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ISTAM ANNUAL SYMPOSIUM

TECHNICAL PROGRAM, 2015

ISTAM 2015 Annual Symposium Program

Location: Room 011, Engineering Studies (Kitot Handassa) building, Tel Aviv University

09:30 – 09:50 Registration and coffee

09:50 – 10:00 Opening: MB Rubin – Technion

Session I, Chairman: S. Rudykh (Technion)

10:00 – 10:20 <u>H. Chai</u> and A. Tamse, (Tel Aviv U.) "The effect of isthmus on vertical root fracture from condensation of gutta-percha."

10:20 – 10:40 T. Cohen and R Abeyaratne, (MIT) "Surface Growth in Polymer Gels."

10:40 – 11:00 <u>B. Bar-On</u>, (Ben Gurion U.) "Multi-Scale Structural Gradients Optimize the Bio-Mechanical Functionality of the Spider Fang."

11:00 – 11:20 <u>D. Sherman</u>, (Tel Aviv U.) "*Hexagonal patterns in thin films: experiments and modeling.*"

11:20 – 11:30 <u>Coffee Break</u>

11:30 – **11:50** <u>V. Slesarenko</u> and S. Rudykh, (Technion), "*Tunable wavy interfaces in soft visco-hyperelastic composites*."

11:50 – 12:10 <u>A. Fershtman</u>, (Tel Aviv U.), "*The relation between hydrodynamics and the instantaneous heat transfer rate around a single Taylor bubble.*"

12:10 – 12:30 <u>I.E. Berinskii</u>, (Tel Aviv U.), "Non-linear electromechanical model of graphene resonator."

12:30 – 12:40 ISTAM elections. MB Rubin – Technion

12:40 – 13:45 Lunch Break

Session II, Chairman: R. Segev (Ben Gurion U.)

13:45 – 14:00 <u>A. Tulchinsky</u> and A.D. Gat, (Technion), "Transient Dynamics of Elastic Hele-Shaw Cell due to External Forces with Application to Impact Mitigation."

14:00 – 14:15 <u>N. Leibowitz</u>, J. Schiffbauer, S. Park and G. Yossifon, (Technion), *"Chrono-potentiometric response of non-ideal ion selective microchannelnanochannel devices."*

14:15 – **14:30** <u>N. Cohen</u>, A. Menzel , and G. deBotton, (Ben Gurion U., Dortmund U.) *"Modelling of the Electro-Mechanical Response of EAPs."*

14:30 – 14:45 <u>R. Getz</u> and G Shmuel, (Technion), "*Complete band-gaps in soft dielectric fiber-composites.*"

14:45 – 15:00 <u>P.I. Galich</u> and S. Rudykh, (Technion), "*Tuning Pressure and Shear Waves in Dielectric Elastomers by External Electric Stimuli.*"

15:00 - 15:15 Coffee Break

Session III, Chairman: Gal Shmuel (Technion)

15:15 – **15:30** <u>P. Kozlovsky</u>, M. Rosenfeld, R.J. Bryson-Richardson and D. Elad, (TAU, Monash U.), "*The Driving Mechanism for Unidirectional Blood Flow in the Tubular Embryonic Heart.*"

15:30 – 15:45 <u>R. Friedman</u>, A. Haimy, Y. Epstein and A. Gefen, (TAU, Sheba Medical Center) "*Modeling non-penetrating projectile impacts targeting a helmethead complex for evaluations of helmet efficacy.*"

15:45 – **16:00** <u>M. Saeed</u>, A. Gefen & D. Weihs, (TAU, Technion), "Modeling celllevel mechanical response in compressed Mesenchymal stem cells using a novel phase-contrast microscopy-based method."

16:00 – **16:15** <u>M.M. Safadi</u>, M.B. Rubin, M. Jabareen, (Technion), "A New Eulerian Theoretical Structure for Modeling Growth in Soft Tissues."

16:15 – **16:30** <u>Y</u>. <u>Shelef</u> and B. Bar-On (Ben Gurion U.), "The unexpected role of the turtle shell skin in enhancing the resistance to indentations."</u>

Student Award – Gal Debotton (Ben Gurion U.)

16:30 - 16:45 Announcement of the winner of the student award

The annual membership fee to ISTAM is 150 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. The program and abstract can be downloaded from https://istam.net.technion.ac.il/

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A New Eulerian Theoretical Structure for Modeling Growth in Soft Tissues
The unexpected role of the turtle shell skin in enhancing the resistance to indentations

The effect of isthmus on vertical root fracture from condensation of gutta-percha

H. Chai¹ and A. Tamse²

Tel-Aviv University, Tel-Aviv, Israel ¹School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, herzl@eng.tau.ac.il ²Goldschleger school of Dental Medicine, tamseaz@post.tau.ac.il

Vertical root fracture (VRF) is a major complication in endodontically treated teeth that often leads to tooth extraction. Wedging forces and pressure transmitted to the canal wall during condensation of gutta-percha (gp) are primary causes for VRF. Analytical studies of VRF due to apical condensation of gp are generally limited to elucidating stress fields in one-canal roots with circular or elliptical canal cross section. It was found that the tensile stress responsible for crack initiation is maximized on the inner canal wall where the radius of curvature is smallest, consistent with well-documented clinical fractures. However, there are no treatment for the growth of the initial cracks to cause VRF and furthermore no analysis connecting between the canal pressure and condensation load.

In this work we studied experimentally and analytically VRF in roots with one or two canals. The interior root morphology in mandibolar molar teeth extracted from patients due to VRF or otherwise was examined from a series of polished cross sections. Two-canal mesial roots were found to be much more prone to VRF than one-canal distal roots. From a mechanistic viewpoint the isthmus connecting root canals can be regarded as natural weak plane or crack. With this in mind, the apical load needed to cause VRF, F_{max} , was determined from 2D fracture mechanics analysis. VRF was taken to occur when a crack initiated on the canal wall grew all the way to the outer canal surface. The results expose the prime role of isthmus in reducing F_{max} , from ≈ 60 N with no isthmus present to ≈ 10 N. Accordingly, it is suggested that VRF may occur during clinical condensation of gp in mesial roots of mandibular molars as well as other roots with canals connected by isthmus. To avoid such a fracture, means need be developed to fill root canals with sufficiently small apical condensation load.

Surface Growth in Polymer Gels

<u>T. Cohen¹</u> and R. Abeyaratne²

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA ¹talco@mit.edu, ²rohan@mit.edu

The present study is concerned with continuum modeling of surface growth phenomena in polymer gels while accounting for both swelling of the gel and the coupled diffusion of a non-dilute solution towards the accretion surface, to supply monomers which are required to sustain growth. Examples of such growth processes of polymer gels, and in particular actin gel, can be found in nature. Persistent polymerization of actin in mobile animal cells pushes against the cell membrane, creating motion of the entire cell and thus playing a major role in the driving mechanism of cell motility; an imperative necessity for maintaining life. A similar mechanism can be exploited in the future to move non-biological cargo for drug delivery or for manufacturing nano-patterns [1]. Other intriguing examples of surface growth can be found in [2].

In this unique growth process the previously formed layers are constantly being pushed out of the way to make room for the newly formed mass, thus resulting in a build-up of internal stresses which may, in turn, affect the growth rate and the conditions at 'birth' of each layer. Additionally, as the gel layer increases in thickness, the diffusion of monomers through the layer may also restrict the growth. In the present study we therefore take into account both the interplay between the biochemical reactions and the mechanical nature of the process as well as the interaction between the polymer network and the solvent, which together compose a compressible medium. The talk will begin with a description of the theoretical framework for general growth conditions and will present the specific constitutive relations chosen to model the gel [3,4,5]. The chemo-mechanical driving force associated with the accretion and subsequent dissociation of the polymer network will then be evaluated by considering the rate of dissipation on the boundaries of the body, which, in absence of external power and mass input, indicates the act of an internal *configurational force.* In accordance with the fundamental thermodynamic principles, a kinetic law is then defined to relate between the driving force and its thermodynamic conjugate - the velocity of the reaction surface in the reference space. A particular challenge in modeling the present ever-evolving process is due to the absence of a stress-free reference configuration in the physical-space. We will therefore suggest the notion of a four-dimensional reference configuration. Finally we will focus on some specific examples of surface growth.

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Multi-Scale Structural Gradients Optimize the Bio-Mechanical Functionality of the Spider Fang

B. Bar-On

Laboratory for the Mechanics of Complex Materials Department of Mechanical Engineering, Ben-Gurion University of the Negev

The spider fang is a natural injection needle, built as a multi-scale composite material with outstanding mechanical properties. In this study we introduce a hierarchical modeling for the spider fang, based on computer tomography and SAXS measurement, and analyze the correlation between the fang architectural motifs and its macroscopic elastic behavior. Analytical methods and Finite-Element simulations are used for the mechanical analysis and the effects of small- and large-scale structural gradients on the macroscopic mechanical properties are investigated.

It is found that the multi-scale structural gradients of the spider fang optimize its performances in term of load-bearing stiffness and strength, and that the naturally evolved fang architecture provides optimal mechanical properties compared to other alternative structural configurations.



Fig. 1. Finite-Element simulation results for the simplified structural models and the reconstructed natural fang configuration

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Hexagonal patterns in thin films: experiments and modeling

D. Sherman

School of Mechanical Engineering, Faculty of Engineering Tel-Aviv University, Tel-Aviv, 69978, Israel

Natural perfect hexagonal columns of cooled basalt lava, such as those in Ireland's Giant Causeway; and polygonal mud patterns, such as those annually formed in California's death-valley drying playas, have captured human imagination for centuries. The origin of the damage mechanism inducing such patterns has stirred debate for decades. Yet, it is commonly accepted that hexagon formation is associated with crack nucleation and propagation.¹⁻³ Recently, perfect periodic hexagonal patterns were obtained in Prof. G.L. Frey Lab (Technion) in µm-thick drying composite films (Fig. 1). By controlling lab conditions and filming the hexagons nucleation in real-time, it was shown that the hexagonal patterns are correlated conclusively with uniformly- and rapidly-generated local plastic deformation (fissures), and not brittle fracture, to efficiently reduce the strain energy in the contracted material.⁴ Although chemistry, environmental conditions, and time- and length-scales of the natural and lab-made patterns are obviously very different, the remarkable similarity suggests that rapid cooling of lava may follow the same deformation mechanism and results in meter-long fascinating hexagonal columns.

A two-layer model, consisting a thin complaint layer on stiff substrate, failed to predict the size of the hexagons. We then turn to a three-layer model (Fig. 2), composed of stiff, thin crust layer on a complaint layer, based on the filmed experimental evidences. The model considers single initiation site at maximum biaxial tensile stresses, plastic deformation (termed fissure), interfacial shear stresses, generation of hexagonal patterns by energy minimization rational at the outer crust layer that evaporates first, which then serve as a template for farther expansion through the thickness of the layer. We farther suggest that this mechanism might be applicable to the nucleation and evolution of the geological lava hexagonal patterns.⁴ The hexagon patterns and the model will be discussed.

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Fig. 1. Optical images of drying patterns observed in films deposited on glass substrates by dip-coating from WCl₆:P123 precursor solutions with increasing polymer content. The WCl₆:P123 wt. ratios in the precursor solutions are: **a**) 4:1, **b**) 3:1, **c**) 2:1 and **d**) 1.5:1. The pattern observed in **d** is the first experiential evidence of prefect hexagonal damage patterns obtained in lab-prepared specimens.



Fig. 2. The basic mechanism of hexagonal pattern formation in the 2 µm-thick elastic-plastic composite film. *a*, A schematic illustration of a fissure's cross section (gray area) and the interfacial shear stresses, τ_{int} (red line), and average tensile stresses, $\bar{\sigma}$ (blue line), in its vicinity. *b*, The initial frailer zone. *c*, The initial failure process grows until, *d*, the sheared zone reaches the steady state circle-like shape. *e*, The fissure bifurcates twice at each edge in an angle of 60° each, a process which generates the hexagon presented in *f*. *g*, The progression of the hexagons in the thin films prepared in this study is opposite to the pull out direction and to the sides. *h*, A schematic comparison between the two models described in the text: a thin film on a glass substrate (left), and a crust-on-soft substrate on glass (right).

Tunable wavy interfaces in soft visco-hyperelastic composites

<u>V. Slesarenko¹</u> and S. Rudykh²

Faculty of Aerospace Engineering, Technion - Israel Institute of Technology ¹slslesarenko@technion.ac.il, ²rudykh@technion.ac.il

In general, mechanical instabilities are usually considered as failure mode, however it is possible to exploit them in order to design materials and structures with enhanced performance, for example to accumulate strain energy (Shan et al. 2015) or control elastic waves (Shan et al. 2014). Particularly, we interested in the mechanical behavior of soft layered composites, that exhibit the so-called buckling phenomenon when compressed to a critical level. At this point, the microstructure switches to the wavy patterns with the geometrical parameters that depend on the phase materials properties and initial internal geometry of the laminates (Li et al. 2013). This phenomenon can be used to actively control the material microstructures and achieve various functionalities, such as tunable band-gaps in elastic waves (Rudykh and Boyce 2014). Moreover, similar effects can be produced via non-mechanical external stimuli such as electric or magnetic field in active composites (Rudykh at el. 2014).

While the geometry of wavy interfaces in hyperelastic soft materials are mainly defined by initial geometry and contrast between elastic modules of layers and matrix, there is no much space for tuning, because no one can change these two parameters for designed and already manufactured composite. However, this difficulty can be overcome, if we take into account time-dependent behavior of layers and/or matrix material. Thus, the objective of this work was to exploit the timedependent behavior of materials to control the post-bifurcation wavy interfaces. Here, we employed the finite element method to numerically predict the performance of the soft composites with visco-hyperelastic layers in the regular and post-bifurcation regime for composites with various geometries. For an experimental validation of numerical predictions, composite samples with various materials for layers and matrix were manufactured by means of 3D printing. These samples were subjected to constrained compression at the different strain rates, and the critical buckling strain and post-bifurcation geometry were determined experimentally. Based on experimental study and numerical simulations, we showed that post-bifurcation geometry of soft composite with visco-hyperelastic layers could be significantly tuned by applying of different strain rates, and it may be useful for the various practical applications.

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The relation between hydrodynamics and the instantaneous heat transfer rate around a single Taylor bubble

A. Fershtman

School of Mechanical Engineering, Tel-Aviv University adamfersh@gmail.com

While many studies have been performed to examine the hydrodynamics of two-phase gas-liquid slug flow, the details of heat transfer mechanism of this flow regime remain largely unknown. The flow field around a single Taylor bubble propagating in a vertical pipe can be subdivided into three distinct hydrodynamic regions: the gas bubble surrounded by a thin liquid film, a highly turbulent liquid wake near the bubble bottom, and the far wake region. Knowledge of the detailed hydrodynamics around a single Taylor bubble [1] provides a basis for understanding the heat transfer mechanism. The present study is aimed to investigate the impact of the hydrodynamic field around a single Taylor bubble, on the instantaneous heat transfer for different flow regimes and heating locations. To enable controlled flow conditions, experiments were carried out for a single Taylor bubble rising in a vertical pipe. Measurements of the instantaneous heat transfer coefficient as a function of the bubble's location relative to the measuring station are carried out for different liquid flow rates, corresponding to stagnant, laminar, transitional and turbulent background flows. The experiments were conducted at several locations corresponding to different heating lengths and thermal boundary layer thickness.

Experiments are carried out in a specially designed facility shown schematically in Figure [1]. It consists of air and water supply systems and a test section made of a 6 m long vertical Perspex pipe that has an internal diameter, D, of 0.044m. Filtered tap water flowing in a closed loop is used as the working fluid. Water flow rate is monitored continuously by rotameters. Individual air bubbles are injected via a computer-controlled valve through a pipe with internal diameters identical to that of the test section. Adjustment of the air pressure in the manifold and the valve opening duration allows control of the bubbles' length. A test section for heat transfer investigations was constructed without introducing any disturbance to the



Figure 1: Sketch of the experimental facility with heat transfer measurements unit. Details of entrance section are given in the inset.

flow. The test section is located in the upper part of the pipe to obtain a fully

developed flow in the test section. Four narrow vertical windows were cut from the pipe wall and replaced by a thin 12.5 μ m stainless steel foil. A constant heat flux, q, is supplied to the foil by a DC current power source. The foil's inner side is open to the flow and the outer side was painted with a black mat spray and filmed by an IR camera to obtain the instantaneous local temperature field of the foil. Temperature distribution on the heated foil is measured using infrared thermography technique, Optris PI450 IR camera. T-type thermocouples were installed at each window along the test section. In order to set the emissivity of the painted foil, the value of emissivity of the IR camera was set so the temperature from the IR camera would agree with the temperature measured by the thermocouples. Two sets of lasers and light to voltage sensors (diode) are mounted at the test section in order to measure the Taylor bubbles' translational velocity and length, as well as to synchronize the Taylor bubble passage with the IR camera. With a set constant heat flux, q, and the temperature of the water and foil, the instantaneous heat transfer coefficient, h, was calculated and normalized by the coefficient calculated for the single phase case, h_L. For each flow condition, over 100 individual events are recorded and serve as the basis for extracting ensemble averaged quantities. The results are given as a function of z/D, the distance of the measuring point from the bubble bottom. The heating length x is measured from the leading edge of the foil. All bubbles injected are of a length of about 3.5D.

The distribution of the measured instantaneous heat transfer coefficient h normalized by h_L along a slug unit is shown in Figure [2] for stagnant, laminar and turbulent flow conditions. A small initial increase in the normalized coefficient takes place in the film region. The thickness of the liquid film reduces with the distance from the bubble nose and is accompanied by an increase of the mean liquid velocity in the film. The accelerated velocity causes an

increase in the heat transfer coefficient by a gain of roughly 5% compared to the single phase heat transfer. The major increase in the heat transfer coefficient is located in the close vicinity of the bubble bottom, beginning at about 1.5-2D from the bubble bottom and reaching a maximum value in the near wake of the bubble. This behavior is related to the flow field caused by the downward liquid film flow entering the liquid slug as an annular wall jet. The



Fig. 2. Normalized heat transfer coefficients along a single slug unit for stagnant liquid $(q=2100 \text{ W/m}^2)$, $Re=820 (q=2100 \text{ W/m}^2)$ and $Re=7500 (q=2550 \text{ W/m}^2)$, x/D=3, $L_b=3.5D$





interaction of the liquid moving upward with the downward axisymmetric wall jet creates a toroidal vortex. The radial velocity of the vortex removes the heated liquid from the foil in an efficient way and causes the increase in the heat transfer coefficient. The Reynolds stress and the maximum negative radial velocity, directed from the pipe wall to the axis, are obtained 1-2D behind the bubble bottom, Figure[3], explaining the major increase in the heat transfer coefficient and its location.

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Non-linear electromechanical model of graphene resonator

I.E. Berinskii¹

Faculty of Mechanical Engineering, Tel Aviv University ¹iberinsk@gmail.com,

Recently two-dimensional materials were proposed for application to nanoelectromechanical systems (NEMS). Two-dimensional materials is a relatively new class of materials having one or several atoms in one of directions. The most famous 2D material is graphene. This work is devoted to study of graphene-based nanoresonator (Fig 1a). A resonator is the electro-mechanical system serving for excitation of mechanical oscillations with electric field. Graphene resonator can be represented as a capacitor having graphene film as one plate and a conducting substrate surface as another one. Capacity of this system depends on the lateral displacement of the graphene film. Electric field inside the capacitor is produced with a source of alternating voltage.



Fig. 1. Graphene-based electromechanical resonator (a) and its electromechanical model (b)

One of the main problems of graphene resonator is its low Q-factor (strong oscillations damping) preventing the determination of resonator natural frequency using its resonance curve. However, recently a new opportunity to find the natural frequency based on consideration of non-linear oscillations of the graphene film was proposed. It was shown experimentally that graphene could demonstrate both softening and hardening non-linear behavior. Current work is devoted to the explanation of this effect and proposes a method of determination the natural frequency based on sudden stop of non-linear oscillations at scanning the from the high frequency of forced electric field to the low one. The proposed electromechanical model (Fig 1b) describes oscillations of mass on the elastic suspension connected with one of the capacitor plates:

$$m\ddot{u} - \frac{Q^2}{2C}\frac{dC}{du} + P(u) = 0, \qquad \dot{Q} + \frac{1}{RC}Q = \frac{U}{R}\sin\omega t$$

where m is a mass of the layer, Q(t) is a capacitor charge, R is an electrical resistance of the chain, and U is a voltage. A capacity can be found as

$$C(x) = C_0 \frac{d_0}{d_0 - x}$$

where C_0 is an initial capacity (at unstrained state), d_0 is an initial distance between the plates. Using molecular dynamics experiments was proved that the elastic force acting on the mass is close to the cubic polynomial:

$$P(u) = \alpha u + \beta u^3$$

The constants α and β are determined by the initial tension, stiffness and length of the film. Different combination of these parameters make constant β either positive or negative. Its sign determines whether the system will demonstrate softening or hardening behavior.



Fig. 2. Oscillations amplitude as a function of the frequency at different voltage

As a result the displacement-time and resonant curves for the model presented above were obtained (Fig 2). As expected, the system shows a parametric resonance. The role of the initial parameters to the system behavior were investigated. Molecular dynamics simulations proved the cubic nonlinearity of the theoretical model. The results of the work can be applied to model the NEMS based on thin films.

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Transient Dynamics of Elastic Hele-Shaw Cell due to External Forces with Application to Impact Mitigation

A. Tulchinsky & A. D. Gat

Faculty of Mechanical Engineering Technion - Israel Institute of Technology Haifa 32000, Israel

We study the transient dynamics of a viscous liquid contained in a narrow gap between a rigid plate and an elastic plate. The elastic plate is under the influence of an externally applied time varying force acting perpendicular to its surface. We model the flow in the narrow gap via the lubrication approximation, and the plate by the Kirchhoff-Love plate theory. The viscous-elastic interaction yields a governing 6th-order linear partial differential equation. A semi-similarity solution is obtained for the case of an external point force acting on the elastic plate. The pressure and deformation field during and after the application of the external force are derived and presented by closed form expressions. We examine a uniform external pressure acting on the elastic plate over a finite region and during a finite time period. The interaction between elasticity and viscosity is shown to reduce by order of magnitude the pressure within the Hele-Shaw cell compared with the externally applied pressure, thus suggesting such configurations may be used for impact mitigation.



Fig. 1. Liquid pressure distribution, (a), and deformation of the elastic plate, (b), during and after impact as a result of a localized point force with a steady amplitude with time (i.e. $P_e = \frac{1}{T_e} \delta(X) [\theta(T) - \theta(T - T_e)]).$

Chrono-potentiometric response of non-ideal ion selective microchannel-nanochannel devices

<u>N. Leibowitz¹</u>, J. Schiffbauer, S. Park and G. Yossifon²

Faculty of Mechanical Engineering, Technion - Israel Institute of Technology ¹netaleib@tx.technion.ac.il, ²yossifon@tx.technion.ac.il

The passage of an electric current through an ion perm-selective medium (e.g. membranes and nanochannels) under an applied electric field is characterized by the formation of ionic concentration gradients which result in regions of depleted and enriched ionic concentration at its opposite ends, i.e. concentration polarization. As a result[1], [2], it can be shown that the chronopotentiometric response of an ideal permselective interface (e.g. permselective membranes) is a monotonic function of the voltage with time regardless of the current intensity[3], [4]. In contrast, a microchannel-nanochannel device exhibits a non-monotonic chronopotentiometric response for overlimiting currents. This is shown both numerically and experimentally to result from the non-ideal ion permselectivity of the fabricated nanochannels. This is further supported using experimental visualization techniques that indicate the existence of concentration-polarization within the nanochannel itself and not only within the microchannels.

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Modelling of the Electro-Mechanical Response of EAPs

 $\underline{N. Cohen}^{1,2}$, A. Menzel^{2,3}, and G. deBotton^{1,4}

¹Dept. of Mechanical Engineering, Ben-Gurion University, Beer-Sheva, Israel ²Institute of Mechanics, Dept. of Mechanical Engineering, TU Dortmund, Dortmund, Germany

³Division of Solid Mechanics, Lund University, Lund, Sweden ⁴Dept. of Biomedical Engineering, Ben-Gurion University, Beer-Sheva, Israel

Due to the increasing number of industrial applications of electro-active polymers (EAPs), there is a growing need for electromechanical models which accurately capture their behavior. To this end, we compare the behaviors of incompressible EAPs undergoing homogenous deformations according to three electromechanical models:

- 1. The macroscopic model the mechanical behavior is characterized by the Gent model [2] and the electrical response is determined from the linear relation $D = \varepsilon E$, where D, ε , and E are the electric displacement, the permittivity and the electric field, respectively.
- 2. The microscopic model the microscopic Langevin model [3] is utilized in order to describe the mechanical behavior. We employ the long-chains model [1] to characterize the dielectric response of the polymer.
- 3. The Gaussian model the mechanical neo-Hookean model is used in conjunction with the electrical long-chains model [1].

In the second and third model, the micro-sphere technique [4] is used in moving from the microscopic to the macroscopic responses. Different states of deformation and loading are considered to compare the behaviors determined for the models discussed. The differences between the predictions of the models are addressed and demonstrate the need for a more rigorous investigation as to the relations between the micro and the macro response.

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Complete band-gaps in soft dielectric fiber-composites

 $\underline{R \ Getz}^1$ and G Shmuel²

Faculty of Mechanical Engineering, Technion – Israel Institute of Technology ¹roeygetz@campus.technion.ac.il, ²meshmuel@tx.technion.ac.il

Dielectric elastomers (DEs) undergo large deformations and their properties are changed in response to electric stimuli. In this talk, we characterize the static response of electrostrictive DE fiber-composites, to a voltage drop along the fibers. We formulate the equations governing the in-plane motion propagating on top of the deformed state of the composite. These equations are solved using the plane-wave expansion method, when the material law is specialized to the augmented Gent model (Gent, 1996), which accounts for the strain-stiffening in elastomers. We explore the dependency of the motion on the phases properties, volume fractions, and most importantly the bias electric field. We find ranges of frequencies, termed *band-gaps*, at which waves cannot propagate. Parts of these gaps coincide with the gaps found for the anti-plane motion (Shmuel, 2013), forming *complete* band-gaps in which propagation is forbidden at all propagation directions. We show how such gaps can be tuned by adjusting the applied voltage. Thus, our analysis further promotes the use of DEs as electrostatically tunable waveguides and isolators.

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Tuning Pressure and Shear Waves in Dielectric Elastomers by External Electric Stimuli

<u>P. I. Galich^{1,*}</u> and S. Rudykh²

Department of Aerospace Engineering, Technion – Israel Institute of Technology ¹galich@technion.ac.il, ²rudykh@technion.ac.il

Elastic wave propagation is of long standing interest in various branches, from medicine to petroleum engineering. Recently, a new class of artificial acoustic metamaterials has attracted considerable attention owing to possibility of such fascinating functionalities as acoustic cloaking and filtering (Rudykh and Boyce, 2014). It is known that elastic wave propagation alters with the change in the media properties, initial stress-strain state and stiffening effects (Galich and Rudykh, 2015a). Thus, elastic waves can be tuned by designing microstructures, which can be further actively controlled by external stimuli, for example, by mechanical loading (Rudykh and Boyce, 2014), electrical or magnetic field. Remarkably, even relatively simple homogenous materials can be used to achieve acoustic functionalities such as disentangling of pressure (P-) and shear (S-) waves (Galich and Rudykh, 2015b). These distinct elastic wave modes possess different characteristics and, hence, serve for different purposes; for instance, in the shear wave elasticity imaging S-wave serves as an instrument for determining the internal properties of the biological tissue (Sarvazyan et al., 1998).

Here, we propose a method for separation of P-and S-waves in dielectric elastomers by bias electric field. We show that the divergence angle between P-and S-wave significantly depends on the magnitude of the applied electric field and direction of wave propagation; moreover, material compressibility influences disentangling of wave modes. Thus, when mechanical manipulation of elastic wave propagation is impossible or challenging, for example, in microelectromechanical systems, the proposed method of manipulating elastic waves by electric field can be utilised.

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The Driving Mechanism for Unidirectional Blood Flow in the Tubular Embryonic Heart

P. Kozlovsky¹, M. Rosenfeld², R.J. Bryson-Richardson³ and D. Elad⁴

^{1,4}Department of Biomedical Engineering and ²School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Israel ³School of Biological Sciences, Monash University, Melbourne, Australia ¹pavelko1@post.tau.ac.il, ²rosenf@eng.tau.ac.il, ³robert.brysonrichardson@monash.edu, ⁴elad@post.tau.ac.il

The embryonic heart of vertebrate embryos, including humans, has a tubular thick-wall structure when it first starts to beat. The tubular embryonic heart (TEH) does not have valves, and yet, it produces an effective unidirectional blood flow. The actual pumping mechanism of the TEH is still controversial with pros and cons for either peristaltic pumping (PP) or impedance pumping (IP) (Forouhar et al., 2006; Taber et al., 2007; Männer et al., 2010). On the other hand, observation of movies of the contractile TEH of the quail revealed a propagating wave from the venous end towards the arterial end that occludes the lumen behind the leading edge (Jenkins et al., 2007). This pattern of contraction represents a complex PP with a duty cycle (DC), and was defined here as biological pumping (BP).

To explore the actual pumping mechanism of the TEH, we developed a threedimensional (3D) idealized heart-like geometry of the HH-10 stage chick embryonic heart for implementation in a fluid-structure interaction (FSI) computational model of blood flow. The vascular resistance and compliance of the embryonic circulation was also implemented in the model (Fig. 1a). The heart wall was assumed to behave as a uniform hepereastic material. The embryonic blood was assumed to be a Newtonial and slightly compressible. The 3D geometry of the TEH was meshed and the governing equations were solved using the finite-element package of ADINA (Watertown, NY, USA). We further proposed boundary conditions to represent the three pumping mechanisms (i.e., IP, PP and BP).

A comprehensive sensitivity analysis was performed to study the effect of structural, system and operating parameters of the model on the pumping outcome of the TEH. The calculated instantaneous blood flow (Q_{out}) for the proposed pumping mechanisms is shown in Fig. 1b. The pulsatile blood flow was observed in cases of IP and BP mechanisms only. Previous studies (Avrahami and Gharib, 2008; Kozlovsky et al., 2015) have demonstrated that IP is especially effective only when operating at the natural frequency of the system. Hence, we established in the case of IP the dependence of the stroke volume (SV) on wide range of heart rate (HR), including unrealistic values of up to 3000 beats/min, as shown in Fig. 1c. However, even this value was one-order of magnitude smaller than in PP, BP (Fig 1d) and experimental value of $0.75 \cdot 10^{-3}$ mm³ (Hu and Clark, 1989).

In conclusion, the pumping mechanism of the TEH is most likely the BP, which is a complex PP with DC, in order to generate pulsatile blood flow with pressures and wall dynamics as was observed in experiments with animal embryo models.



Fig. 1. (a) The domain physical of the heart-like MY model: is myocardium, CJ is cardiac jelly, CAR, CAL are right and left arterial compliances, R_{VR}, R_{VL} are right and left vascular resistances; **(b)** Variation with time of blood outflow, Q_{out}; The effect of the heart rate, HR, on the stroke volume, SV for (c) IP and (d) IP, PP and BP mechanisms.

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Modeling non-penetrating projectile impacts targeting a helmethead complex for evaluations of helmet efficacy

<u>R. Friedman¹</u> A. Haimy¹ Y. Epstein² A. Gefen¹

¹Dept. of Biomedical Engineering, ²Sackler Faculty of Medicine Tel Aviv University ²Heller Institute of Medical Research, Sheba Medical Center ¹gefen@eng.tau.ac.il

Traumatic brain injury (TBI) is defined as damage to the brain due to external mechanical forces, and/or a fast head movements caused by rapid acceleration, deceleration or rotation (Maas, Stocchetti and Bullock 2008). In the last few years there has been a significant increase in the prevalence of head injuries among soldiers, many of which are due to shrapnel and projectiles impacts. A non-penetrating impact of a bullet/fragment with a combat helmet damages the brain by passage of kinetic energy inwards into the skull, generating fast deformations, stretching, shearing, and eventual collapse of the intracranial soft tissues (Brooks, et al. 2011). Helmet testing methods vary between manufacturers, making it highly difficult to compare helmets created by different companies (Aare and Kleiven 2007). There is still no efficient, low-cost and standardized procedure for assessing the effectiveness of a ballistic helmet.

Our objective was to develop an efficient and flexible platform for comparing the performances of various ballistic helmet designs using finite element (FE) modelling. The platform consists of three parts: (1) A three-dimensional finite element biomimetic head model which includes skin, fat, skull, jaw, sinus, cerebrospinal fluid (CSF), brain, optic nerves, eyes, spinal cord, vertebrae and discs was developed (Figure 1a-e). The model was created based on grey scale transversal cranial images from the Visible Human Project. All tissues were modeled as tided and relative sliding between the skull and the brain was achieved by a very soft CSF layer. The mechanical properties of the tissues are based on the literature. (2) A couple of ballistic helmet designs were added to the model (Figure 1f) with realistic measurements. Both helmets were composed of an external Kevlar®-29 layer and an inner layer of expended polystyrene (EPS) foam. A middle layer for the 3-layered helmet was composed of high-density nylon matrix or EPS. Helmet materials were given bulk (macro) properties which were adopted from the literature. (3) A 5.56mm bullet was modeled (standard M-16 ammunition), as being made of 4340 steel with an impact speed of 990 m/sec. All parts of the model were created using ScanIP (Simpleware[®], Exeter, UK). Impact simulations were performed using the different helmets. The bullet was given an initial speed of 990 m/s and then collided with the helmet without penetrating it. Then, a dynamic response of the helmet and all the head structures was simulated (Figure 1.g-i). The performance of each helmet was quantitatively evaluated and compared to other helmets, based on biomechanical metrics such as effective (von Mises) stress, speed, pressure and acceleration that developed in the intracranial tissues after the impact. Example results are presented in Figure 2. It is evident from Figure 2c,d, that a three-layered helmet with two layers of ESP foam provides a far better protection against high levels of coup and countercoup pressures, reducing them by more than 50%, with respect to a helmet with only one foam layer and a middle layer of high density nylon matrix (Graph F vs. E). It is also apparent that a moderate reduction of the shear and Young's moduli of the Kevlar® shell reduces the positive and negative pressures in the brain (Graph B).

Work underway includes validation of the FE model and addition of further helmet designs. However, the potential benefits provided by our modeling framework are already apparent, as it provides a comparative, quantitative, and cost-effective platform for helmet testing and evaluation.



structures). (b) Skull (c) CSF (orange), eyes (yellow) inside the brain. (f) Head with a helmet. (g, h) Bullet-helmet complex just before impact, deform from the center outwards (in the direction helmet as in E, with ESP in the middle layer. of the white arrows).



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Modeling cell-level mechanical response in compressed Mesenchymal stem cells using a novel phase-contrast microscopy-based method

M. Saeed¹, A. Gefen¹, D. Weihs²

¹ Department of Biomedical Engineering, Tel Aviv University, Tel Aviv 6997801, Israel

² Faculty of Biomedical Engineering, Technion-Israel Institute of Technology, Haifa 3200003, Israel

¹mayssams@post.tau.ac.il, ¹gefen@eng.tau.ac.il, ²daphnew@tx.technion.ac.il

We present models of the response of single cells to external mechanical loads, based on three-dimensional (3D) finite element (FE) modeling of single-cell images obtained by bright-field, confocal microscopy. Cells experience mechanical loads continuously, and in cases such as wheel chair use, specific tissues become highly compressed. Models of cells under load will allow us to simulate and analyze the biomechanical and biological cell response and predict ensuing problems. Similar 3D cell-models have previously been obtained by reconstructing 2D fluorescence cell image-slices, requiring cell-specific and costly microscopy equipment. Our goal is to develop a computational tool using image -based FE modeling method for reconstruction of 3D geometrical models from 2D bright-field confocal microscopy single image. Using only bright-field microscopy, we avoid the need for complex fluorescence staining protocols that can damage cell viability as well as reducing costs both in reagents and required equipment.

We present the approach and development of the 3D FE single-cell models and demonstrate their utility in modeling stretching effects on stem cells. Specifically, following modeling of undifferentiated Mesenchymal Stem Cells, we simulate various loading regimes. We calculate the ensuing tensional strains in each cell and changes in cell and nucleus surface areas, indicative of specific cell differentiation. The nucleus and cytoplasm were assumed to be isotropic compressible materials with Neo-Hookean strain energy function W:

(1)
$$W = \frac{\mu}{2} (I_1 - 3) + \mu lnJ + \frac{\lambda}{2} (lnJ)^2$$

(2) $\lambda = \frac{\nu E}{(1 + \nu)(1 - 2\nu)}$ (3) $\mu = \frac{E}{2(1 + \nu)}$

where: μ and λ are the Lame` parameters which relate to the Elastic modulus (E) and Poisson's ratio (ν) of the cell components. I₁ is the first invariants of the right Cauchy-Green deformation tensor and J is the determinant of the deformation gradient tensor. The elastic modulus of the cytoplasm (E_{cp}) and the nucleus (E_n) were adopted from the literature (Jean et al. 2005, Hochmuth et al. 1973), being $E_{cp} = 3 kPa$ and $E_n = 7.25 kPa$. Poisson's ratios for the cellular components were taken as 0.45 (Slomka et al. 2009, Slomka et al. 2010).

The stem cells each had different morphology providing a realistic distribution of cell-specific geometries, including the overall cell shape and the sub-cellular components. We observe that different cells were affected proportionately to the applied stretched, regardless of their initial morphology. Our results show that imagebased FE modeling method can serve as an effective computational model to study the mechanical and biological behavior of cells.

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A New Eulerian Theoretical Structure for Modeling Growth in Soft Tissues

M.M. Safadi¹, M.B. Rubin², M. Jabareen³

^{1,2}Faculty of Mechanical Engineering ³Faculty of Civil and Environmental Engineering Technion - Israel Institute of Technology ¹safadi@technion.ac.il, ²mbrubin@technion.ac.il, ³cvjmah@technion.ac.il

A new Eulerian-based theoretical structure for modeling growth in soft tissues is proposed. The tissue is modeled as a composite of a matrix and additional components that model the response to elastic stretching of the area of a material surface and elastic stretching of material fibers. These additional components introduce anisotropy in both the elastic and inelastic response of the tissue. The constitutive equations are thermodynamically consistent and, in contrast with other formulations, evolution equations are proposed directly for elastic deformation measures. This approach has the advantage that the material response is not influenced by arbitrariness of the choice of a reference configuration or an intermediate configuration. Specifically, the elastic dilatation J_e and a symmetric unimodular tensor B'_e (det $B'_e = 1$) that characterizes elastic distortions of the tissue are determined by the evolution equations

$$J_e = J_e [\mathbf{D} \cdot \mathbf{I} - \Gamma_m (J_e - J_h)] ,$$

$$\dot{\mathbf{B}}'_e = \mathbf{L}\mathbf{B}'_e + \mathbf{B}'_e \mathbf{L}^T - \frac{2}{3} (\mathbf{D} \cdot \mathbf{I})\mathbf{B}'_e - \Gamma \mathbf{A}_g, \ \mathbf{A}_g = \mathbf{B}'_e - \left(\frac{3}{\mathbf{B}'_e^{-1} \cdot \mathbf{H}'}\right)\mathbf{H}' ,$$

Here, $\{\Gamma_m, \Gamma\}$ are nonnegative scalar-valued functions that need to be determined, and $\{J_h, H'\}$ are the homeostatic values of $\{J_e, B'_e\}$ with det H' = 1. Moreover, these evolution equations include terms that cause $\{J_e, B'_e\}$ to evolve towards their homeostatic values $\{J_h, H'\}$, which are modeled directly.

In contrast with other formulations that introduce a growth deformation tensor $F_g = FF_e^{-1}$, the proposed theoretical structure is based on rates of growth. Specifically, the rates of different growth mechanisms can be coupled by simple addition without introducing an order dependence that would occur if different growth tensors are multiplied to obtain a coupled growth tensor, such that

$$\dot{J}_e = J_e \left[\boldsymbol{D} \cdot \boldsymbol{I} - \sum_{i=1}^M \Gamma_{mi} (J_e - J_{hi}) \right] ,$$

$$\dot{\boldsymbol{B}}'_e = \boldsymbol{L} \boldsymbol{B}'_e + \boldsymbol{B}'_e \boldsymbol{L}^T - \frac{2}{3} (\boldsymbol{D} \cdot \boldsymbol{I}) \boldsymbol{B}'_e - \sum_{i=1}^N \Gamma_i \boldsymbol{A}_{gi}, \quad \boldsymbol{A}_{gi} = \boldsymbol{B}'_e - \left(\frac{3}{\boldsymbol{B}'_e^{-1} \cdot \boldsymbol{H}'_i} \right) \boldsymbol{H}'_i .$$

As an example, consider the case of fiber growth with a vanishing stress in the direction normal to the material fiber. Moreover, in this example, the fiber is initially

stress free and it is being stretched for some period of time at a constant logarithmic rate of total deformation. Then, the fiber is held at constant length. Figure 1 shows that during the stretch extension period, the distortional growth measure b_e increases above its homeostatic value of h = 1.1 and the stress σ in direction of the fiber increases. During the second phase with zero rate of total deformation, b_e asymptotically approaches its homeostatic value h = 1.1 and σ relaxes towards its homeostatic state, which is not zero.



Fig. 1. Fiber Growth: (a) distortional growth; (b) normalized stress in the direction of the material fiber.

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The unexpected role of the turtle shell skin in enhancing the resistance to indentations

Y. Shelef & B. Bar-On

Laboratory for the Mechanics of Complex Materials, Department of Mechanical Engineering, Ben-Gurion University of the Negev, Israel

The turtle shell is a functional bio-shielding element, which has naturally evolved to provide a protection against predator attacks, such as biting and clawing. The shell is structured as a layered material, composed of a hard and brittle core (boney interior), coated by a soft and ductile membrane (skin of keratin and collagen) [1], exhibiting high structural stiffness and damage resilience [2-3]. However, despite the work done, the apparently most expected (and critical) functionality of the turtle shell, namely its resistance to penetration, is yet to be analyzed.

In this work we tackle this issue via employing quasi-static elasto-plastic Finite-Element simulations, to analyze the effect of extensive indentations, through the skin layers of the of the turtle shell, on the localized stress distribution and plastic deformations - in the vicinity of the indentation region. It is found that the emergence of the skin layers significantly reduced the development of potential damage and stress concentration in the bulk bone; the external keratin layer appears to function as an indentation bumper while the secondary collagen layer functions as a buffer which disperses the stress toward the bone.

In a broader perspective, the turtle shell architecture is distinctive compared other bio-shields, such as fish scales, tooth enamel, bones etc. [4], and definitely from the traditional man-made protection configurations, in which the outermost layer is typically much harder than the interior bulk material. Such unusual design guidelines may be utilized to the development of novel bio-inspired shielding elements with superior penetration resistance capabilities.



Fig. 1. Finite-Element simulation results for the turtle shell model (skin of keratin and collagen coating a bony interior) upon extensive indentations: Von-Mises stress distribution (left) and plastic equivalent strain (right).

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