Newsletter for the ASME Committee on Constitutive Equations

Spring 2010

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Introduction

Welcome to the spring 2010 edition of the newsletter for the ASME AMD-MD Joint Committee on Constitutive Equations. The purpose of this newsletter is to publicize the activities of the committee and the committee members. The committee meets each year at the ASME International Mechanical Engineering Congress and Exposition. If you are interested in membership, please contact the chair of the Committee, George Voyiadjis (voyiadjis@eng.lsu.edu).

New Committee Members

The following colleagues have been voted into the committee starting in 2010:

- Alireza V. Amirkhizi, University of California at San Diego
- Jennifer Gorczyca, University of Massachusetts at Lowell
- Tarek Hatem, North Carolina State University
- Brian Jordon, Mississippi State University
- Jaihyung Ju, Clemson University
- Sheng Liu, Huazhong University
- Kiran N. Solanki, Mississippi State University

Congratulations to the new members! We look forward to working with them.

Constitutive Modeling of Skeletal Muscle Tissue

Gregory M. Odegard, Michigan Technological University
Duane A. Morrow, Mayo Clinic
Tammy L. Haut Donahue, Michigan Technological University
Kenton R. Kaufman, Mayo Clinic

The main function of skeletal muscles is to sustain loads and provide mobility. Knowledge of muscle forces during given activities can provide insight into muscle mechanics, muscle physiology, musculoskeletal mechanics, neurophysiology, and motor control. Reliable constitutive models are necessary to predict these forces for both active and passive muscle states. Although many three-dimensional constitutive theories for muscle have been developed [1-4], this article will focus on one of these [2, 4].

Skeletal muscle tissue is composed of fibers that are aligned along the fiber axis of the muscle tissue. Passive force production occurs when a muscle has been stretched or compressed from its resting length. This force increases exponentially with relative elongation; that same force will tend to restore the muscle to its resting length once released (Figure 1).

Active force production occurs when skeletal muscle activation causes overlapping muscle actin and myosin filaments to interact, resulting in muscle contraction. The amount of axial force applied by the filaments is directly dependent on the amount of actin and myosin interaction, which is dependent on the deformed length of the filament. An optimized length for the filaments exists at which the amount of overlap provides maximal force generation (Figure 1). As the length of the filament is decreased, interference between actin filaments reduces the amount of interaction and therefore the maximum achievable load is diminished. Similarly, as the length of the sarcomere is increased, the interaction of actin and myosin is reduced, thus reducing the active force developed by the filament. With increased muscle lengthening, however, the passive forces combine to offset the decreasing active force production and the total (passive + active) force production increases.

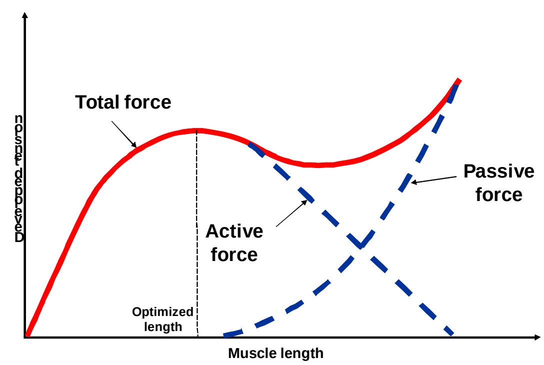


Figure 1 - Force/length relationship of skeletal muscle

Because of the physiological properties of skeletal muscle tissue, it is modeled with an incompressible and transversely-isotropic response. It is assumed that the changes in activation and actin/myosin interaction during a dynamical process are fully reversible with respect to the deformation of the muscle tissue. An energy balance for this system is described by

$$\Psi = \frac{1}{2}\mathbf{S}:\mathbf{C} - U - \theta\eta \tag{1}$$

where Ψ is the free energy density, $\mathbf{S}$ is the 2nd Piola-Kirchhoff stress tensor, $\mathbf{C}$ is the Green deformation tensor, U is the instantaneous potential energy (the energy available to increase the amount of actin/myosin interaction when contraction occurs after an expansion along the filaments), θ is the absolute temperature, and η is the entropy density. Following a similar approach developed for material response with internal thermodynamic variables [5], the strain-energy density due to the mechanical deformation, actin/myosin interaction, and muscle activation level is

$$\Psi = \sum_{i=1}^{3} a_i \left(I_1 - 3\right)^i + \sum_{j=1}^{3} b_j \left(I_2 - 3\right)^j + \sum_{k=2}^{6} c_k \left(I_4 - 1\right)^i + \frac{p}{2}\left(I_3^{1/3} - 1\right) + \frac{1}{2}\gamma q I_4 \tag{2}$$

where a_i, b_j, c_k, and γ are material constants; $I_1, \ldots, I_4$ are the usual scalar invariants of the Green deformation tensor; q $\{q \in R : 0 \le q \le 1\}$ is the scalar muscle activation parameter, and p is a Lagrange multiplier to enforce incompressibility. The final term in Equation (2) is the energy contribution due to muscle activation. From this equation, the constitutive response can be determined as

$$
\mathbf{S} = 2\left[\sum_{i=1}^{3} i a_i \left(I_1 - 3\right)^{i-1}\right]\mathbf{I} + 2\left[\sum_{j=1}^{3} j b_j \left(I_2 - 3\right)^{j-1}\right]\left(I_1\mathbf{I} - \mathbf{C}\right) + 2\left[\sum_{k=2}^{6} k c_k \left(I_4 - 1\right)^{k-1}\right]\mathbf{M} + \frac{p}{2}\mathbf{C}^{-1} + \gamma q \phi \mathbf{M} \tag{3}
$$

where **M** is the usual structural tensor for transverse-isotropic materials, and the time-independent evolution of loss in actin/myosin interaction is

$$
\phi = \exp\left[-\frac{\left(I_4 - I_4^0\right)^2}{\left(I_4^0\right)^2}\right] \tag{4}
$$

In Equation (4) I_4^0 is the value of the fourth invariant for the optimized activation length. The parameter $\phi = 1$ in the state of maximized actin/myosin interaction, and decreases at the muscle is compressed or extended in the filament direction from the optimized length. The material parameters in Equations (3) and (4) have been determined from experimental data [4].

This constitutive model can be used to predict the stress/deformation response of skeletal muscle tissue under a wide range of muscle extension lengths and activation levels. The model can capture the loading response, the subsequent unloading response, and repeated loading/unloading responses. Future improvements to this model are necessary. Specifically, it needs to be adapted to accurately describe force-velocity characteristics of muscle and to account for the influence of muscle fatigue.

1. Blemker, S.S., P.M. Pinsky, and S. Delp, *A 3D Model of Muscle Reveals the Causes of Nonuniform Strains in the Biceps Brachii.* Journal of Biomechanics, 2005. **38**: p. 657-665.
2. Odegard, G.M., T.L. Haut Donahue, D.A. Morrow, and K.R. Kaufman, *Constitutive Modeling of Skeletal Muscle Tissue With an Explicit Strain-Energy Function.* Journal of Biomechanical Engineering-Transactions of the ASME, 2008. **130**(6): p. 9.
3. Yucesoy, C.A., B. Koopman, P.A. Huijing, and H.J. Grootenboer, *Three-Dimensional Finite Element Modeling of Skeletal Muscle Using a Two-Domain Approach: Linked Fiber-Matrix Mesh Model.* Journal of Biomechanics, 2002. **35**: p. 1253-1262.
4. Morrow, D.A., T.L. Haut Donahue, G.M. Odegard, and K.R. Kaufman, *A Method for Assessing the fit of a Constitutive Material Model to Experimental Stress-Strain Data.* Computer Methods in Biomechanics and Biomedical Engineering, 2010. **13**.
5. Coleman, B.D. and M.E. Gurtin, *Thermodynamics with Internal State Variables.* Journal of Chemical Physics, 1967. **47**(2): p. 597-613.

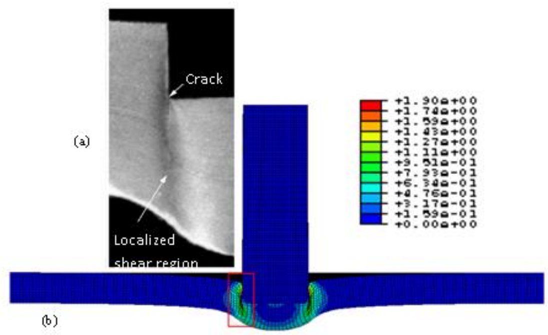
Nonlocal Modeling of Materials

George Z. Voyiadjis, Louisiana State University

One of the key challenges in improving existing or developing new engineering materials with fine tailored mechanical performances is to link microstructure with macroscopic material behavior. While mean-field theories based on classical continuum approaches appropriately capture this link for elastic behavior, the development of a macroscopic model embedded with a micromechanics-based theory of inelasticity that could be used as an engineering theory for both the analysis and computer-aided design of materials, is still a challenging endevour. The main difficulty stems from the fact that the inelastic deformation which develops in materials, is not homogeneous. In contrast, it reveals fluctuations on various length scales, that cannot be captured within the classical framework of continuum mechanics. In turn, this heterogeneity plays a key role in determining the macroscopic properties of materials. All this motivates the development of a theory that is able to bridge the gap between conventional continuum theories and micromechanical theories.

Here we adopt the perspective that a nonlocal macroscopic continuum theory has the potential to capture the heterogeneity of inelastic deformation. With this focus in mind, we investigate the fundamental mechanisms responsible for the inelastic behavior of advanced engineering materials from nano to macro scales (e.g., plasticity, visco-plasticity, damage, friction, wear) within the framework of computational solid mechanics. This includes the development of mathematical models, numerical algorithms and software with the final aim of predicting the behavior of engineering materials using computer simulations.

This approach is key to answering some key questions such as: (i) the effect of grain size, interfaces, and number of grains on the yield strength and flow stress of thin film materials; (ii) optimal deposition parameters for achieving the desired microstructure; (iii) explore the strengthening deformation mechanisms due to their unique microstructure; and (iv) multiscale and physical-based theoretical and computational models to capture the observed mechanical response and scale-dependent characteristics.



Simulation of perforation of the target plate by a high-speed blunt projectile using proposed computational model showed that high speed impact damage lead to fracture due to global inelastic strains, bending and dishing at end of the plate.

Our recent works [1-5] reveal that introducing interface energy as an additional contribution to internal virtual power establishes a physical base for nonstandard boundary conditions as well as the description of the boundary layers in thin film structures. The decomposition of the state variables into energetic and dissipative components helps us understand the hardening and strengthenning mechanisms in nano/micro structured materials. Length scales are also used to link the material behavior with the microstructure. It is demonstrated that material length scales identified via nano indentation are shown not to be constant but vary with grain size, accumulated plastic strain, and rate of loading.

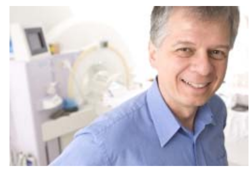
The research findings contribute to advancing the development of fundamental understanding of rate dependent behavior, damage evolution, friction and wear in nano/micro structured material investigations. Thanks to these findings, it becomes now possible to redesign, and redefine material choices for wide-range applications in aerospace industry, materials science, and mechanical, civil, polymer, and electrical engineering.

1. Voyiadjis, G.Z., Deliktas, B., 2009a. Formulation of strain gradient plasticity with interface energy in a consistent thermodynamic framework. *Int. J. Plasticity* 25 (10), 1997-2024.

2. Voyiadjis, G.Z., Deliktas, B., 2009b. Mechanics of strain gradient plasticity with particular reference to decomposition of the state variables into energetic and dissipative components. Int. *J. Engineering Science* 47 (11-12), 1405-1423.
3. Voyiadjis, G.Z., Almasri, A.H., 2009. Variable material length scale associated with nanoindentation experiments. *J.Engrg. Mech.*, ASCE 135(3), 139-148.
4. Voyiadjis, G.Z., Abu Al-Rub, R.K., 2007. Nonlocal gradient-dependent thermodynamics for modeling scale-dependent plasticity. *Int. J. Multiscale Computational Engineering* 5 (3-4), 295-323.
5. Abu Al-Rub, R.K., Voyiadjis, G.Z., 2005. A direct finite element implementation of the gradient-dependent theory. *Int. J. for Numer Meth in Engrg* 63 (4), 603-629.

Announcements

New Book by Martin Ostoja-Starzewski



Professor Martin Ostoja-Starzewski has published a book "Thermoelasticity with Finite Wave Speeds," Oxford University press. The new book focuses on dynamic thermoelasticity governed by hyperbolic equations, and, in particular, on the two leading theories: that of Lord-Shulman (with one relaxation time), and that of Green-Lindsay (with two relaxation times). While the resulting field equations are linear partial differential ones, the complexity of the theories is due to the coupling of mechanical with thermal fields. The mathematical aspects of both theories - existence and uniqueness theorems, domain of influence theorems, convolutional variational principles - as well as the methods for various initial/boundary value problems are explained and illustrated in detail and several applications of generalized thermoelasticity are reviewed.

Symposia for the 2010 ASME IMECE

The following sessions are being planned for the 2010 IMECE meeting in Vancouver, Canada:

- *Modeling and Simulation at Atomic Scale*, Organizers: Cemal Basaran (cjb@eng.buffalo.edu) and George Z. Voyiadjis (voyiadjis@eng.lsu.edu)
- *Modeling and Experiments in Nanomechanics and Nanomaterials*, Organizers: Yozo Mikata (aquarius_ym@hotmail.com)
- *Multiscale Modeling of Micro/Nano Structural Thin Films*, Organizers: George Z. Voyiadjis (voyiadjis@eng.lsu.edu), Douglas J. Bammann (Bammann@cavs.msstate.edu), and Kiran N. Solanki (kns3@cavs.msstate.edu)
- *Plasticity and Formidability of Advanced Materials*, Organizer: Xin Wu (xwu@eng.wayne.edu)
- *Damage and Fracture Characterization of Engineering Materials*, Organizers: Chi L. Chow (clchow@umich.edu), Kiran N. Solanki (kns3@cavs.msstate.edu), H. Eliot Fang (hefang@sandia.gov), Jie Shen (shen@umich.edu), and Xuming Su (xsul@ford.com)
- *Low Cycle Fatigue Failure of Materials: Experiments and Constitutive Modeling*, Organizer: Tasnim Hassan (thassan@ncsu.edu)