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Heterogeneous fracture mechanics for multi-defect analysis

Kenneth Reifsnider [a,*], M.D. Rassel Raihan [a], Vamsee Vadlamudi [b]

[a] University of Texas Arlington Research Institute, Department of Mechanical and Aerospace Engineering, Box 19045, Arlington, TX 76019, USA
[b] Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208, USA

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Discrete flaw computational damage mechanics is often used to certify the life of composite aircraft parts made from continuous fiber reinforced composite laminates. Other modes and combinations of damage that define changes in the defect state and the attendant loss of integrity and increased risk of operation of composite structures throughout the life of a component do not yet have a corresponding general representation. The present paper postulates a more general "heterogeneous fracture mechanics" concept based on an experimental observable and a multiphysics analysis used to interpret such observations, for multi-defect representations. Experimental and analytical foundations for the new concept are presented. The method can provide a foundation for the conception and design of durable and damage tolerant heterogeneous material systems for a myriad of applications, including vehicular and civil structures, medical prosthetics, and energy conversion and storage devices.

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1. Introduction

Classical fracture mechanics (CFM) was created as a conceptual physical understanding and modeling approach to represent the local singularity at a crack tip in terms of physical observables (state variables), and thereby to enable the prediction of remaining strength and life of materials and structures. With various additions of elastic–plastic response, anisotropy, and non-local mechanics it has become a universal foundation for design and the basis for countless codes the world over. It has also become the industry standard for model-based predictive monitoring and supervisory control in which real time information (including uncertainty) is used to alter operational variables and greatly increase system efficiency, output, and reliability with greatly reduced cost [1,2].

Fracture mechanics was conceived for homogeneous materials, and is usually discussed for single cracks or countable assemblies of cracks. When one speaks of "fracture toughness" in this context, the global material observable is used. Modern applications of CFM to discrete defect analysis in heterogeneous (composite) materials have followed these precepts, typically using anisotropic physical properties to account for heterogeneity or micromechanics to discuss specific damage mechanisms [1]. But the physical foundation of CFM is one mechanism (a single self-similar crack) in a single homogeneous material (or an interface between two dissimilar materials). When applied to heterogeneous materials, the simple connection to global behavior is lost; crack initiation is not "failure;" single cracks almost never "act alone" to control strength and life; and we have no single measureable "crack length" or "toughness" to characterize damage tolerance – the most important single mechanical characteristic of heterogeneous materials (man-made and natural).

Historically, this barrier has been widely recognized. Perhaps the single most frequent proposed solution to the conundrum is what has become "classical damage mechanics" (CDM) which argues that a proper physical observable for the multi-scale evaluation and interpretation of heterogeneous damage is stiffness change [3,4]. The appeal of this approach is strongly based; the original papers of Irwin [5] and Kies [6] and the subsequent work of Griffith [7] (and many others) showed that multiple defect initiation and growth can be discussed in terms of total strain energy release rate which is proportional to global compliance change, now a standard method for evaluating crack growth rates and global toughness, and universally used in countless standard analysis codes (e.g., DARWIN, ABAQUS, ANSYS, etc.) [8]. Unfortunately, stiffness/compliance change is not unique to specific defects or mechanisms, so it is not possible to discriminate the specific contribution of different material constituents or defect types to a given stiffness change observation unless much more information is available. And it is very difficult to measure stiffness locally, in a specific material volume.

In the present work, we construct a new foundation for heterogeneous fracture mechanics (HFM) based on a different material

* Corresponding author.
E-mail address: Kenreifsnider@gmail.com (K. Reifsnider).

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property/observable, the dielectric material response to a time variable vector electric field. In earlier work, we have shown evidence that dielectric physical data directly relate to *individual* specimen strength (including uncertainty) [9]; that the multi-scale multiphysics analysis that relates the micro-response to global observations correctly predicts relationships between *constituent* responses (including defects) and their interactions and the global mechanical behavior such as strength and life [10,11]; and that the resulting electrical/mechanical HFM (unlike damage mechanics) can be inverted (the inverse problem can be solved, at least in some cases) as a foundation for the design of materials and systems, and for supervisory control [12]. These results suggest that a new discipline can be constructed for heterogeneous materials that is an analog to fracture mechanics for homogeneous materials. It is the purpose of the present paper to explore that possibility.

For continuous fiber reinforced composites, the general nature of the development of defects during quasi-static and fatigue loading is well established and widely accepted [13,14]. A typical representation of that sequence is shown in Fig. 1.

An example of these damage modes is shown in the sequence of surface replicas in Fig. 2. In that figure, scanning electron microscope images were taken of the same area on the edge of a coupon specimen during quasi-static 45 degree off-axis loading of a plain weave continuous glass fiber reinforced epoxy coupon to successively higher load levels until fracture occurred. The initial patterns (a,b) show no damage; matrix cracking is clearly seen in replicas (c,d), coupling of cracks is found near the end of loading, (e), and just before fracture a through-the-thickness coupling of cracks is resolved in (f) [15]. One focus of the present work is an effort to construct a non-invasive assessment method of discriminating the mechanisms, modes, and rates of the development of such damage.

Similar damage patterns develop during cyclic (fatigue) loading of such materials. Fazzino recorded damage development patterns during the end-loaded bending fatigue of glass–epoxy materials, which showed that progressive damage grew from the two surfaces towards the interior, as expected. An example of such damage is shown in Fig. 3.

Fazzino also recorded the changes in the dielectric properties (through the thickness measurements of the capacitance and material permittivity) for his specimens and discovered that there is a unique and logical relationship between the changes in dielectric response during fatigue damage as a function of the fraction of life, a discovery that earned the Silver Prize from the Royal Aeronautical Society in 2010 [10]. An example of those results is shown below.

From Fig. 4 it is seen that the impedance response begins with a straight line with monotonic negative slope as one would expect for a dielectric material between two conducting plates (the response of a parallel plate capacitor). As damage develops, in this case through the thickness, in the presence of ambient air which has some finite moisture content, the response becomes flat, i.e., independent of frequency, which is characteristic of a conductor. So the development of damage (even in the very early stages of life) is clearly detected, and the development of a fracture plane is clearly defined by the data.

More generally, our research (and a foundation of other work) has taught us that when micro-damage that creates new internal surfaces or volumes is formed in a material subjected to a vector electric field applied through the thickness of the damaged section, changes in dielectric polarization properties of the material are caused, precisely, uniquely, and directly by the new internal surfaces and volumes that are formed, and that the rate of change of those dielectric properties is controlled by the rate of new surface and crack volume formation. The 'new work of polarization' caused by the new surfaces and volumes created by progressive damage is directly related to the strain energy release rate from that same damage in a fundamental way. Since, for heterogeneous structural materials, it is arguably difficult or impossible to measure point-wise strain energy release rate (e.g. local compliance changes, or all local crack lengths) but demonstrably straight forward to measure local dielectric compliance changes and polarization in a material or structure, our approach is to use through-thickness changes in dielectric properties as a measure of the collective rate of degradation and to interpret those rates, directly, in terms of strength and life.

Griffith (and Eshelby, and others) have taught us that when cracks are formed in a material subjected to a tensor stress field, the (strain) energy released by the crack phase region is used to form the new surfaces of the crack, and that the amount of energy released is determined uniquely by the material properties, the crack (surface) area, the geometry of the specimen, and the tensor values of the applied stress field. This "strain energy release rate" (change per unit area crack surface increase) uniquely defines the crack formation event, and a material property called the "critical strain energy release rate" defines the onset of the fracture event (final failure, end of life, etc.). This discipline is generally referred to as Linear Elastic Fracture Mechanics (LEFM). In the present work, we formulate a dual concept based on an observable material state variable, the dielectric permittivity of the material, and postulate that it is possible to develop a heterogeneous fracture mechanics discipline for multiple defects that functions in the same general way as LEFM does for single defects.

2. Analysis and methods

In a series of papers over the last five years or so, the authors have reported several advances in the understanding of the

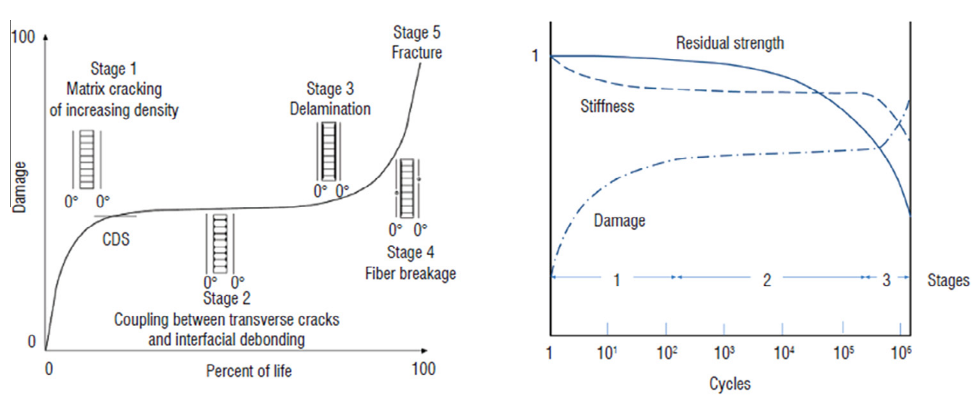

Fig. 1. Mechanisms and stages of damage development, accumulation, and fracture for continuous fiber reinforced polymer matrix composites.

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