האיגוד הישראלי למכניקה עיונית ושימושית

The Israel Society for Theoretical and Applied Mechanics (ISTAM)

ISTAM Meeting on:

"Multiscale Phenomena and MEMS"

12 December 2004

Tel Aviv University

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Technical Program

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09:30 – 09:50 Registration and coffee

09:50 – 10:00 *Opening:* M.B. Rubin, Technion, President of ISTAM

<u>*Morning Session*</u> *Chairman:* T. Elperin, Ben-Gurion University

10:00 – 10:25 E. Tadmor, Technion, *Nano-scale Plasticity at Crack Tips: Deformation Twinning in FCC Metals*

10:25 – 10:50 D. Elata, Technion, *Using static equilibrium states to predict dynamic instabilities of electrostatic actuators*

10:50 – 11:15 V. Krylov* and I. Harari, Tel Aviv University, *Improved Computational Efficiency by Structural Reduction with Reference to MEMS Applications*

11:15 – 11:40 E. Zussman, Technion, *Mechanical and structural characterization of carbon nanofibers*

11:40 – 12:00 D. Elata, Technion, *Poster session overview*

12:00 – 13:00 Lunch (The registration fee includes lunch)

13:00 – 14:00 *Graduate student poster session: S. Abu Salih, A.H. Barber, C.A. Cooper, Y. Cohen, L. Edery-Azulai, R. Fedida, Y. Freed, T. Gabay, I. Hariton, G. Kósa, F. Lipperman, D. Raz, W. Salalha, S. Seretensky, O. Shomer, L. Tevet Deree, O. Yogev*

<u>*Afternoon Session*</u> *Chairman:* I. Goldhirsch, Tel Aviv University

14:00 – 14:25 S.A. Safran, Weizmann Institute of Science, *Elastic Interactions of Biological Cells*

14:25 – 14:50 K. Schulgasser* and A. Witztum, Ben-Gurion University, *The Hierarchy of Chirality*

14:50 – 15:15 Z. Yosibash, Ben-Gurion University, *High-order FE-simulations of bio-mechanical systems: Blood flow in compliant arteries and the mechanical response of a proximal femur*

15:15 – 15:40 G. deBotton, Ben-Gurion University, *Transversely Isotropic Composites Undergoing Finite Deformations*

*Lecturer

Nano-scale Plasticity at Crack Tips: Deformation Twinning in FCC Metals

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Deformation twinning (DT) and slip are two fundamental mechanisms for plastic deformation in metals. DT occurs in two phases: a critical nucleation phase followed by growth at a lower stress level. Theoretical analysis in recent years suggests that nucleation of twins most likely occurs heterogeneously at pre-existing defect sites such as grain boundaries, dislocation structures and crack tips. In this talk, an analytical criterion for heterogeneous nucleation of a twin at a crack tip in an fcc metal is presented. The criterion is based on the Peierls-Nabarro framework for dislocation emission from a crack tip due to J. R. Rice. The predictions of the criterion are compared with atomistic simulations of crack-tip plasticity using the quasicontinuum method and are found to be in very good agreement. In addition, a scalar measure for the inherent "twinnability" of fcc metals is defined through homogenization of the nucleation criterion. The resulting simple measure depends on material parameters that can all be computed from first principles. The twinnability of eight fcc metals is computed using parameters obtained from quantum mechanical tight binding calculations and compared with the available experimental evidence. The agreement is encouraging.

Using static equilibrium states to predict dynamic instabilities of electrostatic actuators by

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Electrostatic actuators are prevalent in MEMS because of their compatibility with microfabrication technology. The simplest electrostatic actuator is the parallel-plates actuator (Fig. 1). Application of a voltage V to the upper electrode induces electrostatic forces that pull it down towards the grounded, fixed bottom electrode.

The quasi-static electromechanical response of this system is illustrated in Fig. 2. For a given applied voltage (line 1) the system has two equilibrium states. One equilibrium state is stable (solid) and the other is unstable (dashed). These two equilibrium states approach each other as the voltage is increased. At a specific voltage the two solutions converge and at this point the equilibrium state is critically stable. This critical point is the *static pull-in* point of the system. At this point the top electrode can spontaneously collapse into contact with the bottom electrode. For voltages above the pull-in voltage (line 2) the system has no equilibrium states.

However, many electrostatic actuators are driven from rest, at the unloaded state, by a step-function of applied voltage. The resulting electromechanical response is dynamic. Due to this dynamic response, the top electrode can collapse into contact with the bottom electrode even though the applied voltage is lower than the static pull-in voltage.

The present study focuses on the dynamic response of electrostatic actuators that are subjected to a step function of applied voltage. Specifically, the critical states in which the movable electrode can spontaneously collapse into the fixed electrode, is investigated. A useful method for computing a lower bound for the dynamic pull-in voltage is proposed. This lower bound is based on stagnation curves that are derived from the Hamiltonian of the system. Figure 3 illustrates the equilibrium and stagnation curves of the parallel-plates actuator. The intersection of these two curves is the dynamic pull-in point, and the voltage associated with this point is a lower bound for the actual dynamic pull-in voltage

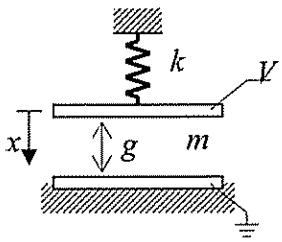

Fig 1 The parallel-plates electrostatic actuator

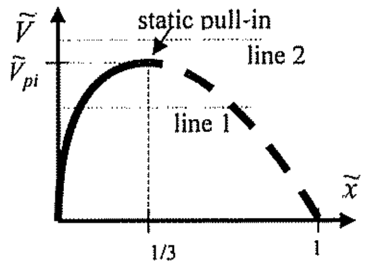

Fig 2. The quasi-static response of the parallel-plates actuator

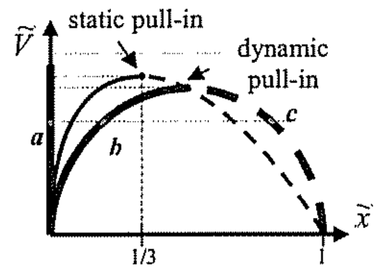

Fig. 3. The equilibrium curve (thin line) and the stagnation curve (thick line) of the parallel-plates actuator

Keywords: Dynamic pull-in, Electrostatic actuation

Reference:

D. Elata and H. Bamberger, "On the dynamic pull-in of electrostatic actuators with multiple degrees of freedom and multiple voltage sources", Journal of Microelectromechanical Systems (in press).

Improved Computational Efficiency by Structural Reduction with Reference to MEMS Applications

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In multiphysics problems, various fields are often coupled via interface conditions. This is the situation in the case of the electric-solid interaction that lies at the very foundation of MEMS devices. In many problems of MEMS, such as analysis of flexible beams, the solid body is of slender geometry.

In solid mechanics the classical approach to the analysis of bodies with high aspect ratios is often to perform a dimensional reduction to an appropriate structural model. The dimensional reduction of the differential operator describing the original elasticity problem is often performed by variational procedures combined with kinematic assumptions. Alternatively, hierarchies of reduced order models of elastic bodies with high aspect ratio are built using asymptotic methods. However, while such procedures are well-established for the differential operators governing problems of solid mechanics, the reduction of the data of the problem is often performed on an *ad hoc* basis, at least in part. This approach can be adequate for most standard applications such as structural analysis of civil engineering, but for the analysis of many coupled problems more rigorous procedures are required.

In MEMS applications the interaction forces are obtained in terms of electric or magnetic fields. These forces are highly dependent on the distance between interacting bodies. As a result, in a typical MEMS device the distance between the actuating electrode and the mechanical deformable element is of the order of magnitude of the element thickness. The high gradients of interface forces arising in MEMS applications may require three-dimensional analysis of the data. On the other hand many of these structures can be considered as slender flexible elements, with thickness and sometimes width that are considerably smaller that the length. High aspect ratios of this kind of elements make the use of structural descriptions attractive. However, due to the high gradients of the three-dimensional interface forces, *ad hoc* procedures for their reduction are not longer sufficient.

In the present work we propose to economize the analysis of solids with high aspect ratios that are interacting with, or merely loaded by, three-dimensional fields, by developing rigorous, comprehensive Structural Reduction (SR) procedures, that may be automated and integrated with standard computational processes. Special attention is paid to the rigorous SR of the original problem data – interaction forces and boundary conditions. The SR procedures are based on dimensional reduction to structural representations and use a variational framework to consistently convert the solid-field interface data to the form required by the structural representations. The full, three-dimensional displacement field may then be reconstructed as a post process step.

The suggested SR procedure combines the generality of the three-dimensional treatment with the effectiveness of the structural representation. It can be used also as an integral stage in the reduced order model construction or for the reduced order model verification. We anticipate that the proposed SR procedure can provide a reliable and highly efficient framework analysis of solids with high aspect ratios that are loaded by, and/or in interaction with, three-dimensional fields and can be effectively implemented into the design tools.

Keywords: *reduced order models, structural reduction, coupled problems, MEMS*

Mechanical and structural characterization of carbon nanofibers

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Carbon nanofibers with diameters of 30-100nm were obtained by carbonization of electropsun polymer nanofibers made of a solution of poly acrylonitrile. The chemical composition, orientation and crystal size of a series of electropsun fibers and carbonized acrylonitrile fibers were investigated by X-ray diffraction analysis, Raman spectroscopy, and electron energy loss spectrometry (EELS). The effect of different processing steps in the electrospinning is examined. The molecular orientational order parameter of the polymer nanofiber, as measured by X-ray diffraction, correlates linearly with its birefringence. The central region (core) of the carbonized fiber shows a random arrangement (Turbostratic structure), while the outer region (sheath) has a circumferential arrangement. The fracture strength of the carbonized nanofibers investigated using a special tensile testing inside a SEM chamber. The data show that fracture strength follows a Weibull distribution. Furthermore, we show that the Weibull parameters are highly dependent on the precursor of the carbonized fibers – the electrospun nanofibers. When high electrostatic field was used the stress resulting in a probability of failure of 63% was found to be 0.9 GPa, and the Weibull modulus was 4.70. By contrast, when electrospinning was performed with lower electrostatic field, the stress resulting in a probability of failure of 63%, reduced to 0.6 GPa, and the Weibull modulus was 3.1. The tests also provided the elastic modulus of the carbonized fibers, which was found to vary from 65 to 75 GPa for both cases. The investigation highlights the role of microfabrication defects on material properties and reliability, as a function of the electrospinning and further on the carbonization process. The parameters identified in this study are expected to aid the designer of composites materials or nano-electronic systems employing carbon nanofibers as fillers or as conducting elements.

Elastic Interactions of Biological Cells

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This talk will review recent theoretical work that analyzes experimental measurements of elastic interactions of biological cells with their environment. Recent experiments have shown that adhering cells exert polarized forces on substrates. The interactions of such "force dipoles" in either bulk gels or on surfaces can be used to predict the nature of self-assembly of cell aggregates and may be important in the formation of artificial tissues. Cell adhesion strongly depends on the forces exerted on the adhesion sites by the tension of the cytoskeleton. The size and shape of the adhesion regions is strongly modified as the tension is varied and we present an elastic model that relates this tension to deformations that induce the recruitment of new molecules to the adhesion region.

The Hierarchy of Chirality

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Twisting is a prevalent feature of long, thin vertical leaves; it has been shown that this twist contributes to the mechanical integrity of the leaf. We address the question as to how this twist comes about, and posit that it is a reflection of twist at a lower structural (geometric) level. The stiffness required for maintaining verticality in leaves is due to turgescent parenchyma cells, sometimes thickened epidermis, cuticle, and is generally most significantly contributed to by vascular bundles and fibers. These contain cellulose in the cell walls. Such cellulose chains spiral upward within the cell wall layers which are of a characteristic handedness. This results in an isolated cell behaving mechanically in a chiral manner; specifically elongation (contraction) of a single cell will result in rotation of the cell about its axis of particular handedness. We propose a mathematical model that shows that when cells are mechanically associated in groups, the chiral behavior of the cell will be expressed at larger scales, albeit to a mitigated degree. Thus cell extension during leaf development may explain the characteristic twist of such leaves.

High-order FE-simulations of bio-mechanical systems: Blood flow in compliant arteries and the mechanical response of a proximal femur

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In collaboration with Prof. Karniadakis (Brown Univ.,USA), Prof. Milgrom (Hadassah Hospital), Prof. Joskowitz (Hebrew Univ), Prof. Yakhot (BGU), Mr. Fedida (Grad.student BGU)

Problems associated with the mechanical response of biological tissues are of enormous interest and at the same time of enormous complexity. Several of the complexities are tractable nowadays using new technologies and advanced finite element methods. This talk addresses two bio-mechanical problems for which new techniques and technologies make it possible to tackle. The first is related to numerical simulations of blood flow in compliant arteries, and especially the carotid artery. These are challenging due to the need of realistic geometries of both the lumen and artery wall, lack of reliable constitutive laws describing the artery wall and the complicated hemody-namics characteristics in moving vessels. The aforementioned ingredients are essential for a reliable fluid structure interaction (FSI) analysis, and a brief explanation on the required steps together with state-of-the-art methods available to acquire the necessary information is provided. We address the re-construction of the topology and mesh creation obtained from MRA images, the non-linear constitutive laws for arterial walls, and the special features of p-FEMs for their response, the spectral DNS fluid-dynamics simulation tool for the hemodynamics simulation and the weakly-coupled algorithm for the FSI analysis, allowing different codes to share the necessary information over different computational platforms.

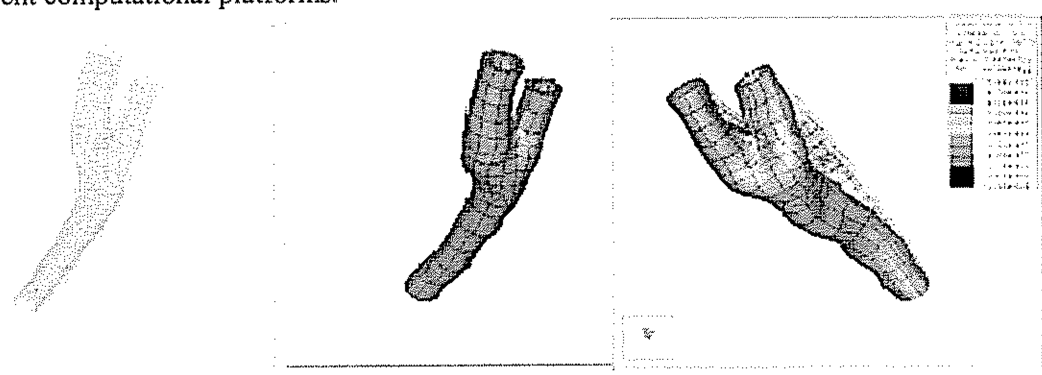

Figure 1: Steps in the CSM analysis of the carotid artery.

In the second part of the talk, the simulation of the proximal femur (hip bone) under mechanical loading is addressed. The geometrical representation constructed from CT scans, and determination of the mechanical properties, which are anisotropic and non-homogeneous will be presented. The generation of a p-FEM model and preliminary results will be provided if time allows.

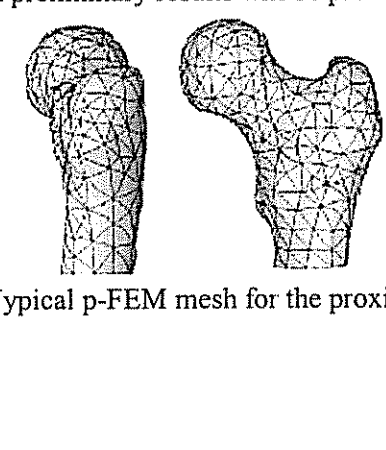

Figure 2: Typical p-FEM mesh for the proximal femur.

Transversely Isotropic Composites Undergoing Finite Deformations

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In the limit of infinitesimal linear elasticity it is a straightforward process to construct and determine the effective properties of a transversely isotropic composite made out of two isotropic constituents. An analogous question concerning the ability to produce and determine the properties of transversely isotropic two-phase composites undergoing large deformation is raised. To this end an exact expression for the effective energy density function of sequentially laminated composites with arbitrary behaviors of the phases is developed. This allows to determine the stress potentials of rank-N sequentially laminated composites with arbitrary volume fractions and lamination directions.

In passing, a simple explicit expression for the effective energy density function of a rank-1 composite under plane strain conditions is obtained. Under certain loading conditions this expression attains the Ogden-Reuss-Voigt bounds. The behavior of a composite made out of a hierarchical structure of laminates is investigated next. A two-phase rank-1 laminate is iteratively laminated with one of its constituents to generate a composite with distinct fibers surrounded by a continuous matrix phase. By following an appropriate lamination sequence the behavior of the composite tends to be transversely isotropic. An expression for the effective behavior of this transversely isotropic composite is given in terms of the phase volume fractions. The behavior of the transversely isotropic composite is compared with corresponding estimates for fiber-reinforced composites which are based on the second order variational procedure of Ponte Castañeda.

Poster session

A novel test device for measuring residual stress in MEMS

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The performance of many micro-systems is strongly affected by the internal stress. Internal stress emanates from micromachining processes and from thermal expansion mismatch.

Several methods were proposed to measure the level of the internal stress in micro-systems. In some of these methods the internal stress is measured by identifying its affect on the crystallographic structure of the material. Such methods require expensive equipment. In other methods, internal stress is deduced by measuring its affect on the response of test structures that are subjected to mechanical loads.

The internal stress can also be deduced by measuring the electromechanical instability response (i.e. pull-in state) of test structures. Such test structures are simultaneously subjected to electrostatic field and to internal stress.

A different approach for measuring the internal stress is based on its affect on passive test structures. The buckling phenomenon in such structures is utilized to measure the internal stress. Notable among these passive test structures are clamped-clamped beams and Gukel rings. Compressive internal stress can cause buckling in clamped-clamped beams and therefore internal stress can be identified by fabricating many such beams with different dimensions. The number of beams and the incremental geometrical variations between them determine the range and resolution of the measurement, respectively. However, this method is incapable of measuring tensile internal stress. To this end, the Gukel rings were proposed to convert tensile stress to a compressive stress in a test structure.

In the present work we present a new single test-structure that has the ability to extract wide range of internal stress. The proposed test structure can measure tensile internal stress as well as compressive internal stress. The extraction of the internal stress is obtained from identifying its affect on the electromechanical buckling (EMB) response of the electromechanical system. It is shown that the accuracy of the internal stress measurement can be increased by satisfying geometrical constraints. These geometrical constraints determine the instability of the electromechanical postbuckling state.

Keywords: Electromechanical buckling, Electromechanical instability, Bifurcation, Residual stress.

Direct measurement of individual nanotube-polymer interfacial strength

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The force required to separate a carbon nanotube from a solid polymer matrix has been measured by performing reproducible nano-pullout experiments using atomic force microscopy. The separation stress is found to be remarkably high, indicating that carbon nanotubes are effective at reinforcing a polymer. These results imply that the polymer matrix in close vicinity of the carbon nanotube is able to withstand stresses that would otherwise cause considerable yield in a bulk polymer specimen.

References:

1. A.H. Barber, S. Cohen, H.D. Wagner, "Measurement of carbon nanotube-polymer interfacial strength", Applied Physics Letters 82(23) (2003), 4140-4142. [Selected to appear in the Virtual Journal of Nanoscale Science & Technology, June 2003]

2. A.H. Barber, S. Cohen, S. Kenig, H.D. Wagner, "Interfacial fracture energy measurements for multi-walled carbon nanotubes pulled from a polymer matrix", Composites Science and Technology, 64 (2004), 2283-2289

Active detection of faults in rotating structures
A "model - based" active probing and signal processing approach

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A novel approach in fault detection of minute, developing faults in a rotating structure is presented. Faults in such systems are often manifested as mass or stiffness asymmetry. Rotating machines have many sources of excitation and often a measurement of the normal response cannot be separated from the effect of a minor defect.

Active excitation devices open a new dimension for detecting faults. The capability to actively detect and quantify minute, developing faults is achieved by utilizing a sophisticated excitation pattern, a model-based signal processing technique and an external excitation device (e.g. Active Magnetic Bearing) as a non-synchronous force exciter. Speed-dependent fault-tuned forces, which make any mass or stiffness asymmetry evident, can thus be injected into the rotating system and allow for early warnings and scheduled maintenance shut-downs, only when necessary.

Analytical, numerical and experiment results demonstrate the enhanced detectability of the new, diagnostic scheme. As a result, the proposed method is able to detect defects that are several orders of magnitude smaller than what can be found by detection techniques that only use vibration condition monitoring.

Direct measurement of detachment of individual nanotubes from a polymer matrix

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A technique to investigate the adhesion of carbon nanotubes to a polymer matrix is described. Carbon nanotubes bridging across holes in an epoxy matrix have been partially or fully drawn out using the tip of a scanning probe microscope while recording the forces involved. A full force-displacement trace could be recorded and correlated with transmission electron micrographs observations prior and subsequent to the tip action. Based on these experiments, an approximate calculation of the nanotube-polymer interfacial shear strength has been performed.

Reference: C.A. Cooper, S.R. Cohen, A.H. Barber, H.D. Wagner, "Detachment of nanotubes from a polymer matrix", Applied Physics Letters, 80 (20)(2002), 3873-3875.

Structural Integrity of smart structure having Piezoelectric Patches

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The present research deals with the investigation of the "Structural Integrity of smart structure having Piezoelectric Patches". A smart structure usually includes sensors/actuators embedded into a carrying structure, mainly airborne ones. The application of cyclic mechanical loads together with electric loads on the piezoelectric patches, which serve as a sensor or actuator, can alter its lifetime yielding a reduced output.

Smart structures are seeing more and more usage throughout the aerospace world, but the technical knowledge of these structures remains low and actually, the integration of piezoelectric patches in airborne vehicles is still in its infancy.

In this research we investigate the effects of the piezoceramic material, PZT, on the behavior of a part of airbourn structure, beam and plate. Two piezolelectric mechanisms are known: extension and shear. The Extension piezoelectric patches are usually bonded to the surface of the host structure and poled in the thickness direction, while the shear piezoelectric patches are poled in the plane's structure direction and are embedded in the core of the structure, and thus are less exposed to high bending stresses.

The application of an electric field in the thickness direction causes the surface of the patch to extend (shrink) . These deformations induce lateral displacement on the host structure. Application of this electric filed, in the thickness direction, will generate transverse deflection of the sandwich structure. To be able to predict the structural integrity of smart structures, the static and dynamic response of a structure with actuator and/or sensor of PZT (shear and/or extention type patches) has to be understood and their application have to be implemented. For example, the abilities of using both PZTs type ,actuators and sensors, in a "closed-loop" can offer an application of active damping.

A great deal of research has been performed to understand smart materials, such as piezoelectric (PZT) materials; however, very little work has being done on the structures with integrated smart materials.

It is the aim of the present research to investigate the various effects in order to be able to predict the structural integrity of a given smart structure as a function of its use.

One of the key field in structural integrity of smart structures used for aerospace application is its fatigue research. To date, virtually all research related to fatigue of smart structures has either focused on mechanical fatigue of the structure with an inactive PZT (or some other materials simulating an inactive piezoelectric), or mechanical fatigue studied on the PZT, cycling loads directly on a piezoelectric and then checking its ability to serve as a sensor or actuator. Only a few studies have used active smart structures while evaluating the structural integrity of the smart structure. Therefore, the present research is addressing this issue by investigating the integrity of smart structures under both mechanical and electrical fatigue, of both types of PZT –shear and extention.

A reliable mechanical simulation of the proximal femur by high-order FEA

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Hip fracture is among the most common injuries necessitating hospitalization. For several cervical fractures in the proximal femur (Garden I / II types), the fracture fixation is performed using cannulated screws inserted by an orthopedic surgeon. In order to rigorously investigate the influence of these screws and their geometrical placing on the mechanical response, a combined finite element analysis and in-vitro experimental procedures are in progress to reliably simulate the mechanical response of the proximal femur.

The realistic geometry of the bone is extracted from quantitative computerized tomography (QCT) scans. The QCT scan provides accurate data on bone geometry as well as data that can be related to bone density and its material properties. Although bone material is known to be inhomogeneous and anisotropic, past analyses assumed a heterogeneous isotropic material, (usually with discrete and limited number of material properties) due to computational complexity.

In the current research a reliable mechanical simulation of the proximal femur by high-order FEA (p-FEM) is sought. An accurate geometry of the bone structure is used and a continuous function will be facilitated in order to evaluate the mechanical properties at each integration point. As a first attempt, isotropic inhomogeneous material properties are assumed, followed by transversely isotropic material properties in the future. The numerical results are being compared to laboratory experiments so to validate the modeling assumptions.

This poster presents the steps undertaken to reliably analyze the mechanical response of the proximal femur using QCT scans, p-FEM and experimental observations.

Keywords: finite-element, proximal femur, bone, QCT

[1] - Presenter

Delaminations for a $\pm 45°$ Transversely Isotropic Pair

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This investigation deals with composite materials, in particular fiber reinforced composites that may be treated effectively as transversely isotropic. This research focuses on an interface crack between a $\pm 45°$ transversely isotropic pair. While a three-dimensional numerical approach has been taken when analyzing this crack, the first term of the asymptotic displacement and stress fields is determined analytically under conditions of plane deformation, using the Stroh and Lekhnitskii formalisms. The plane deformation assumption is reasonable for a through straight crack between these two materials. The stress field has both a square root, oscillatory singularity, a well known singularity for interface cracks, as well as an additional square root singularity. It should be noted that this is a coupled problem, where all modes are involved for all displacements.

Two different methods are extended for calculating stress intensity factors. With the first method, displacement extrapolation, stress intensity factors are calculated directly from the crack face displacements. The second method, the path independent *M*-integral, is an energy based method which is derived from the three-dimensional *J*-integral.

Several problems are considered in order to examine the accuracy of both methods. Three test cases are analyzed, with accurate results obtained by means of the *M*-integral. The displacement extrapolation method is not as accurate as the *M*-integral, and it is used mostly to check the results obtained by the *M*-integral method. A central interface crack in a balanced composite under different loadings, namely tension, in-plane and out-of-plane shear is studied. In addition, a central crack in another lay-up with applied tensile stresses is considered. In all cases, stress intensity factors and Griffith's energy are obtained along the crack front. Some conclusions concerning crack propagation in these different situations are promulgated.

Finally, a Brazilian disk specimen has been modified to include a composite strip containing a delamination between the $\pm 45°$ layers. The interface energy release rate and two phase angles are calculated for this specimen, and a preliminary failure criterion is obtained for specimen loading only.

Keywords: Interface Crack, Transversely Isotropic Materials, Stress Intensity Factors, Three-Dimensional *J*-integral, Three-Dimensional *M*-integral, Fiber Reinforced Materials.

Carbon Nanotube Sites for Neuronal Patterning

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Extra-cellular recording with multiple electrode array (MEAs) systems has been used for the last several decades to study the formation and behavior of *in-vitro* neuronal networks. Studies with MEAs were demonstrated helpful to uncover mechanisms such as long term potentiation (LTP), which is thought to demonstrate a synaptic memory. Therefore, advanced MEAs, with better control on cell density and patterning, are expected to be useful to expand our understanding of high brain functions without the complications of *in-vivo* models.

This work presents a new approach for realizing MEAs for studying neuronal networks. Here, electrically viable neuronal networks are engineered according to lithographically defined carbon nanotube (CNT) templates on quartz substrates. The CNT templates strongly anchor cells to pre-defined locations and enable the formation of stable networks (See Figure1). Each electrode in the new scheme is coated by a layer of several microns of dense and entangled CNTs, synthesized by chemical vapor deposition (CVD) process. This process results in great flexibility in determining the size and the shape of the patterning features.

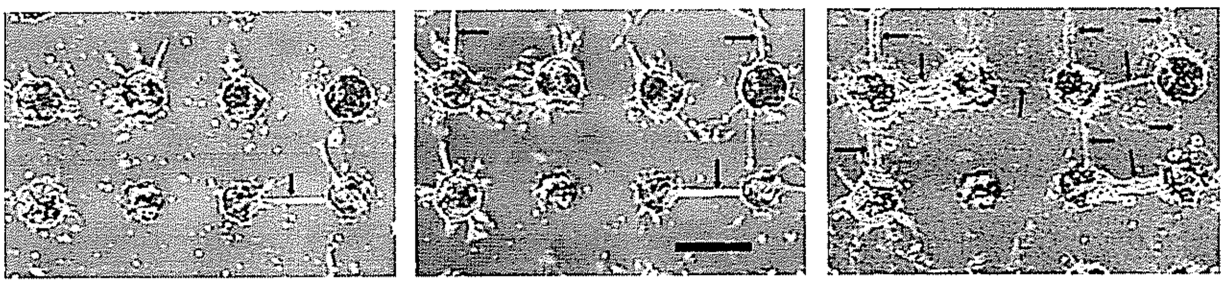

Figure 1: Inverted microscope images of interconnected network formed with CNT islands. Left after 96 hours, Middle after 128 hours and Right after 150 hours after plating. Cell density was $1x10^{-3}$ cells/μm^2. Arrows indicate well defined connections between neuronal clusters. (Scale bar is $150\mu m$)

Keywords: cell patterning, nano topography, carbon nanotube, chemical vapor deposition

A Model of Human Carotid Bifurcation Incorporating Collagen Fiber Orientation

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Atherosclerotic plaques are often found at arterial bifurcations. Likewise, intracranial saccular aneurysms often occur at bifurcations. It is important then, that reliable biomechanical models are addressed to sites of complex geometry (and not only to straight segments). Unfortunately, only a few such studies have been reported in the literature.

In the present work the arterial wall is considered as an incompressible, single-layered, anisotropic and nonlinear material. A numerical model of the human carotid bifurcation is generated in view of a new methodology for the incorporation of collagen fiber directions within a bifurcating vessel. The soft tissue is modeled as a hyperelastic material, reinforced by collagen fibers, which are aligned in two directions. The strain-energy function is formulated in terms of invariants, including the pseudo-invariants of the right Cauchy-Green tensor and the vector describing the direction of the associated fibers (for more details see [2]). It is hypothesized that the two families of collagen fibers are embedded in the plane spanned by two principal directions, which are associated with the two largest principal (Cauchy) stresses. In addition, the collagen fibers are symmetrically aligned with respect to the principal direction, which belongs to the maximum value of principal stress.

Hence, in a first step, principal stresses and directions are computed on the basis of a slight modification of the isotropic strain-energy function documented in [1]. Material parameters for the anisotropic strain-energy function [2], incorporating collagen fiber orientation, are then obtained by fitting the function to data from a common carotid artery, as documented in [1]. Finally, the mechanical response of the carotid bifurcation is analyzed under physiological loading conditions (mean arterial pressure and pre-stretches). Maximum principal stresses and the uniformity factor of the stresses throughout the wall thickness obtained with the anisotropic model [2] are compared with the results obtained from the modified Delfino model. Initial results indicate that the stress magnitudes are about the same for both models investigated with the exception of the apex and the proximal part of the carotid artery.

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Medical Swimming Micro-Robot

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Medical doctors use radiology, endoscopy and smart pills to inspect the inside of the human body. This paper suggests a novel swimming method for propelling a micro-robot through the body by creating a traveling wave in an elastic tail made of piezo-electric actuators. This novel swimming method was analyzed and optimized analytically by solving the coupled elastic/fluidic problem. The results show that under extreme size limitations, a tail manufactured by current MEMS technology is able to swim through water at the order of several mm/sec.

Keywords: Micro System Modeling, Coupled Field Analysis, Swimming, Piezoelectricity, Viscous Flow, Traveling Wave.

Stabilization of electrostatically actuated microstructures using parametric excitation

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Electrostatically actuated micro structures are inherently nonlinear and can become unstable. Nonlinearity usually arises either from the electrostatic forces or from large deformations of the structure resulting in stress stiffening. Pull-in instability is encountered as a basic static instability mechanism. Various methods were suggested in order to stabilize the structure in the vicinity and beyond the pull-in point. In the present work we demonstrate that the parametric excitation of a micro structure by periodic (AC) voltages may have a stabilizing effect and permits an increase of the steady (DC) component of the actuation voltage beyond the pull-in value. An elastic string as well as cantilever beam is considered. The main conclusions about the stability are drawn using the simplest model of a parametrically excited system described by the Mathieu and Hill equations and stability regions in terms of excitation frequency and AC voltage are built. Theoretical results are verified by numerical analysis of microstructure subject to nonlinear electrostatic forces and performed by using Galerkin decomposition with undamped linear modes as base functions. The parametric stabilization of a cantilever beam is demonstrated experimentally.

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Nucleation of Cracks in Two-Dimensional Periodic Cellular Material

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The brittle fracture behavior of cellular material modeled as 2D regular beam lattice is examined. The lattice is subjected to remote uniaxial or isotropic tensile loading and flaw development from failure of a single beam element to a macrocrack(s) produced by multiple beam breaks in sequence is observed. Employing the representative cell analysis method based on the discrete Fourier transform enabled to obtain the exact solution for infinite lattices of different topologies without any simplifying assumptions. Lattices with triangular, square, hexagonal and kagome-type cells are considered. The obtained fracture patterns are in agreement with results on fracture toughness which were calculated separately. The revealed influence of the material microstructure on the crack propagation direction shows that in cellular materials, in contrast to homogeneous ones, the condition of zero Mode II stress intensity factor can not be employed for predicting the crack propagation path.

Keywords: Cellular materials, cracks, repetitive structures.

X-Ray Tomographic Investigation of Stochastic Damage in Polymer Composites

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Fibrous arrays and composites are among the strongest structures created by man or found in nature. Examples of strong synthetic structures range from very large cables such as those found in suspended bridges or radio telescope facilities, to high-performance composites used in aerospace components. Bamboo, bone and nacre are representative tough counterparts found in nature. A major function of the unidirectional brand among such structures is to resist axial forces. Although fracture of an isolated fiber is often of a brittle, catastrophic nature, the fibrous array in composite materials most often prevents the occurrence of rapid structural collapse: fibrous composites preferentially fail in a slow, cumulative fashion. Two decades ago, theoretical schemes have led to mathematical correlations between the stochastic strength distributions of single fibers and of unidirectional composites based on the same fibers. Both distributions were found to be approximately of the Weibull type, and the ratio of shape parameters was calculated to be a constant, N*, which represents the size of a critical cluster of adjacent broken fibers inevitably leading to final failure.

We used synchrotron X-ray tomography at high resolution (2 μm) to monitor the nucleation and growth of damage and fracture in three-dimensional unidirectional composites under in-situ axial tension. The experimental value of N* is found to be 3 to 5 times larger than the value predicted by stochastic theory. We propose a straightforward fracture mechanics argument that rationalizes the experimental data and credibly relates the critical fiber cluster size to the material strength.

Reinforcement of electropsun nanofibers with carbon nanotubes

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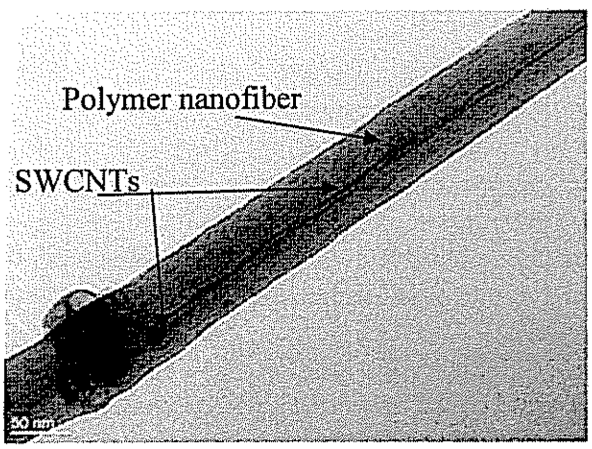
The electrospinning process was used successfully to embed single-walled carbon nanotubes (SWCNTs) in a poly(ethylene oxide) (PEO) matrix forming composite nanofibers. Initial dispersion of SWCNTs in water was achieved by the use of an amphiphilic alternating copolymer of styrene and sodium maleate. The resulting dispersions were stable having a dark, smooth, ink-like appearance. For electrospinning, the dispersions were mixed with PEO solution in an ethanol/water mixture. Due to the sink flow in a wedge and the high extension of the electrospun jet it is expected to align the nanotubes during the electrospinning process as was also predicted by a mathematical model. Initially the SWCNTs are randomly oriented, but due to the sink-like flow they are gradually oriented mainly along the stream lines, so that straight SWCNTs are sucked into the electrospun jet almost oriented.

The distribution and conformation of the nanotubes in the nanofibers were studied by transmission electron microscopy (TEM). Oxygen plasma etching was used to expose the nanotubes within the nanofibers to facilitate direct observation. Nanotube alignment within the nanofibers was shown to depend strongly on the quality of the initial dispersions. Well-dispersed and separated nanotubes were embedded in a straight and aligned form (see Figure) while entangled non-separated nanotubes were incorporated as dense aggregates. X-ray diffraction demonstrated a high degree of orientation of the PEO crystals in the electrospun nanofibers with embedded SWCNTs. This result is in pronounced distinction to the detrimental effect of incorporation of multi-walled carbon nanotubes (MWCNTs) on polymer orientation in electrospun nanofibers, as reported previously by our group. We found that for a 1% (w/w) of SWCNT embedded in electrospun nanofibers the Young modulus increases about 6 times and the max stress increases nearly 5 times in comparison with electrospun nanofibers. This result is an important feature of these composite nanofibers, particularly for their reinforcement.

TEM micrograph of a composite nanofiber with two SWCNTs well centered and aligned along the nanofiber axis. At the left bottom corner of the image a cluster of catalyst and amorphous carbon is observed.



Multistability of electrostatically actuated curved beam

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Bistable mechanisms are useful in various MEMS devices such as RF relays, valves and threshold switches. One advantage of such mechanisms is that they can apply a contact force without or at much lower actuation power. Bistability mechanisms implemented in MEMS devices can be separated into two categories. Electrostatically bistable elements are based on the difference between pull-in and pull-out voltages. Mechanically bistable devices utilize snap-through phenomenon while actuating force is either constant or monotonic function of deflection. In the present work we investigate the stability of a curved micro beam actuated by distributed electrostatic force. We show that the presence of mechanical snap-through and electrostatic pull-in instabilities in the system leads to the multi stability of the beam. The governing equations of the geometrically nonlinear extensible beam are simplified based on the shallow arch assumptions. Reduced order model is built by using Rayleigh-Ritz method with linear undamped eigenmodes as base functions. Influence of various design parameters of the beam on the location of the instability points in terms of actuation voltage and deflections is analyzed.

On the Behavior of Viscoelastic Fiber Reinforced Composites

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We consider the class of composites where the behavior of the matrix phase is viscoelastic under shear. By application of the correspondence principle, simple explicit expressions for the temporal variations of the effective relaxation moduli of a composite with a matrix, whose behavior can be approximated by the standard-linear model, are developed. The standard model, which corresponds to a Maxwell element in parallel with a spring, is represented by a single-term Prony series with a single relaxation time. The expressions for the effective relaxation moduli are based on the random array model of Hashin and Rosen (1964) and the composite cylinder model of Hill (1964) for linear elastic fiber reinforced composites. The analytic expressions for the class of fiber reinforced composites are compared with corresponding numerical results based on finite element simulations of a composite with hexagonal distribution of the fibers. The numerical model is based on the geometry and the periodic boundary conditions for a hexagonal unit cell of Aravas et al. (1995).

It is found that, in addition to an exponentially decaying term with a relaxation time identical to that of the matrix, the expressions for the effective relaxation moduli involve an additional term with a relaxation time, which is always larger than that of the matrix. In the limit when the fibers are markedly stiffer than the matrix the effective relaxation time of the composite approaches that the matrix. *The exception is the relaxation time for the transverse shear relaxation modulus which, in this limit of stiff fibers, approaches a constant depending on the matrix initial Poisson's ratio.* It is further shown that, due to the interaction between phases with different viscoelastic behaviors, these composites may exhibit a non-monotonous behavior. It is further demonstrated that under quasi-static loading conditions the analytic expressions provide accurate estimates for the numerically determined behavior of the periodic composite. The behavior of the composite under dynamic loading conditions and the applicability of the homogenized approach under these conditions are discussed too.

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Experimental and analytical investigation of dynamic lateral torsional post-buckling of an elastic beam-mass system using the theory of a Cosserat Point

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An elastic beam-mass system was designed to exhibit coupled dynamic nonlinear phenomena. Specifically, the thin beam was made of spring steel and its cross-section was rectangular with the height being about 10 times the width. One end of the beam was attached to a motor shaft which was controlled to oscillate using a sinusoidal function of time. The other end of the beam was attached to a relatively large rectangular block of steel. Oscillation of the motor shaft causes the beam and mass to move in the plane with the highest bending stiffness of the beam. The dimensions and mass of the system were designed so that a range of amplitudes and frequencies of oscillation will cause the shear force applied by the mass on the beam to be larger than the value associated with static lateral torsional buckling of the beam. Consequently, for a range of amplitudes and frequencies the mass starts to twist and move out-of-plane as the beam exhibits dynamic lateral torsional post-buckling vibrations. Measurements were taken for a number of calibration tests which examined the lowest frequencies of torsion, weak bending (in the plane with the weakest bending stiffness) and strong bending (bending in the plane with the strongest bending stiffness). Measurements were also taken for the lowest frequency of weak bending with the mass removed. The response of this beam-mass system was simulated using finite elements based on the theory of a Cosserat point. This theory includes full geometric and material nonlinearity and it models, axial extension, bending, torsion, tangential shear deformation, normal cross-sectional extension and normal cross-sectional shear deformation. An analytical tangent stiffness was developed and the equations were programmed using Matlab. Damping was also included. The simulations are in relatively good agreement with all of the observed phenomena. In particular, it is shown that the frequencies of vibration are significantly affected by gravity. Specifically, for the beam-mass system, the lowest frequencies of weak bending are: 2.70 Hz with the mass vertically down; 2.28 Hz with the beam and mass horizontal; and 1.82 Hz with the mass vertically up. Also, it is shown that when the beam-mass system is horizontal gravity causes torsional modes to be converted into bending modes.

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