critical mode-I strain energy release rate, G_{IIc} is the critical mode-II strain energy release rate. G_{shear} is the shear energy release rate in a mixed mode loading case which can be expressed by the summation of the first and the second shear directions. G_T is the total energy including shear and normal energies. η is a constant which the criterion provides a good fit to the delamination initiation results for carbon-fibre/epoxy composites with taking the value of 2.1 [22]. The fatigue load condition is specified by applying a sub-critical cyclic displacement loading. The strain energy release rates are computed by the VCCT approach at the maximum and minimum loadings. The approach implemented in this modeling software uses contact surfaces between the two faces to tie and then progressively unload the nodal surfaces. The obtained, ΔG , is used to predict the crack onset by the Paris law where the applicable Paris regime is bounded by the energy release rate threshold, $G_{threshold}$ and energy release rate upper limit, G_{pl} . The crack initiation and propagation criterion are defined by [23]:

$$e_{fatigue} = \frac{N}{c_1 \Delta G c_2}$$