ESTIMATION OF LIMIT STRAINS IN DISK-TYPE FLYWHEELS MADE OF A COMPLIANT ELASTOMERIC MATRIX COMPOSITE UNDERGOING RADIAL CREEP

G. G. Portnov* and Ch. E. Bakis**

Keywords: fiber reinforced elastomeric matrix composite, flywheel, radial creep, safety

Fiber reinforced elastomeric matrix composites (EMCs) offer several potential advantages for construction of rotors for flywheel energy storage systems. One potential advantage, for safety considerations, is the existence of maximum stresses near the outside radius of thick circumferentially wound EMC disks, which could lead to a desirable self-arresting failure mode at ultimate speeds. Certain unidirectionally reinforced EMCs, however, have been noted to creep readily under the influence of stress transverse to the fibers. In this paper, stress redistribution in a spinning thick disk made of a circumferentially filament wound EMC material on a small rigid hub has been analyzed with the assumption of total radial stress relaxation due to radial creep. It is shown that, following complete relaxation, the circumferential strains and stresses are maximized at the outside radius of the disk. Importantly, the radial tensile strains are three times greater than the circumferential strains at a given radius. Therefore, a unidirectional EMC material system that can safely endure transverse tensile creep strains of at least three times the elastic longitudinal strain capacity of the same material is likely to maintain the theoretically safe failure mode despite complete radial stress relaxation.

Introduction

Fiber reinforced polymeric materials have compelling advantages over homogeneous metallic materials for kinetic energy storage flywheel rotors because of their theoretically greater energy storage per unit mass and possibly less catastrophic failure mode [1]. While the widespread commercial application of composite flywheel rotors has yet to materialize, most current prototypes use one or more concentric rings (or cylinders) of filament wound carbon, glass, and/or aramid fibers in a matrix of high strength epoxy. The concentric filament wound epoxy composite is favored for its good combination of low cost and high circumferential strength. However, its lack of radial reinforcement necessitates a strategy to limit the development of high tensile radial stresses due to inertial loading or cooldown after elevated temperature processing.

In current prototypical composite rotors, the most common strategy for dealing with tensile radial stress is to wind multiple concentric layers of composite material with outwardly increasing circumferential stiffness. This approach places the most expensive fibers only where they are needed and also places most of the rotor in radial compression during high-speed rotation. A disadvantage of such “radially loaded” thick rotors is the potential for catastrophic failure by fiber fracture at the innermost portion of the layer providing the most constraint against radial expansion. Another disadvantage of such rings, when manufactured in practical thickness, is their tendency to circumferentially crack due to tensile radial stresses induced during cooldown following processing. Numerous other design strategies for high-speed rotors have been reviewed in [1].

An alternative but still not widely investigated strategy for the management of tensile radial stresses in filament wound composite rotors uses a low modulus, high elongation matrix material that can better accommodate the ultimate circumferential limit strain of the fibers without premature cracking. Such highly compliant and anisotropic composites are referred to in this paper as elastomeric matrix composites (EMCs). EMC flywheel rotors offer two potential advantages over epoxy matrix composite rotors. First, the high compliance and limit strain of the elastomeric resin allows very thick rings (inner/outer radius ratio of 0.1) to be


manufactured directly onto simple, small diameter hubs without the extra expense of multiple rings, press-fittings, or elaborate large diameter hubs and without the adverse effects of radial residual tensile stresses after processing. Second, the high ratio (~10^4) of circumferential to radial elastic moduli of the material causes the peak values of circumferential and radial stresses to occur within the outermost 5% of radial thickness of a thick disk. This unique stress distribution forms the basis for the “fail-safe” rotor first conceptualized in the mid-1980’s [2]. The still unproven fail-safe concept hinges upon the theorized self-arresting failure process initiating at the outer radius of a thick EMC disk.

Previous attempts to develop flexible epoxies for glass reinforced EMC flywheel rotors resulted in insufficiently high short-term limit strains and stresses transverse to the fibers [3]. Glass and carbon reinforced polyurethane composites, on the other hand, have been shown, via coupon tests, to have short-term elastic and strength properties across the fibers that are adequate for use in EMC rotors [4]. When designing composite structures to sustain stress transverse to unidirectional fibers, as in the EMC rotor concept, one must consider the effects of creep and creep rupture in addition to the short-term properties. Creep during the transverse loading of unidirectional epoxy matrix composites is well documented in the literature [5], with delayed rupture strains in the range of only 0.02 to 0.04%. Not surprisingly, polyurethane matrix composites also creep readily across the fibers, but limit strains of over 10% without failure have been reported, as shown in Fig. 1 [6]. The creep phenomenon and the performance requirements it places on candidate EMC material systems for “fail-safe” flywheel rotors are the primary motivations for the present investigation.

The objective of this investigation is to evaluate the limit stress and strain states in a circumferentially wound EMC disk-shaped flywheel that is presumed to completely creep (and relax) in the radial direction. The circumferential fibers are assumed to remain linearly elastic and perfectly bonded to the matrix. With the limit strain state thus determined, one can screen candidate EMC systems for “fail-safe” flywheel applications by examining the ability of the material to accommodate the predicted creep deformation without failure. If a material satisfies the creep deformability requirement and the redistributed stresses in the rotor are still amenable to “fail-safe” operation, then the candidate material would be deemed suitable for further investigation.

Analysis

As may be seen from scientific publications [7], the analytical calculation of stress states in rotating disks with creep is a very difficult problem even for the isotropic case. Solutions have been obtained only for steady state creep in an isotropic rotating disk. It is intuitively evident that radial creep in an anisotropic disk with high elastic modulus in the circumferential direction cannot be unlimited. It is appropriate for qualitative and partly quantitative estimation of stresses and strains in an anisotropic rotating disk with radial creep to consider approximate approaches. One such approach may be as follows.

Let us suppose that, after spin-up, the distributions of circumferential and radial stresses in an anisotropic disk, \( \sigma_0^0 \) and \( \sigma_r^0 \), respectively, correspond to their distribution in a linear elastic material (i.e., spin-up is sufficiently fast so that creep during acceleration may be neglected). Then, as radial creep and relaxation begin in the disk rotating with a constant speed, radial displacements change and radial stresses decrease. In an approximate sense, the creep and relaxation processes are equivalent to the reduction of the radial modulus of elasticity from \( E_0^0 \) to \( E_r^* \). An approach of this type has been used for the examination of residual stress generation in wound composite rings at the heating stage [8]. Then, stresses \( \sigma_r^* \) and \( \sigma_0^* \), after such decrease of radial modulus, may be presented in the following form:

\[
\sigma_r^* = \sigma_0^0 \frac{E_r^*}{E_r^0} + E_r^* \frac{du^*}{dp}, \quad \sigma_0^* = \sigma_0^0 + E_0^0 \frac{dE_0^*}{dp},
\]  

(1)