Crack propagation analysis of woven-fabric reinforced composite laminates

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Chapter 1 Introduction

Composite materials can be defined as a select combination of dissimilar materials formed with a specific internal structure and with a specific external shape or form. Composites are designed to achieve unique mechanical properties and superior performance characteristics not possible with any of the constituent materials alone. Quite often, the unique combinations of materials, structure and form found in composites lead to synergistic effects wherein the behavior of the whole is much greater than the sum of the parts, from a performance point of view. Fiber-reinforced composites, for example, consist of high strength and high modulus fibers in a matrix material. In these composites, fibers are the principal load-carrying members, and the matrix material keeps the fibers together, acts as a load-transfer medium between fibers, and protects fibers from being exposed to the environment (e.g. moisture, humidity, etc.).

One type of fiber-reinforced composite is the textile composite. In recent years, there have been rapid technological developments in the range of application of textile composites. Fibers in textile forms are used in composites to derive advantages from textile structures such as better dimensional stability, subtle conformability, and deep draw moldability/shapability. The combination of different fibers and matrix materials leads to various composites with excellent characteristics. Woven-fabric composites represent a class of textile composites in which two or more sets of fiber bundles are interlaced at a 90° angle. Currently, most of the woven fabrics used in composites are simple two-dimensional fundamental weaves, i.e. plain, twill and satin weaves, which are identified by the repeating patterns of interlaced regions. The plain weave is the oldest and most common weave pattern. Woven-fabric composites are often made in the form of a thin layer, called lamina. Structural elements, such as bars, beams or plates are then formed by stacking the layers to achieve desired material properties for a specific application.

The low cost, reasonable strength properties and low thermal and electrical conductivities have made woven-fabric/polymer-matrix composites very popular for cryogenic applications. Glass-fabric reinforced epoxy
composites continue to dominate cryogenic interest. Efforts to understand composite behavior better at cryogenic temperatures have largely been stimulated by the need to develop power generation systems as alternatives or improvements to conventional systems. ITER (International Thermonuclear Experimental Reactor) will be the first operating fusion reactor. Although operational conditions and the design of ITER in-vessel components may differ from the design for reactors producing electricity, ITER will provide an unique opportunity to test different reactor components and reactor materials for the next step fusion reactor. World-wide interest in energy generation by MFE (magnetic fusion energy) technology has required construction of large superconducting magnets which must function for many years under demanding service conditions. This has placed increasing demands on the performance of woven-fabric glass/epoxy composites that serve as electrical and thermal insulators and structural supports for the superconducting magnet coils.

The development of carbon and aramid fiber fabrics has extended the usable engineering range of woven-fabric composites to aerospace structures. Structural weight reduction through the use of advanced materials and manufacturing is one of the targeted outcomes of NASA's Space Launch Initiative. One way to achieve this objective is through the replacement of metallic cryogenic fuel-tanks with polymer-matrix composite tanks for RLVs (reusable launch vehicles). Woven-fabric carbon/epoxy composites are being explored as possible materials for the storage of cryogenic fuels, due to their high strength-to-weight ratio and impact resistance.

Homogeneous engineering materials subjected to loads usually fail as a result of critical crack propagation. Composite materials, in contrast, exhibit gradual damage accumulation to failure, and the failure process in composites is often viewed as a process of formation, accumulation, and coalescence of damages of different types. Many damage micromechanisms are observed in composites. For woven-fabric composite laminates, the most typical damage mechanisms are matrix microcracking, bundle matrix cracking, bundle delamination, interlaminar delamination and fiber breakage. In the case of uniaxial tensile loading, microcracking in the transverse fiber bundles, i.e. the fiber bundles which lie in the direction perpendicular to the applied load, is the first readily observable type of damage in these materials. The exposure to cryogenic temperatures combined with mechanical loading can produce extensive damage in woven-fabric/polymer-matrix composites that can alter their properties, and damage development in woven-fabric composites at cryogenic temperatures starts early in the loading history. Results from some experiments on standard woven-fabric glass/epoxy high pressure industrial laminates showed that "knee" behavior, i.e. a phenomenon by which the stress-strain curve exhibits a knee or change in slope, resulted at strains well below the ultimate strain and that the epoxy failures in the transverse fiber bundles corresponded with the knees.

At cryogenic temperatures, residual thermal stresses can significantly affect the failure process of woven-fabric composites. The residual thermal stresses are caused by the mismatched CTEs (coefficients of thermal expansion) between the composite constituents and the large difference between the manufacturing and in-service temperatures. In addition, the fracture and failure behavior of woven-fabric composites is influenced by the type of weave, fabric geometry, fiber volume fraction and the material system used. Because of the geometrical complexity of the woven-fabric composites and the cost of testing, it is not practical to investigate their fracture and failure mechanisms at cryogenic temperatures through experiments alone. The efficiency of the designs of cryogenic composite structures is highly dependent on our ability to predict accurately damage initiation and subsequent damage growth. Therefore, analytical studies on the cryogenic fracture and failure behavior of woven-fabric composites are essential for better understanding of their life and the confident application of these materials in cryogenic structures.

Most of the analytical research on woven-fabric composites has been focused on predicting their thermo-elastic properties. Some works related to the stress and strain analysis of woven-fabric composites are presented. The analyses of damage evolution in woven-fabric composites were also performed by many authors. However, all of the
above work has pertained to the behavior of woven-fabric composites at room temperature and analytical investigations on their cryogenic response are still very limited, since an adequate property database does not exist for woven-fabric composites and composite constituents at cryogenic temperatures.

This paper presents a systematic numerical study on the fracture and failure behavior of woven-fabric composite laminates at cryogenic temperatures. Experimental studies on the cryogenic response of woven-fabric laminates are also presented. The present work considers only the case of the glass/epoxy plain weave fabric-reinforced composite system, NEMA (National Electrical Manufacturer's Association) grade G-11, under tensile loading. The G-11 product is fabricated to meet normal temperature electrical insulation performance criteria established by NEMA. The objectives of this paper are twofold: (1) to investigate the behavior of G-11 woven-fabric laminates involving transverse fiber bundle cracking, i.e. the first damage mode, and (2) to study their damage characteristics due to failure of the constituents.

Chapter 2  Stress Intensity Factors for Woven Glass/Epoxy Laminates with Cracks at Cryogenic Temperatures

We investigate the stress intensity factors for several crack configurations in G-11 woven glass/epoxy laminates with temperature-dependent properties under tension at cryogenic temperatures. A state of generalized plane strain is assumed. Cracks are assumed to have occurred in the transverse fiber bundles. Cases of a single stack and doubly-periodic arrays of cracks are considered. The order of stress singularities at the tip of a crack is obtained for the case where the crack is normal to and ends at an interface between two fiber bundles. A finite element method is used to determine the stress intensity factors at the crack tip of two-layered woven laminates. Special singular elements containing the exact stress singularity are placed around the crack tip. Numerical results for the stress intensity factor and the order of stress singularities at cryogenic temperatures are obtained and are presented in a graphical form.

Chapter 3  The Thermo-Mechanical Problem of Internal and Edge Cracks in Multi-Layered Woven GFRP Laminates at Cryogenic Temperatures

This chapter presents the thermo-mechanical response of multi-layered G-11 woven glass/epoxy laminates with internal and/or edge cracks under tensile loading at cryogenic temperatures obtained from a two-dimensional finite element analysis. A condition of generalized plane strain is assumed to exist in the composite. Cracks are considered to occur in the transverse fiber bundles and extend through the entire thickness of the fiber bundles. The finite element model accounts for the temperature-dependent constituent properties. A detailed examination of the Young's modulus and stress distributions near the crack tip is carried out which provides insight into material behavior at cryogenic temperatures.

Chapter 4  Fracture Mechanics Analysis of Multi-Layer Plain Weave Fabric Laminates with Transverse Cracks at Cryogenic Temperatures

This chapter presents the stress intensity factors for internal and edge cracks in multi-layer glass/epoxy plain weave fabric laminates subjected to uniaxial tension load at cryogenic temperatures. Cracks are considered to have occurred in the transverse fiber bundles. Finite element analysis of the limiting case when the cracks extend to the interfaces between two fiber bundles is carried out. Special singular elements containing the exact stress singularity are used to model the singular stress field near the crack tip. Numerical results for the stress intensity factor at cryogenic temperatures are displayed graphically and discussed in detail.
Chapter 5  Cryogenic Mechanical Response of Multi-Layered Woven-Fabric Glass/Epoxy Laminates with Cracks – Sinusoidal Description of Fabric Geometry

This chapter deals with the thermo-mechanical behavior of multi-layered G-11 woven glass/epoxy laminates with internal and/or edge cracks and temperature-dependent material properties under tension at cryogenic temperatures. Sinusoidal shape functions are used to define the cross-section and undulation of fiber bundles. Cracks are assumed to be located in the transverse fiber bundles and extend to the interfaces between two fiber bundles. Young’s modulus and stress distributions near the crack tip under combined mechanical and thermal loads are predicted by a finite element model that assumes generalized plane strain. The effects of residual thermal stresses, cracks and number of layers on the mechanical behavior of multi-layered G-11 woven laminates at cryogenic temperatures are calculated, and the numerical results are presented in graphical form.

Chapter 6  Three-Dimensional Thermoelastic Analysis of Cracked Plain Weave Glass/Epoxy Composites at Cryogenic Temperatures

This chapter examines the thermo-mechanical behavior of cracked G-11 woven glass/epoxy laminates with temperature-dependent material properties under tension at cryogenic temperatures. Three-dimensional finite elements are employed to model the architecture of the two-layer woven laminates. It is assumed that the cracks are confined to individual fiber bundles oriented transverse to the tensile load direction and span the thickness of the fiber bundles. The effects of residual thermal stresses caused by differences in the coefficients of thermal expansion of the composite constituents, and cracks on the mechanical behavior of two-layer G-11 woven laminates at cryogenic temperatures are explored. Numerical results for Young’s modulus, Poisson’s ratio, and stress distributions and concentrations are obtained and discussed in detail.

Chapter 7  Tensile Deformation and Progressive Failure Behavior of Woven-Fabric GFRP Laminates at Cryogenic Temperatures

This chapter focuses on understanding the deformation and progressive failure behavior of glass/epoxy plain weave fabric-reinforced laminates subjected to uniaxial tension at cryogenic temperatures. Cryogenic tensile tests were conducted on the woven-fabric laminates, and the damage development during loading was characterized by AE (acoustic emission) measurements. A finite element model for progressive failure analysis of woven-fabric composite panels was also developed, and applied to simulate the “knee” behavior in the stress-strain responses and the damage behavior in the tensile test specimens. Failure of the epoxy resin matrix in the transverse fiber bundle was predicted to occur using the maximum strain failure criterion. The effect of strain concentrations due to the fabric architecture on the failure strain of the material was considered by incorporating the SVF (strain variation factor) from the meso-scale analysis of a woven-fabric composite unit into the macro-scale analysis of the specimens. A comparison was made between the finite element predictions and the experimental data, and the agreement is good.

Chapter 8  Conclusions

The main results and conclusions of the present research work are summarized.
論文審査結果の要旨

本論文は、超電導応用・航空宇宙機器の設計・開発および信頼性・安全性評価のための織物有機複合材料の極低温破壊・損傷挙動に関する理論的・実験的研究成果をまとめたもので、全編8章からなる。

第1章の序論では、本研究で対象とした織物有機複合材料の特徴・応用および極低温破壊・損傷挙動に関する研究の位置付けを述べると共に、本研究の目的と意義を明らかにしている。

第2章～第6章は、引き裂を受けるき裂材の破壊力学的観点から、負荷垂直方向の繊維束（縦繊維束）内に存在するき裂を考え、平繊GFRP（ガラス繊維強化プラスチック）積層材料G-11を対象に著者マイクロ構造を有する複合材料モデルの有限要素解析（冷却残留熱応力考慮）を行ったもので、極低温における熱弾性・破壊力学的挙動を解明している。解析は、物性値温度依存性を考慮し、き裂は機械的負荷方向に垂直な場合を考えた。先ず、第2章では、一般化平面ひずみを仮定し、繊維束の繊維構造を直線により近似した中央線き裂を有する二層平繊GFRP積層材料の二次元モデルを対象に、高精度の特異要素を組み込んで有限要素解析を行い、応力拡大係数などの破壊力学パラメータに及ぼす冷却残留熱応力・温度・き裂長さおよび繊維束中における繊維体積含有率の影響を解明している。また、き裂が繊維束界面に到達している場合についても、同様に考察を加えている。第3章では、き裂を有する多層平繊GFRP積層材料の二次元モデルを対象に、弾性係数およびき裂先端近傍応力を、第4章では、破壊力学パラメータを解明・考察している。続く第5章では、繊維束の繊維構造を正弦関数により近似して多層平繊GFRP積層材料中におけるき裂の極低温挙動を明らかにし、二次元モデルによる熱弾性力学的挙動の簡便評価に成功している。第6章では、これらの解析を拡張し、弾性定数およびき裂先端近傍応力に関して、二次元モデルによる厳密評価を行ったもので、極低温における熱弾性力学的挙動について総合的考察を加えている。

第7章は、極低温構造機器の設計上重要な、織物有機複合材料の応力～歪曲線におけるKnee×点と材料内部に生じる損傷との関係を明らかにするため、平繊GFRP積層材料G-11を取り上げ、AE（アコースティック・エミッション）法を併用した極低温引張試験および平滑材のマクロスケールモデル（マイクロメカニックスモデルを用いて推定した弾性定数を有する均質直交異方性体モデル）を対象に有限要素法による損傷進展解析を行ったもので、平滑材の材料強度学的視点からの検討を行い、極低温引張・損傷挙動を解明している。

最後に、第8章の結論では、各章で述べた内容を概括すると共に、得られた知見を整理して本論文の総括としている。

以上要するに、本研究は、織物有機複合材料の極低温破壊・損傷挙動の理論的・実験的解明に成功し、高性能な極低温用複合材料の設計・開発・評価に資する結果を提供したもので、材料加工プロセス学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。