State Variable Methods of Assessment, Prognosis, and Control of Composite and Bonded Structures

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ABSTRACT

It is generally recognized that the determination of material state is the baseline foundation for the assessment and prognosis of current and future performance of structural materials in which distributed damage leads to progressive property degradation. Many classes of composite materials, both naturally occurring and engineering designs, are governed by such behavior. However, finding appropriate measurable physical variables to make such assessments, especially for as-manufactured and subsequent real-time assessment and prognosis conditions is challenging. Measurement and analysis of multiple single defect initiation, interaction, and collective effects is the most rigorous current methodology, and is the foundation for certification and quality assessment in the aerospace industry. But it can be difficult (or impossible) to find all of the defects in as-manufactured composites or (especially) to assess their growth and interaction during real-time service, and to conduct the proper analysis of their collective effect on strength and life as a function of real-time load and environmental history of a given structure. Global state variables are well suited to this challenge, but finding suitable measurables and methods is challenging. The current paper will examine several aspects of this problem for structural composite materials, bonded joints, and additive manufactured composite elements with complex shapes. Recent experience and results of development efforts in our group to exploit electrical and dielectric methods will be described. Applications to materials aging, degradation during highly nonlinear deformation, bonded joints, and “materials in the loop” structural control concepts and examples will be presented [1].

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STATE VARIABLE METHODS

We have become accustomed to thinking about composite materials as material systems, and systems are defined by their state variables [1]. State variables consist of all information about the physical state that is necessary to define the behavior of that system under current conditions. It can be said that the state of a (material) system is defined when all the information necessary for a complete characterization of the system is in hand [2]. The definition depends on the purpose at hand, i.e., there is an implied function of the system when state variables are defined. Our focus here is the function of composite material systems under the influence of mechanical, thermal, and chemical applied conditions.

The literature provides ample evidence that state variables are well defined for reversible functions, especially for familiar materials such as metals and polymers. The corresponding literature for composite materials is remarkably vacant. The need for a definition of state variables (and state functions) for irreversible processes in composite materials has spawned the concept of "damage mechanics" (still in its infancy) and many other related approaches.

The “purpose at hand” for the present discussion is performance, especially on specific elements of performance such as durability and reliability. For the purpose of our present discussion, we will focus on composite material state variables that, in our experience, best define the state of composite material systems in this context.

DIELECTRIC STATE VARIABLES

Our understanding of the dielectric response of materials and material systems has greatly matured in the last ten years or so. At the fundamental level, “dielectric” materials transmit electric force without conduction. The mechanism for this electric force transmission is general charge displacement (without conduction of an electric current in a static electric field). Many mechanisms of charge displacement are discussed in the literature. Classical mechanisms are shown in Figure 1.

![Figure 1: Dielectric response of material constituents at broad band frequency ranges.](image-url)
Traditional literature has focused on the high frequency dielectric response of materials, especially as they relate to optoelectrical devices. However, for the last 15 years or so the present authors have focused on the relationship of these dielectric state variables to the mechanical, electrical / electrochemical, and thermal performance of composite material systems. The charge displacement in such systems may depend on an array of charge carriers, e.g., ionic forms of oxygen or many other species associated with the presence of moisture, or more generally the diffusion of ions between phases or through grain boundaries in a heterogeneous material in the presence of an alternating global electric field.

We discovered that the exact nature of this charge displacement behavior can be measured with Broadband Dielectric Spectroscopy (BbDS) and that those data are directly and uniquely related to the material state and performance of a variety of composite material systems. In this short space, only a few examples will be given.

**ASSESSMENT**

Raihan, et al. recovered the details of damage development in woven cross ply glass reinforced epoxy during off-axis quasi-static loading of composite coupons using edge replication, as a function of load level [3]. An example of those data is shown below.

![Figure 2: Edge replicas showing the sequence of damage development during off-axis loading of woven glass epoxy coupons. [3]](image)

During that loading the dielectric response was measured through the thickness of the coupons and those results were compared with all other variables. An example of those data is shown in Figure 3, along with a general interpretation of the relationship of the micro-details with the dielectric measurements. The changes in dielectric response are not monotonic; they show unique changes in magnitude and direction depending on the changes in the mechanisms of damage. We have observed over a
wide range of composite materials and applied conditions (mechanical, thermal, electrical, chemical) that the through thickness dielectric response is directly and uniquely related to the internal microstructure and changes in local morphology [4,5,6].

Figure 3: Through thickness measurement of dielectric response: method (a) and example of results, (b), for off-axis loading of woven glass epoxy coupons. [3]

More recently, Vadlamudi has succeeded in coupling ABAQUS predictive modeling of the development of microdamage (at the fiber – matrix level) with COMSOL multiphysics modeling (by coupling those analyses) to predict the response
to microdamage observed in Figure 3 (and in many other results obtained by the authors) [7,8]. An example of those results is shown in Figure 4.

![Stress Strain Curve](image)

**Figure 4:** Fiber matrix damage predicted with ABAQUS and resulting stress strain curve for shear loading of a glass epoxy composite element.

The prediction of a stable highly – nonlinear stress strain curve using micromechanics is a significant advance; prediction of the details of laminate response such as that shown in Figure 3 is the next step in that process.

Using the data from Figure 3 it can be seen that the dielectric response clearly indicates the “beginning of the end,” i.e., the “tipping point” in damage development when the damage rate changes from decreasing to increasing as a function of load level. Figure 5 illustrates this important capability. If the change in stress-strain slope is a measure of damage, then we see that the change in the dielectric permittivity is also following that variation. If we then observe that the second derivative, the variation of the slope of the dielectric response is the damage rate, then we can identify “the smallest rate of change of damage,” as in Figure 5 as the point in the loading (or by extension the life) of the element after which the rate of damage development is accelerating, i.e., the “tipping point” for risk and safety. We know of no other non-invasive, real – time method that clearly identifies this critical point for composite materials. In [6] the authors also show that the second variation of the stored strain energy (as a function of strain) and the second variation of the stored dielectric energy have essentially identical values and slopes.
PROGNOSIS: LIFE PREDICTION

In earlier work from our group, Fazzino recorded the changes in the dielectric properties (using 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 [9]. An example of those results is shown below.

From Figure 6 it is seen that the through – thickness 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) for undamaged material. As damage develops, in this case through the thickness, in the presence of ambient air which has some finite moisture content, the dielectric 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. Moreover, the general interpretation that discrete defects create space charge concentrations, which upon further cyclic loading grow and finally connect to form a conductive fracture path is a rational and intuitive interpretation. Our subsequent research supports this concept of the damage progression scenario.
More generally, our research has taught us that when micro-damage creates new internal surfaces or volumes 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 surfaces that are formed, and that the rate of change of those 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 difficult or impossible to measure point-wise strain energy release rate (e.g. local compliance changes, or all local crack lengths) but demonstrably straightforward 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.

PROGNOSIS: BONDED JOINTS:

One of the most remarkable capabilities of the dielectric material state determination method is to detect and predict the strength of bonded materials, especially the strength of bonded heterogeneous materials. Banerjee, et al have pioneered this method development, and much current research is underway in our group [10]. This topic deserves much more space that we have in this discussion, but an example of the capabilities will be provided.

Banerjee has discussed the Dielectric Relaxation Strength (DRS) as a parameter for the estimation of the strength of bonded materials (not just the identification of “good” and “bad” bonds). An example of the capability of this method is provided in Figure 7 which shows a comparison of the DRS values recorded for several types of bonded joints in polymer – based composite coupons as a function of the bonding surface pre-treatment.
The relative strength of the bonds decreases as a function of the surface treatment, from the “no defect” condition to the insertion of a polymer (VB) film into the bonding area, from left to right in that figure. The proportion of those changes is closely matched by the increases in the DRS parameter, a direct prediction of the proportionate quality of the bond before the measurements were made. At this writing, we know of no other non-invasive method for making this proportionate measurement.

SYSTEM STATE ANALYSIS AND CONTROL:

The concepts and methods of data analytics has become pervasive in our technical and social society, and appears in diverse settings from identification of inebriated passengers in taxis to the flight control of hypersonic missiles. The classical sequence for such a venture can be traced to writings by Dykes, and is illustrated below [11].
In general, for engineering and other fields, the data driven challenge is to use the past with information from the present to predict the current state and future behavior of a system. In turn, the user must pay for collection and processing, hosting and maintenance of the data, and for the cost of analysis, etc. and address the risk of breach of the system.

In the present context, the first and perhaps the most important question in this approach is the nature of the data itself, i.e., the “source of truth.” We have many measurable quantities for composite materials. We must decide which of those we should use for the objectives of our analysis. Traditional data such as “failure rates” result in sparse data sets that may be impossible to analyze (“failure” is, by definition, after the fact). Also, abundant data from “health monitoring” systems may be distantly related to the physics of our objective function. Data interpretation and analysis for composites is especially challenging. For example, there may be “missing physics” that motivates the use of machine learning or more general artificial intelligence / neural network systems for interpretation.

As we have discussed above, dielectric material state data generally show a distinct, unique, and quantitative relationship to the state of the composite material systems we have investigated. Elencchezian et al. have discussed the application of Recurrent Neural Networks (RNN) and Random Forest Regression (RFR) to estimate the strength of notched composite coupons, with Machine Learning models [12].

![Figure 9: R^2 Score of the Machine Learning Models developed from physics based equation [13].](image)

In this case, the data used in the sampling and predictions was generated by a physics based model. Work is underway in our research group to use this approach to “teach” a machine to control a fatigue test of a composite coupon to prevent failure and control the risk of continued loading after specimen degradation using this methodology.

That brings us to the last point of the present discussion, the question of uncertainty in all of these methods. This subject deserves more space than we have for the discussion in this paper, but we must be aware of some essential tenants for our current discussion. ([13] presents a recent discussion that is pertinent to the present context.) The concepts of confidence intervals and A and B Allowables are familiar to the aerospace community; indeed, they are industry standard concepts. Perhaps the
greatest challenge for our community in this context is to recognize the sources of uncertainty, not only in the physical data but also in our estimation schemes, and to translate that understanding into specific statements of confidence and prediction interval, tolerance interval, and risk in the context of the intended application, i.e., the “performance” in the technical sense for our applications. These concepts must be correctly applied not only to the interpretation of the material state data, but also to the material system state analysis and control for the vehicles, bridges, medical devices, and other applications required of us.

CONCLUSIONS AND CONTINUING CHALLENGES:

The present short discussion has focused on state variable methods of assessment, prognosis, and control of composite and bonded structures. In particular, we have pursued the question of what physical observables we can readily measure at the global level that clearly define the material state in a way that enables us to use our interpretive models (physics based or data based) to predict future performance of the material system, especially for composite material systems. We use our current and past research on the relationships of various dielectric state variables to engineering performance of composite materials and bonded joints to address this subject and suggest that this approach is a robust and science-based foundation for progress in this general subject. While this research is still in the initial stages, the results of a decade of research reported in over two dozen archival papers provides encouragement for further investigations.

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