Composite Flywheels Assessed Analytically by NDE and FEA

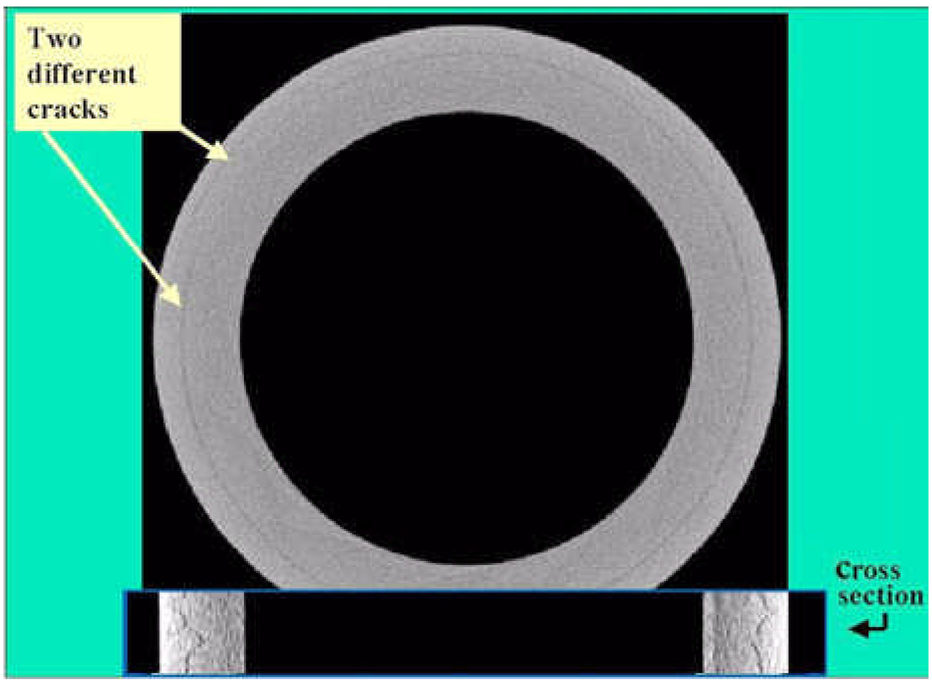
As an alternative to expensive and short-lived lead-acid batteries, composite flywheels are being developed to provide an uninterruptible power supply for advanced aerospace and industrial applications. Flywheels can help prevent irregularities in voltage caused by power spikes, sags, surges, burnout, and blackouts. Other applications include load-leveling systems for wind and solar power facilities, where energy output fluctuates with weather. Advanced composite materials are being considered for these components because they are significantly lighter than typical metallic alloys and have high specific strength and stiffness. However, much more research is needed before these materials can be fully utilized, because there is insufficient data concerning their fatigue characteristics and nonlinear behavior, especially at elevated temperatures.

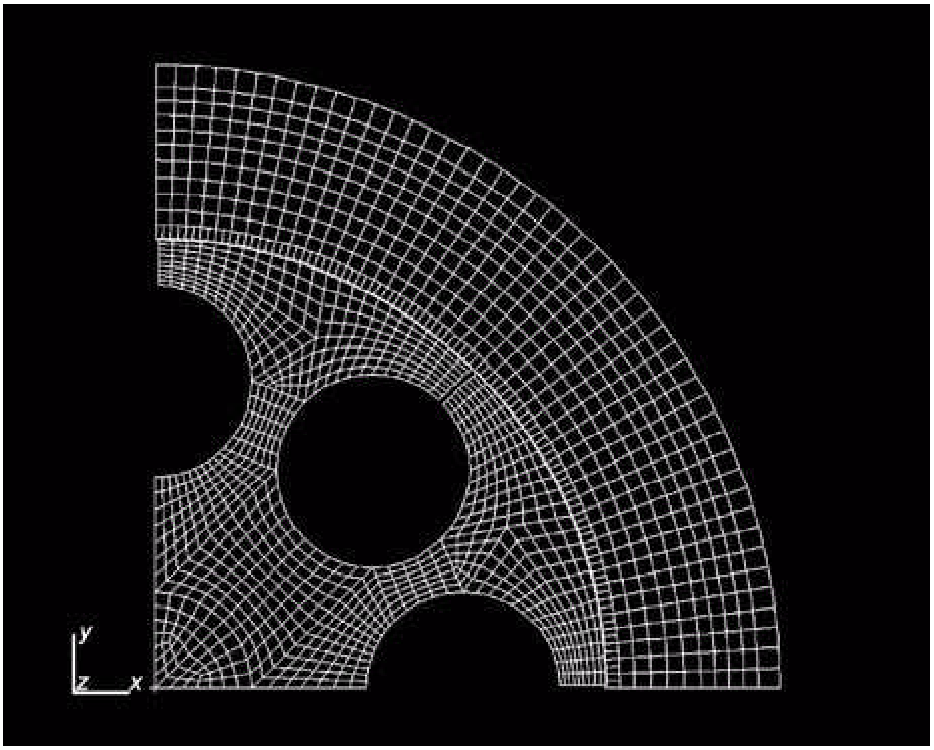
Moreover, these advanced types of structural composites pose greater challenges for nondestructive evaluation (NDE) techniques than are encountered with typical monolithic engineering metals (refs. 1 and 2). This is particularly true for ceramic polymer and metal matrix composites, where structural properties are tailored during the processing stages. In fully densified components, NDE techniques must detect and characterize various types of discrete defects like cracks, voids, and other overt discontinuities. It is also important to detect and characterize microstructural and diffuse flaw conditions that govern overall strength, fracture toughness, impact resistance, and resistance to thermal-mechanical-chemical degradation. These diffuse flaw states can reduce reliability and diminish service life just as much as discrete flaws (ref. 3).

In addition, the processing of innovative high-temperature materials requires the concurrent development of innovative NDE technologies. Sanders and Baaklini (ref. 4) demonstrated that the nondestructive characterization of materials and proper feedback help optimize the processing procedures. Applying American Society for Testing and Materials (ASTM) standards in nondestructive quality inspection assures the reliability of selected materials. Vary (ref. 5) suggested that new NDE standards and methodologies should mature simultaneously with advancements in materials development.

Current efforts involving the NDE group at the NASA Glenn Research Center at Lewis Field are focused on evaluating many important structural components, including the flywheel system. It has been shown that, with proper motor-generator and rotor design, flywheels have potentially higher efficiencies and longer lifetimes than other power systems, especially those made of fiber-reinforced polymer composite materials (ref. 6). However, the challenge of designing high-energy flywheel systems that can withstand the stresses caused by high rotational speeds is still considerable. At certain centrifugal loads, steel or titanium flywheels have shattered and been destroyed, which has increased interest in investigating the use of composite materials for future flywheels.

Glenn’s in-house analytical and experimental capabilities are being applied to analyze data produced by computed tomography (CT) scans to help assess the damage and defects of high-temperature structural composite materials. Finite element analysis (FEA) has been used extensively to model the effects of static and dynamic loading on aerospace propulsion components. This technique allows the use of complicated loading schemes by breaking the complex part geometry into many smaller, geometrically simple elements. In-house and commercial software packages are being used to construct three-dimensional models of images from CT scan slices. For example, Velocity[2] (image processing and three-dimensional reconstruction visualization software, ref. 7) is being used to construct the three-dimensional model and subsequently to generate a stereolithography file that will be suitable for computer-aided design applications. Tools developed in-house are being used to convert Velocity[2] stereolithography files to solid, three-dimensional FEA meshes. The entire process that outlines the link between the data extracted via NDE and FEA will be published soon.

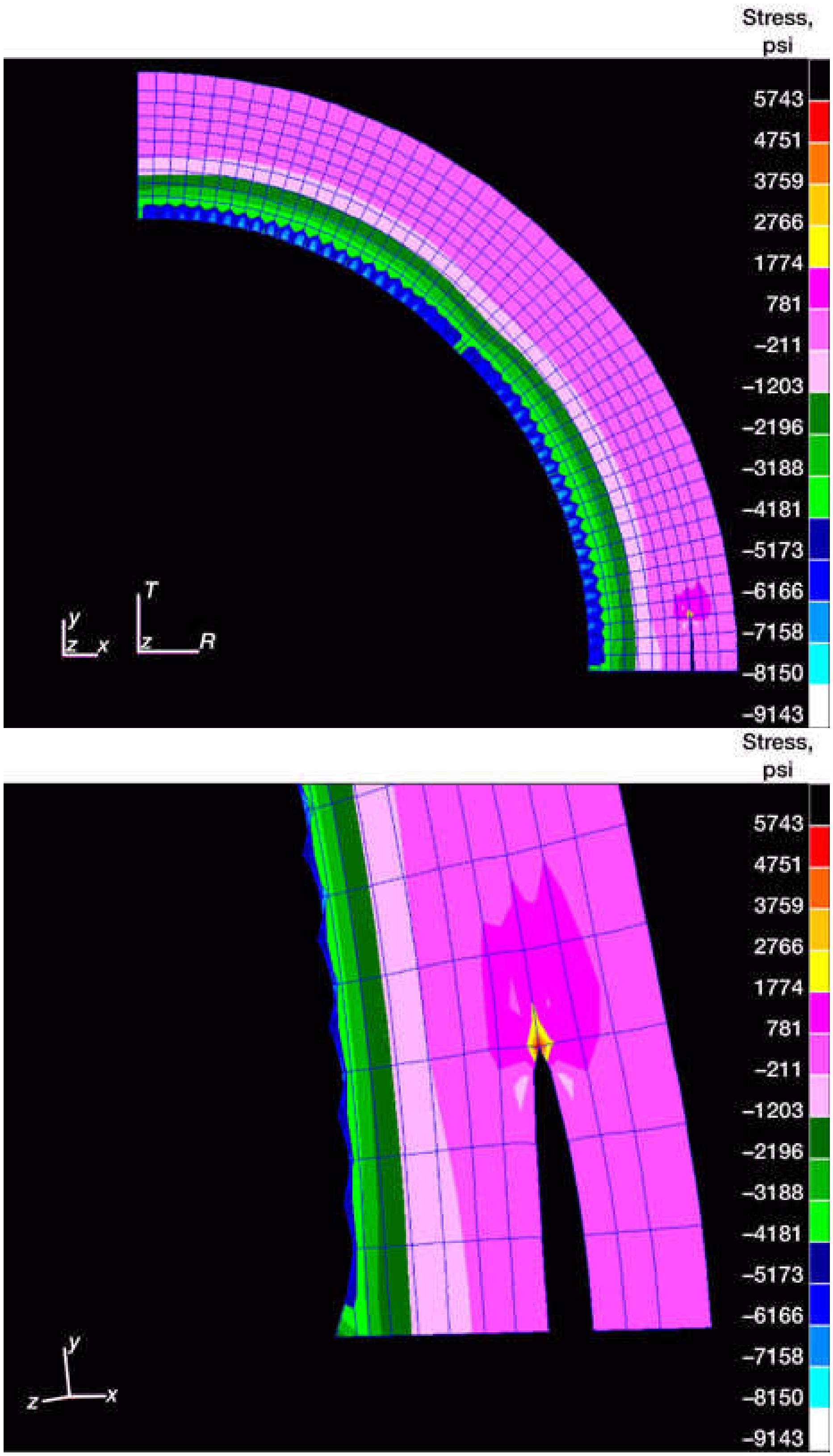




Top: CT cross section of a tested flywheel and cross section from a limited three-dimensional data set. Bottom: Finite element model of rotor-hub assembly.

The figures presented in this article represent typical NDE–FEA results. The first preceding figure shows a computed tomography (CT) scan for a polymer matrix composite rotor. It illustrates the defects due to centrifugal loading extracted by the CT scan in the rotor (spun at 34,000 rpm); two cracks along the circumferential direction are clearly shown. In addition, a cross-sectional view of the crack that is parallel to the axis of rotation of the rotor is shown at the bottom of the first figure. The second figure is the FEA model of the rotor-hub assembly.

The following figures represent the FEA results obtained via fracture mechanic analyses; radial stress distribution is presented. Crack propagation is also documented in these figures. Stress levels due to the applied loading are noted. Tensile stresses at the crack tip reached nearly 6 ksi while the region where the rim contacts the hub remained compressive as anticipated. It can be concluded from the data that the finite element fracture mechanics closely simulated the CT scan findings. Furthermore, this work has established the preliminary grounds for an NDE–FEA–Fracture Mechanics interface methodology that can be used for the structural analysis of composite rotors.



Top: Fracture mechanics analysis, radial stress distribution. Bottom: Fracture *mechanics analysis, radial stress distribution, and closer view of crack propagation.*

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