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Inverse characterization of composite materials via surrogate modeling

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ABSTRACT

Methods for the inverse characterization of mechanical properties of materials have recently seen significant growth, largely because of the availability of enabling technologies such as automated testing, full-field measurement techniques, and inexpensive computing resources. Unfortunately, as the complexity of the material systems and their associated behaviors increase, even the most advanced methods for inverse characterization require impractically large computation time to produce results. To overcome this limitation we present a method that employs Non-Uniform Rational B-spline (NURBs) based surrogate modeling to generate a very efficient representation of the combined constitutive and structural model response required for inverse characterization. Building on our previous work, we present an inversion method for identifying the constitutive material properties that minimize an appropriate objective function. Verification of this methodology is achieved through synthetic numerical experiments that include material systems of isotropic-elastic, orthotropic-elastic, and orthotropic-hyperelastic with damage nature on selected geometries. Statistical analyses on the effects of experimental noise supplement our analysis. We then proceed to demonstrate the use of this approach to characterize actual specimens tested using a multiaxial robotic system. In conclusion, we discuss the effectiveness and limitations of the surrogate model-based methodology and outline further research required to advance this approach.

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1. Introduction

The continuously increasing proliferation of composite materials in manufacturing, along with the associated need for designing composite structures, has further expanded the need for establishing their constitutive behavior and associated material parameters. Unfortunately, recent research [1–5] has shown that the characterization of composite materials can be computationally expensive, especially when specimens are tested using a six degree-of-freedom automated test frame such as the NRL66.3 system developed at the Naval Research Laboratory [3–6]. While the constitutive response models or "forward" models of composite material behavior are well understood, their repeated usage in the optimization loop required to solve the "inverse" problem of determining the material properties from multiple test datasets corresponding to multiple tests, has been shown to require impractically long computation times [6]. To address this problem, we have initiated an effort to explore more computationally efficient representations and methods.

Consequently, in the present work we investigate the potential of increasing the efficiency of conventional physics-based composite material characterization methods, by attempting to replace the structural system model with a physics-agnostic, but numerically accurate representation as is introduced in Section 2. To accomplish this goal we introduce surrogate models that are based on Non-Uniform Rational B-splines (NURBs). Although there is computational cost associated with their construction, the operation is efficient and is a one-time process. On the other hand, querying these surrogates is an extremely efficient activity (equivalent to evaluating a polynomial function) that enables the implementation of an inverse methodology framework that can be used to rapidly recover the material constitutive properties. The implemented numerical methodology for determining the proposed NURB-based surrogate models is the subject of Section 3.

The effectiveness and efficiency of the proposed method is presented in terms of a series of synthetic test problems in Section 4. We begin with the simple case of an aluminum specimen with a central hole subjected to in-plane loading. The material

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constitutive behavior is considered to be elastic and isotropic. A laminated composite specimen with an open hole discretized by a 3D finite-element representation that is based on a linear elastic orthotropic constitutive model is the next characterization example. A final synthetic experiment considers also a laminated composite test specimen with dual opposing edge notches and involves an orthotropic hyperelastic material. These results are accompanied by a statistical study on the effects of experimental noise on the accuracy of the recovered material properties. The extension of these synthetic results to the characterization of physical specimens tested in NRL's six degree-of-freedom robotic test frame (NRL66.3) is given in Section 5. Section 6 presents the conclusions drawn from the analysis conducted for these test experiments, as well as future plans.

The findings presented here are an extension of the developmental work found in [7]. The principle novelty of the present work is the mathematically rigorous description of the methodology employed. The details of many minor, but important aspects of the methodology are investigated and explicitly defined. Additionally, the present work extends the methodology into the domain of physical experimentation, and provides concrete support of the merit of this approach.

2. Constitutive characterization of composite materials

2.1. Outline of the forward problem

In the context of continuum mechanics, the complete behavior of a deformable anisotropic elastic body without body forces and inertial terms and for the case of infinitesimal strain theory assumptions, is described by the well known system of equations [8],

$$\nabla \cdot \boldsymbol{\sigma} = 0, \tag{1a}$$

$$\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon}, \tag{1b}$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T\right]. \tag{1c}$$

In this description, Eq. (1a) represents the elastostatic form of the conservation of momentum, while Eq. (1b) represents the linear elastic constitutive law (otherwise known as generalized Hooke's law) and Eq. (1c) the strain–displacement equations for the case of infinitesimal strains and small displacements. The quantities $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$ and $\boldsymbol{u}$ represent respectively, the two second order tensors of the Cauchy stresses and infinitesimal strains, as well as the displacement vector. The fourth order tensor $\boldsymbol{C}$ contains as its elements all the anisotropic constitutive parameters of the material system and is usually referred to as the elasticity tensor. When these parameters are known for a material system enclosed in some volume Ω and bound by a surface $\partial\Omega = S$ as shown in Fig. 1, then this composition of material and geometry is what is usually referred to as a structural system (i.e. a material testing coupon, or a specific structure such as an aircraft or a bridge, etc.).

Substitution of Eq. (1c) in Eq. (1b) leads to an expression that when is substituted into Eq. (1a) along with the recognition that the elastic tensor is symmetric, yields the Navier form of the elastostatic system in the form,

$$\nabla \cdot (\boldsymbol{C} : \nabla \boldsymbol{u}) = 0. \tag{2}$$

When a material system described by either of the two equivalent forms of Eq. (1) or (2), is exposed to some tractions $\hat{\boldsymbol{t}}$ and displacements $\hat{\boldsymbol{u}}$ on the boundary, then $\boldsymbol{\sigma}\mathbf{n} = \hat{\mathbf{t}}$ on $S_t \subseteq S$ ($\mathbf{n}$ is the unit normal vector to the boundary) and $\boldsymbol{u} = \hat{\boldsymbol{u}}$ on $S_u \subseteq S$ correspond to the Neumann and Dirichlet boundary conditions respectively.

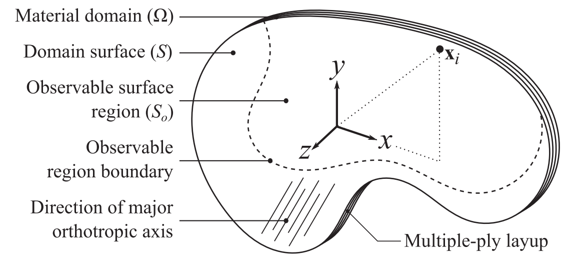

Fig. 1. A typical structural continuum system represented by a domain Ω enclosed by a surface S (where S_o is the observable part of the surface and $S - S_o$ is the rest of it), consisting of layup composed by multiple plies each of which typically exhibits transverse isotropic (orthotropic) behavior.

Under those constraints the determination of any of the unknown quantities in Eq. (1) is the solution of a boundary value problem, and it corresponds to the solution of the so-called forward problem. In the general case where closed form solutions of this boundary value problem cannot be found, an approximating solution is usually established by various methods that involve a projection of the continuous system described by Eq. (1) or (2) into a finite discrete space referenced by a collection of particular points $\mathbf{x}_i \in \Omega \subset \mathbb{R}^3$. As it is well known, the solution of the problem reduces to the solution of a linear system of equations involving the column vectors $\mathbf{u} = \{\boldsymbol{u}_i\}$ and $\mathbf{f} = \{\boldsymbol{f}_i\}$ that collect nodal components of the displacement $\boldsymbol{u}_i = \{u_x, u_y, u_z\}_i^T$ and force $\boldsymbol{f}_i = \{f_x, f_y, f_z\}_i^T$ vectors respectively, and has the familiar form,

$$\mathbf{Ku} = \mathbf{f}, \tag{3}$$

where $\mathbf{K}$ is the stiffness matrix. The stiffness matrix $\mathbf{K}$ carries geometry and material parameters and when expression (3) has been derived by applying a standard finite element analysis (FEA) approach [8], then it can be expressed as,

$$\mathbf{K} = \sum_e \int_{V_e} \mathbf{B}_e^T \mathbf{C} \mathbf{B}_e dV_e, \tag{4}$$

where $\sum_e$ denotes the stiffness matrix assembly processes over all elements that the domain has been discretized into, $\mathbf{C}$ is the matrix form of Hooke's tensor, and $\mathbf{B}_e$ is the usual displacements to strain transformation matrix [8]. This transformation is expressed by,

$$\boldsymbol{\varepsilon}^e = \mathbf{B}_e \mathbf{u}^e, \tag{5}$$

where $\boldsymbol{\varepsilon}^e$ is the column array containing the components of strain of element e with its nodal displacements stored in the column array $\mathbf{u}^e$.

It is now a matter of simple array partitioning to collect to a subarray any quantities related to the system of Eq. (1) that may relate to quantities that can be potentially measured by an experiment during for example a mechanical test of a material coupon or structural component. If displacements at discrete points can be measured then the solution of Eq. (3) can be used to collect the proper model predictions as a subset of the total column array $\mathbf{u}$ in order to compare them with the experimental values. With the advent of full field strain measurement techniques a similar approach would be followed to collect an array of strain component values predicted by the model at an observable subset of surface points of the structure. It is a matter of simple algebraic substitutions, to demonstrate that the strain components vector associated with an arbitrary point i shared by N_i elements that belongs onto the observable surface of the deformable body can be represented by,

$$\boldsymbol{\varepsilon}_i = \mathop{\mathrm{A}}_{e}^{N_i}\left(\Phi_e\left\{\left[\mathbf{K}^{-1}\mathbf{f}\right]_e\right\}\right), \tag{6}$$

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