האגוד הישראלי למכניקה עיונית ושימושית

The Israel Society for Theoretical and Applied Mechanics

ISTAM

An Adhering Organization of the
International Union of Theoretical and Applied Mechanics
(IUTAM: http://www.iutam.net**)**

ISTAM Annual Symposium

TECHNICAL PROGRAM

9 December 2012

Tel Aviv University

ISTAM Annual Symposium

9 December 2012
TECHNICAL PROGRAM

Location: Rosenblatt Auditorium, Computer and Software Engineering Building, Tel Aviv University

09:30 – 09:50 Registration and coffee

09:50 – 10:00 *Opening:* MB Rubin

Morning Session Chairman: Y Benveniste

10:00 – 10:30 **R Segev** and M Epstein. *On the mathematical description of dislocations*

10:30 – 11:00 **R Haj-Ali**, H Zemer, R El-Hajjar, J Aboudi. *Piezoresistive fiber-reinforced composites: A new coupled nonlinear micro-mechanical-electrical modeling approach*

11:00 – 11:30 **Z Cooper**, MB Rubin. *Modeling spall failure in silicon carbide*

11:30 – 12:00 **Y Ben Simon**, D Raz, J Tirosh, L Rubinsky. *Deep Drawing of Hydro-rim Forming Process with Differential Temperature*

12:00 – 12:30 **A Gat**, M Gharib. *Elasto-Capillary Coalescence of Multiple Parallel Sheets*

ISTAM Society Meeting (Registered members only) Chairman: E Altus

12:30 – 12:45 Election of the President of ISTAM

12:45 – 14:30 Lunch (The registration fee includes lunch)

Afternoon Session Chairman: Z Yosibash

14:30 – 15:00 **A Hadid**, Y Epstein, N Shabshin, A Gefen. *Biomechanical studies of the aetiology of overuse injuries as related to military medicine*

15:00 – 15:30 **B Bar-On**, HD Wagner. *Hard biological tissues as multi-scale composite materials*

15:30 – 16:00 **N Trabelsi**, Z Yosibash, *Patient-specific finite element analysis of the human femur – validation by experiments and possible applications in clinical practice*

The annual membership fee to ISTAM is 100 NIS. It includes the lunch at the symposium and can be paid during the registration.

All lectures are open to the public free of charge

On the mathematical description of dislocations

R Segev[†] and M Epstein[‡]

[†]Department of Mechanical Engineering, Ben-Gurion University. Email: rsegev@bgu.ac.il
[‡]Department of Mechanical Engineering, The University of Calgary, AB, Canada. Email: mepstein@ucalgary.ca

We present a mathematical description of dislocations in crystalline solids having the following two features: (1) Formulated on the body manifold with no particular Riemannian metric, it specifies the geometry of dislocations independently of the configuration of the body in space. (2) It applied to both continuous distributions of dislocations as well as discrete dislocations.

It is first recalled that a family of crystallographic planes is specified traditionally using the Miller indices. This description of the planes may be generalized using a covector. Thus, if the lattice is conceived as a vector space W, a linear mapping $f\colon W \to \boldsymbol{R}$ specifies the family of planes in the form $f^{-1}(k)$ for every integer k. Thus, in addition to the orientation of the plane in space, f specified the density of the planes. Let B be an n-dimensional differentiable manifold with tangent bundle TB and cotangent bundle T^*B. Thus, for each $x \in B$, T_x^*B contain the covectors defined on the tangent space T_xB to B at x. A 1-form is a mapping $\phi\colon B \to T^*B$ with $\phi(x) \in T_x^*B$. Thus, a 1-form specifies at the infinitesimal neighborhood of each point in the body a family of crystallographic planes. A form ϕ, representing the structure of a system of crystallographic planes in the infinitesimal neighborhoods of the various material points, is the basic object in the proposed theory of continuous dislocations. The question arises then: do the families of planes at the various points in the body fit together and form a family of curved layers that describe a collection of possibly deformed crystallographic planes in the body?

The various families of planes fit together if there is a function $h\colon B \to \boldsymbol{R}$ such that $\phi = dh$, where d denotes the exterior derivative, which is identical to the gradient for the case of a real valued function such as h. The function h, if exists, labels the various layers which are level sets corresponding to it. The integrability condition, analogous to the condition $\operatorname{curl} v = 0$ for a vector field v on a vector space, is $d\phi = 0$. Here, $d\phi$ is the antisymmetric 2-tensor, a 2-form, obtained by taking the anti-symmetric part of the derivative of ϕ. Thus, we identify the geometry of dislocations in the body with the exterior derivative $d\phi$. A continuous distribution of dislocations exists in regions where $d\phi \neq 0$.

The generalization of the foregoing setting to discrete dislocation is made using the notion of de Rham current – a linear operator on the space of differential forms. We first recall a few relevant constructions. Let α and β be differential forms of degree k and l, respectively, i.e., completely anti-symmetric tensors of degree k and l. The exterior product $\alpha \wedge \beta$ is a form of degree $k + l$ obtained by anti-symmetrizing the tensor product $\alpha \otimes \beta$. We also recall that an n-form, say θ is an integrand on an n-dimensional manifold M. The integration operation may be described roughly as follows. Subdivide B into small simplices each of which defined by n tangent vectors, at each point x_p apply $\theta(x_p)$ to the vectors defining the simplex at x_p, add up, and take the limit as the size of the simplices tends to zero. It follows that a 1-form ϕ induces a linear functional T_ϕ on the space of $(n-1)$-forms that vanish outside a compact subset of B which is defined by

$$T_\phi(\omega) = \int_B \phi \wedge \omega,$$

for each ω. Let $D^k(B)$ denote the space of smooth k-differential forms which vanish outside a compact subset of B. A sequence of forms in $D^k(B)$ tends to zero if the local representatives of forms as well as the representatives of all their partial derivatives tend to zero uniformly in any compact subset of B. In geometric measure theory, a continuous linear functional $T\colon D^k(B) \to \boldsymbol{R}$ is referred to as a de Rham k-*current*. Thus, a 1-form induces by the equation above an $(n-1)$-current. The natural generalization of the 1-form ϕ representing the crystallographic layering in the body is therefore an $(n-1)$-current, T.

As an example of an $(n-1)$-current which is quite different from the picture of a smooth 1-form on B, consider an $(n-1)$-submanifold C of the body B. Since any $(n-1)$-form may be integrated on C, one may define an $(n-1)$-current T_C by

$$T_C(\omega) = \int_C \omega.$$

In analogy with the continuous system of families of hyperplanes induced by a 1-form ϕ, the $(n-1)$-current T_C is associated with a "discrete" submanifold.

$$T_{d\phi}(\psi) = \int_B d\phi \wedge \psi,$$

for any $(n-2)$-form ψ that vanishes outside a compact subset of B. A standard relation for the exterior derivative asserts that for a k-form α and an l-form β,

$$d(\alpha \wedge \beta) = d\alpha \wedge \beta + (-1)^k \alpha \wedge d\beta.$$

$$d(\alpha \wedge \beta) = d\alpha \wedge \beta + (-1)^k \alpha \wedge d\beta.$$

Thus, one may write

$$T_{d\phi}(\psi) = \int_B d(\phi \wedge \psi) + \int_B \phi \wedge d\psi.$$

The Stokes theorem for the integration of forms on a manifold B with boundary ∂B, a generalization of the Green, Gauss and Stokes's theorems of vector analysis, states that

$$\int_B d\alpha = \int_{\partial B} \alpha.$$

It follows that

$$\int_B d(\phi \wedge \psi) = \int_{\partial B} \phi \wedge \psi = 0$$

because ψ vanishes on the boundary ∂B, and so

$$T_{d\phi}(\psi) = \int_B \phi \wedge d\psi.$$

This observation motivates the definition of the *boundary of a k-current T* to be the $(k-1)$-current ∂T defined by the condition

$$\partial T(\psi) = T(d\psi).$$

Furthermore, it follows that

$$T_{d\phi} = \partial T_\phi.$$

Thus, we conclude that for a (possibly discrete) distribution of families of crystallographic hyperplanes specified by the $(n-1)$-current T, the dislocations are described by the boundary ∂T.

If we return to the example of the current induced by the $(n-1)$-submanifold C, we observe that for any $(n-2)$-form ψ we have

$$\partial T_C(\psi) = T_C(d\psi) = \int_C d\psi = \int_{\partial C} \psi.$$

Hence, if C is a compact submanifold with boundary ∂C in B, then, the dislocation is concentrated along the boundary ∂C as expected.

In the presentation we will describe further examples and will show how the Frank rules for dislocations follow from the identity $\partial^2 T = 0$ for any current T.

Keywords: *Dislocations, Differential forms, de Rham currents.*

Reference:

M. Epstein and R. Segev, 2012, "Geometric aspects of singular dislocations", Mathematics and Mechanics of Solids (in press).

Piezoresistive Fiber-Reinforced Composites: A New Coupled Nonlinear Micro-Mechanical-Electrical Modeling Approach

R Haj-Ali[1], H Zemer[1], R El-Hajjar[2] and J Aboudi[1]

[1]Mechanical Engineering, Faculty of Engineering, Tel-Aviv University, Israel
[2]Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, WI, USA
rami98@eng.tau.ac.il

Piezoresistive composites are materials that exhibit effective electrical resistivity changes as a result of mechanical deformations in their constituents or phases. These materials have a wide array of applications from non-destructive evaluation to sensor technology. In this study, we propose a new coupled nonlinear micro-electro-mechanical modeling framework for periodic electro-mechanical heterogeneous media. The proposed model enables the prediction of the effective piezoresistive properties along with the corresponding spatial distributions of local electro-mechanical fields, such as stress, strain, current densities, and electrical potentials. To this end, the high fidelity generalized method of cells (HFGMC) micro-mechanical model is extended to include the electrical formulation. In this coupled micro-electro-mechanical method, the various governing equations (equilibrium and charge conservation) are satisfied in an average sense. The displacement vector and electrical potential are expanded using quadratic polynomials in each subvolume (subcell). The periodicity and continuity of the displacements, electrical potential, tractions, and current density are satisfied at the interfaces on an average basis. One way coupling is established between the nonlinear mechanical and electrical effects, whereby the mechanical deformations affect the conductivity in the fiber and/or matrix constituents. Incremental and total formulations are used to arrive at the proper nonlinear solution of the governing equations.

The recent two-dimensional (2D) parametric formulation of the HFGMC developed by Haj-Ali and Aboudi (2010, 2012a) has been recently generalized for the micromechanical analysis of two and three-dimensional (3D) multiphase composites with periodic microstructure, Haj-Ali and Aboudi (2012b, 2012c). In the latter, arbitrary hexahedral subcell geometry is developed to discretize a triply periodic repeating unit-cell (RUC). Linear parametric-geometric mapping is employed to transform an arbitrary hexahedral subcell shape from the physical space to the parent coordinates, where a complete quadratic displacement expansion is performed. Previously in the 2D case, additional three equations are needed in the form of average moments of equilibrium as a result of the inclusion of the bilinear terms. However, the present 3D parametric HFGMC formulation eliminates the need for such additional equations. This is achieved by expressing the coefficients of the full quadratic polynomial expansion of the subcell in terms of the side or face average-displacement vectors. The 2D parametric and orthogonal HFGMC are special cases of the present 3D formulation. The continuity of displacements and tractions, as well as the equilibrium equations, are imposed in the average (integral) sense as in the original HFGMC formulation. Each of the six sides (faces) of a subcell has an independent average displacement micro-variable vector which forms an energy-conjugate pair with the transformed average-traction vector. This allows generating symmetric stiffness matrices along with internal resisting vectors for the subcells which enhances the computational efficiency.

The micro-electrical HFGMC is first verified by comparing electrical solutions predictions with the finite element method for different doubly periodic composites. One advantage of the proposed nonlinear coupled micro-model is its ability to predict the effective electro-mechanical behavior of a composite with periodic microstructure with different conducting phases. The HFGMC framework is based on the homogenization technique of composites with periodic microstructure as shown in Fig. 1. The repeating unit volume of such a composite, Fig. 2, is divided into arbitrary number of rectangular subcells, labeled by the index (β) each of which has its local coordinate system and may contain a distinct nonlinear homogeneous material, see Fig. 2. Figure 3 illustrates the experimental data of the mechanical and the piezoresistivity behaviors (dots), as well the HFGMC calibrations (solid lines). The change in the resistivity of the regular CFRP is linear and relatively large compare to the nonlinear piezoresistivity of the enriched CFRP. We examined a hypothetical composite material with conductive T700 carbon fibers (63%) and the calibrated PEO conductive polymeric matrix. The results of the effective electro-mechanics behaviors and of the local responses are shown in Fig. 4.

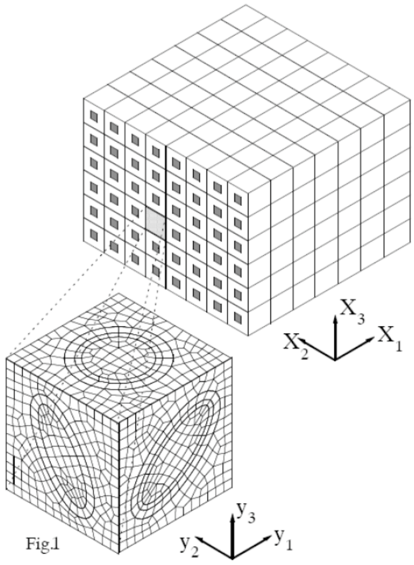

Fig. 1. Schematic illustration of a general refined triply periodic array of multiphase composite media with its repeating unit-cell (RUC), defined with respect to its local coordinate system.

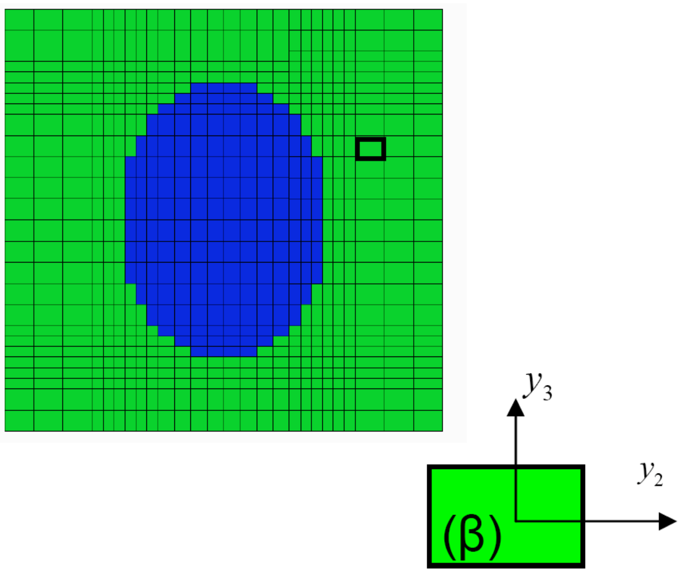

Fig. 2. An example of HFGMC repeating unit-cell with one ellipsoidal fiber embedded in a matrix showing a regular array of rectangular subcells used to discretized the geometry.

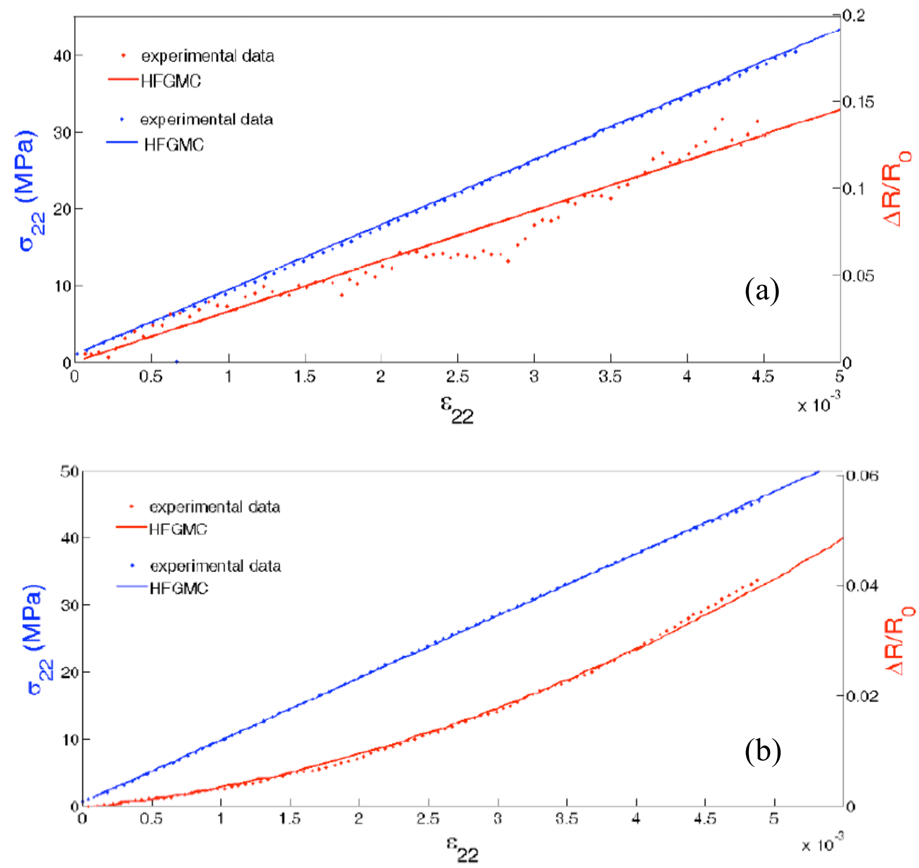

Fig. 3. Effective transverse stress-strain of T700 carbon-epoxy composite under tension tested in the current study to examine the relative piezoresistive responses (a) without graphite particles (b) with graphite particles.

In conclusion, a coupled nonlinear electro-mechanical micro-model is proposed to solve for the nonlinear coupled mechanical and electrical behavior of the composites. The general capability of the modeling framework has been demonstrated numerically and experimentally. More research is needed to define how damage influences the local and effective responses.

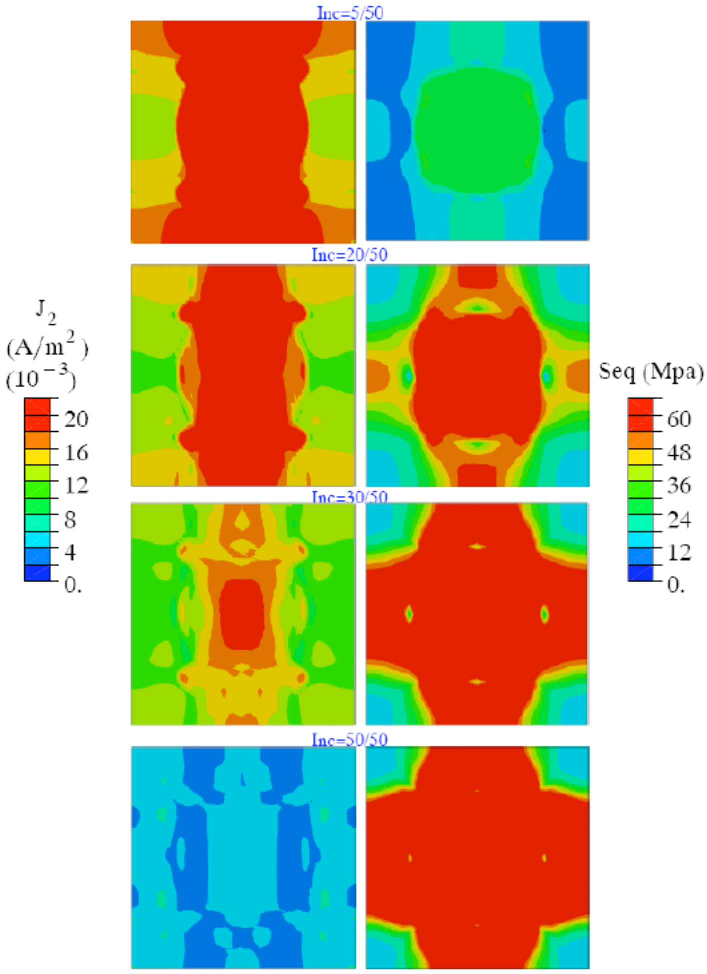

Fig. 4. The spatial evolution of coupled mechanical-electrical nonlinear responses of an RUC subject to remote transverse axial stress. The long fiber is T700 carbon and the PEO matrix is also conductive and reinforced with MWCNT. The mechanical constitutive model of matrix is deformation plasticity. The final axial transverse strain is 0.05 divided by 50 increments. The effective stress is shown in the right column and the nonlinear electrical response is shown in the left column where the current density in the loading direction is decreasing with continued applied mechanical loads. The composite is subjected to a remote electrical field of 0.01 V/A in the X_2 direction.

Keywords: Micromechanics, composites, coupled, multi-scale, multi-physics, damage, heterogeneous material

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Haj-Ali R, Aboudi, J. (2012c) A New and General Formulation of the Parametric HFGMC Micromechanical Method for Two and Three-Dimensional Multi-Phase Composites, *Int. J. Solids and Structures,* 2012:Under Review.

Modeling spall failure in silicon carbide

Z Cooper[1], MB Rubin[2]

[1]IDF - Israel Defense Forces, Mil. P.O.B 01154, Israel
Email: zvi.cooper@gmail.com
[2]Faculty of Mechanical Engineering, Technion - Israel Institute of Technology
Email: mbrubin@tx.technion.ac.il

Silicon carbide is one of a few ceramics used in various armor applications due to its high hardness and low density. The response of different grades of silicone carbide to impact and dynamic loading has been extensively investigated. In particular, spall tests on silicon carbide have been conducted over a wide range of impact levels. The Hugoniot Elastic Limit (HEL) conventionally represents the impact level at which inelastic deformation is initiated. It is typically determined by measuring the axial stress in plate impact experiments at the point when a significant change in slope occurs in the plots of particle velocity versus time. For many types of polycrystalline silicone carbide the spall stress increases with increasing impact stress and then gradually decreases. These trends in the spall stress occur at impact levels significantly below the HEL. Consequently, the observed HEL does not truly separate elastic from inelastic response in these materials. Moreover, some grades of silicon carbide maintain measurable spall strength at some impact levels above the HEL, indicating that inelasticity at impact levels up to the HEL does not necessarily lead to complete failure. Similar behavior has been observed in other ceramics as well.

A constitutive model has been formulated in which the reduction in the spall stress below the HEL is caused by rate-dependent damage evolution that is coupled to effective rates of inelastic distortion and porous dilation. It has been shown that while damage and inelastic distortion may reduce the strength of the ceramic, bulking (i.e. porous dilation at positive pressure) coupled to rate-dependent inelasticity may stiffen the stress loading wave such that the HEL of the material appears to be higher.

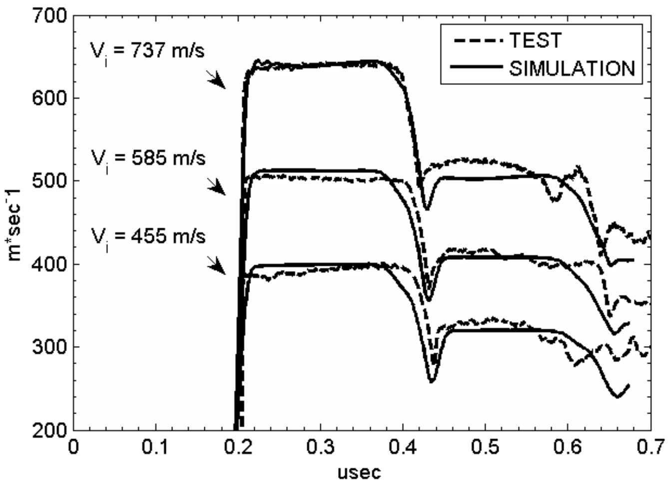

Fig. 1: Test measurements and simulation of rear surface particle velocity fore three different impact velocities.

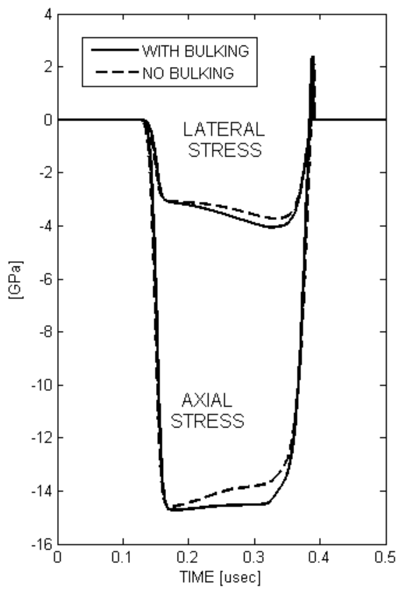

Fig. 2: Simulation results of the axial and lateral stress in the target.

The constitutive model has been implemented in the AUTODYN 2D hydrocode. Simulations of planar impact were conducted over a range of impact levels below the HEL and the calculated particle velocities are in good agreement with the tests. Fig. 1 shows examples of the particle velocity history obtained from tests and simulations.

To illustrate the effect of bulking, Fig. 2 shows the axial and lateral stress history predicted inside a sample impacted above the damage threshold yet below the HEL. Damage evolution causes a reduction in the deviatoric stress, evident here by reduction in difference between axial and lateral stress. Simulation results are shown both with bulking and without to illustrate how bulking keeps the axial stress from dropping.

Keywords: plate impact, ceramic, damage, constitutive model.

Deep Drawing of Hydro-rim Forming Process with Differential Temperature

Y Ben Simon, D Raz, J Tirosh and L Rubinsky

Metal Forming Lab., Faculty of Mechanical Engineering
Technion - Israel Institute of Technology
yaron.bensimon@gmail.com

The purpose of this study is to enable a (possible) increase of the Limit Drawing Ratio (LDR) in Deep Drawing by using Hydro-rim process while adding temperature effects. The idea is to facilitate the plastic flow along the flange by local heating it and simultaneously to cool down places where tensile strength is needed (i.e. along the wall and the bottom of the drawn cup). The analysis that follows is based on 'approximate bounding approach'. It is applied to rather general material behavior (presented by a known Johnson-Cook's constitutive model). It incorporates temperature dependency, strain hardening and strain rate sensitivity. The advantage of combined hydraulic pressure with relatively high blank temperature (with magnitude of about one third the melting temperature of the considered material) in the same operation is discussed. Emphasis is given to the rule of the blank *temperature difference* (between the flange and the wall of the product) conjugate with hydro rim pressure to augment the limit drawing ratio of the products.

In the conventional deep drawing process the drawing ratio is restricted to its operational limit, namely, that the drawn blank will not fail by rupture or wrinkling. In classical deep drawing process the theoretical drawing ratio is limited to at most e=2.71 in the absent of friction. In actual manufacturing practice, LDR does not exceed the ratio of about 2.2.

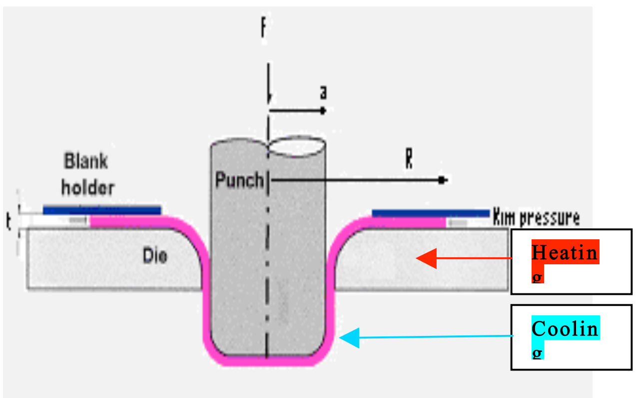

Fig. 1 Deep drawing process, with hydro-rim pressure

In several investigated trials, the authors found that the LDR can reach the value of 3 by imposing relatively high blank temperature along the flange portion of the blank. Under such case the material, besides being softened, usually becomes more strain rate sensitive. Both effects increase the formability of the blank. In parallel, the cooling of the punch lowers the temperature of the attached wall of the drawn cup and thus leads to inherent strengthening exactly in areas where failure by rupture is mostly intercepted.

The final aim is to anticipate analytically (but with few laboratory experiments for validation) the performance of this suggested improvement. In particular, the role of the temperature gradient on achieving higher LDR than otherwise existed.

Elasto-capillary coalescence of multiple parallel sheets

A Gat*, M Gharib

*Faculty of Mechanical Engineering, Technion - Israel Institute of Technology
Haifa 32000, Israel. Email: amirgat@tx.technion.ac.il URL: http://gat.net.technion.ac.il

We study the interaction between elastic solid sheets and a liquid in contact with the solid sheets (see fig. 1) as a model case for understanding the dynamics elasto-capillary coalescence. The liquid applies a pressure field on the solid-liquid boundary which may deform the solid sheets. The deformation of the solid sheets can, in turn, affect the pressure field by influencing the location of the solid-liquid boundary and by affecting capillary, viscous and gravity forces acting within the liquid. This interaction between elastic and capillary forces can yield coalescence of the elastic sheets.

The study of coalescence of solid structures emanating from interaction between capillary and elastic forces is relevant to phenomena such as densification of patterned arrays of carbon nanotubes, coalescence-related deformation of micro-structures, and self-assembly and modification of the mechanical and geometrical properties of arrays of solid structures.

Previous studies of elasto-capillary coalescence used minimal energy analysis of capillary and elastic energies of the post-coalescence state to estimate the size of the coalesced regions. In contract with the existing literature, we analyze the stability of the unperturbed configuration. We improve on existing works by obtaining an estimate to the average coalesced size, in contrast with the maximal stable post-coalescence size estimated in the literature, as well as obtaining previously unreported effects of body forces and viscosity on the elasto-capillary instability. Our analysis suggests methods to control elasto-capillary coalescence by manipulation of viscous and gravity forces. In addition, our model (via modal stability analysis) mathematically describes the process which creates the hierarchical coalescence structure, yielding that the mean number of sheets per coalesced region is limited to the subset 2^N where N is the set of natural numbers, in contrast with previous theoretical predictions and in agreement with experimental observations.

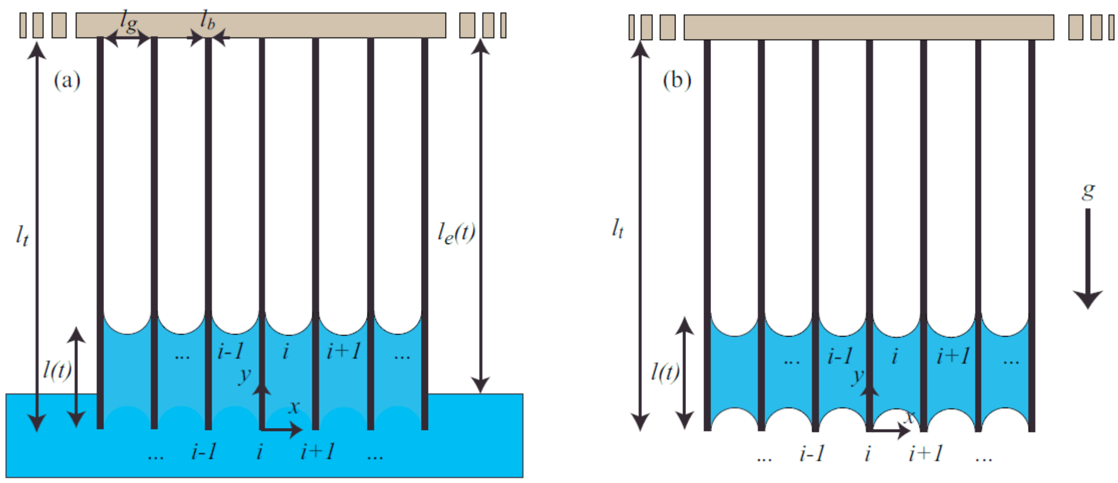

Fig. 1. Schematic description of multiple parallel elastic sheets immersed within a liquid before (a) and after (b) extraction from the liquid.

Keywords: *coalescence, capillary forces, elasticity.*

Biomechanical studies of the aetiology of overuse injuries as related to military medicine

A Hadid[1], Y Epstein[2,4], N Shabshin[3], A Gefen[1]

1. Department of Biomedical Engineering, Tel Aviv University, 2. Heller Institute of Medical Research, Sheba Medical Center, 3. Division of Diagnostic Imaging, Sheba Medical Center, 4. Sackler Faculty of Medicine, Tel Aviv University, Israel. Email: gefen@eng.tau.ac.il

Soldiers and recreational backpackers are often required to carry heavy loads on their body during military operations or hiking. These loads impose an extreme physiological strain as well as soft tissue deformations, which frequently result in discomfort, pain and musculoskeletal injuries. Shoulder loads and resulting tissue strains appear to be one of the limiting factors of load carriage. Additional common and potentially serious overuse injuries are stress fractures (SF). Many recruits or athletes who are engaged in frequent and repetitive physical activity may suffer a SF. Although SF were reported to occur in most parts of the skeleton, the most common site is the tibia: 50% of the SF in the active population occur along this bone. Although there is a large volume of literature regarding SF, most studies have been designed as clinical observations with limited control of the underlying factors. The current studies utilized MRI-based finite element (FE) modeling to: 1) Characterize mechanical loading conditions (strains and stresses) that develop within the shoulder's soft tissues when carrying a backpack, 2) Study the underlying risk factors for SF development.

Open-MRI scans were used for reconstructing a 3D geometrical model of an unloaded shoulder and for measuring the soft tissue deformations caused by a 25 kg backpack; subsequently, a subject-specific FE model for non-linear, quasi-static large deformation stress-strain analyses was developed (Fig. 1). Skin pressure distributions under the backpack strap were used as reference data and for verifying the numerical solutions. The parameters of the model were adjusted to fit the calculated tissue deformations to those obtained by MRI. Using similar techniques, a 3D FE model of the lower leg was developed.

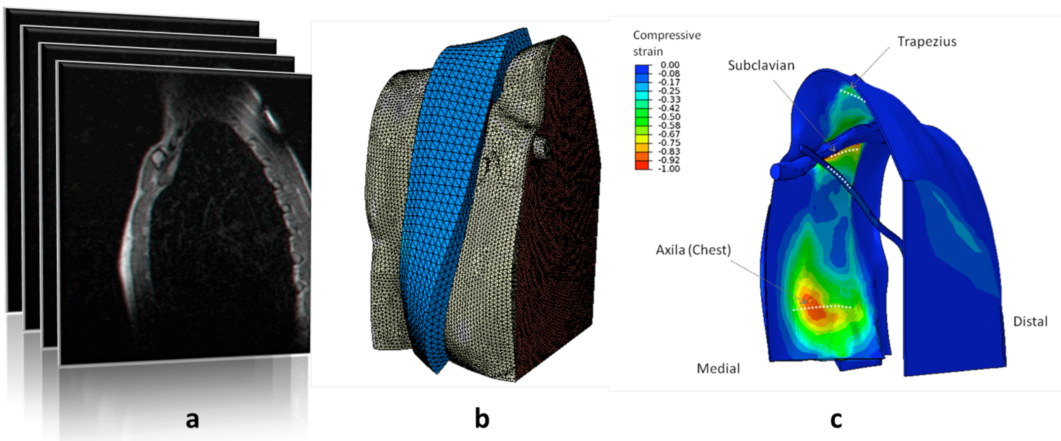

Figure 1: development of a human FE 3D model. (a) MR scans (b) reconstruction and meshing (c) FE analysis for strains distribution(1).

The MRI scans revealed significant compression of the soft tissues of the shoulder, with substantial deformations in the area of the subclavian muscle and the brachial plexus. The maximal pressure values exerted by a 25 kg load were substantial, and reached ~90 kPa. In the muscle surrounding the brachial plexus, the model predicted maximal compressive strain of 0.14, and maximal tensile strain of 0.13, which might be injurious for the underlying neural tissues. The computational simulations of the calf showed that for an individual with a bodyweight of 80 kg, the maximal tensile strain during walking peaks at ~500 με, and the maximal compressive strain peaks at ~1600 με and that the strains were concentrated in the anterior distal third and the posterior medial third of the tibia.

Keywords: *Finite element modeling of the human shoulder*

Reference:

A Hadid, Y Epstein, N Shabshin, A Gefen, "Modeling Mechanical Strains and Stresses in Soft Tissues of the Shoulder during Load Carriage Based on Load-Bearing Open-MRI", J Applied Physiology, 2011.

Hard biological tissues as multi-scale composite materials

B Bar-On and HD Wagner

Weizmann Institute of Science, Rehovot, Israel
Benny.bar-on@weizmann.ac.il
Daniel.wagner@weizmann.ac.il

A “bottom up” modelling approach for Young’s modulus of hard tissues is presented. The generic structure that is modelled includes stiff nano-platelets arranged in a staggered micro-array within a flexible matrix, and scales up to complex macroscopic biological structures such as bones and teeth. Simple staggered structures, as in nacre, enamel micro-structure and collagen fibril, are studied first by a mechanical model based on shear-lag assumptions. Next, multi-scale mechanical models are proposed for the tooth enamel and dentin, which include a micro-scale array of shafts inside an anisotropic matrix. The analytical predictions obtained from the models are in a good agreement with finite element simulations and experimental results. The models developed in this study demonstrate the possibility, in certain cases, to generate special mechanical effects linked to the structural complexity of these tissues.

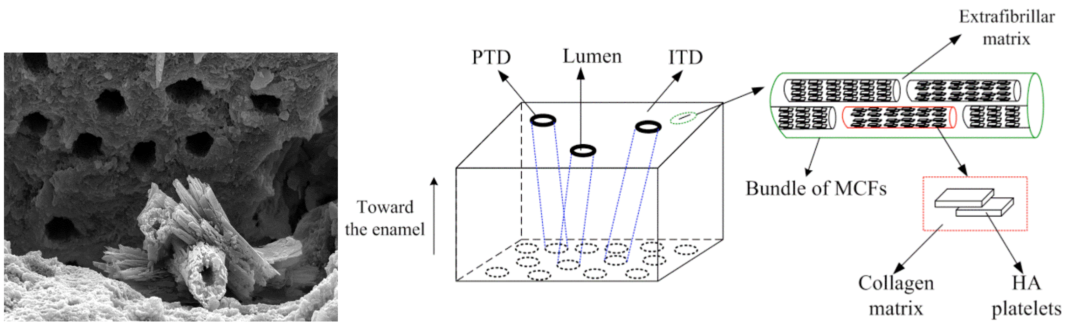

Figure 1 SEM image of the tooth dentin, courtesy of Prof. Steve Weiner (left), and the corresponding multi-scale composite model (right).

References:

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Patient-specific finite element analysis of the human femur – validation by experiments and possible applications in clinical practice

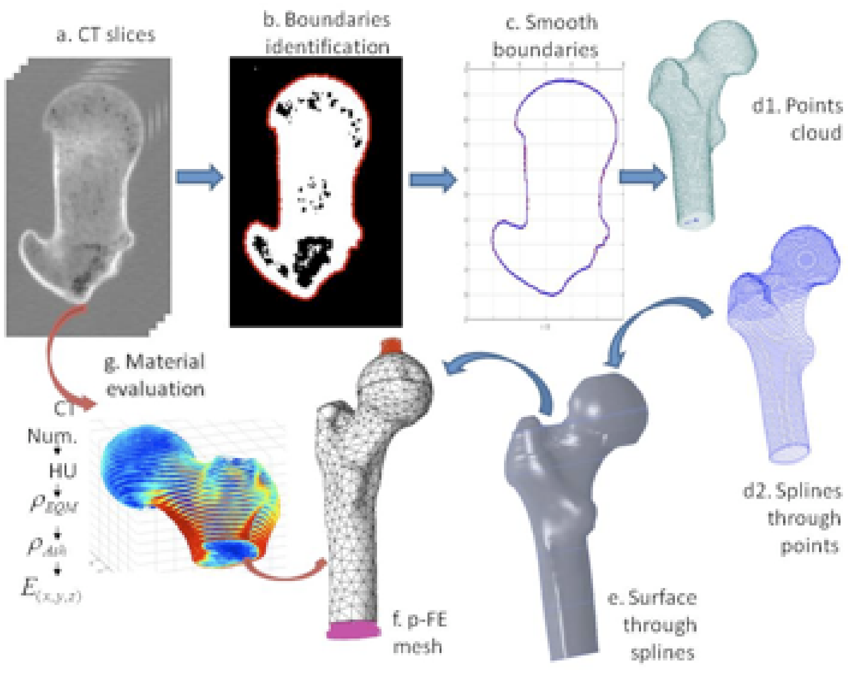
N Trabelsi* and Z Yosibash**

*Dept. of Mechanical Engineering, Shamoon College of Engineering (SCE) , Beer-Sheva, Israel.
Email: nirtr@post.bgu.ac.il
**Dept. of Mechanical Engineering, Ben-Gurion Univ. of the Negev, Beer-Sheva, Israel.
Email: zohary@bgu.ac.il

The mechanical response of human bones is of major importance in both research and clinical practice. The femur serves an important biomechanical function, supporting the majority of the human body, and hip fractures are one of the common types of fractures, mostly as a consequence of osteoporosis. Worldwide, approximately 1.6 million elderly subjects suffer from hip fractures each year.

To determine it for an individual, one must infer the geometrical representation and mechanical properties (that are inhomogeneous and anisotropic) by non-invasive means. We identify these based on quantitative computer-tomography (QCT) scans, and developed reliable FE models (illustrated in the figure below) that were validated by experimental observations. The automatic generation of the FE model, determination of material properties, the performed experiments and the validation of the FE results by the experimental observations are discussed.

The validation process was performed on 17 fresh frozen human femurs (in 12 femurs a double-blinded process was followed to avoid any bias). Overall, the FE analyses show excellent predictability of strains and displacements. This work provides a verified and validated tool which is in an advanced stage, ready to be used in clinical computer-aided decision-making. Several example for clinical use were investigated and will be presented in the session.



Schematic flowchart describing the generation of the p -FE model from QCT scans