International Workshop

Multi-Scale and Multi-Physics Testing of High-Performance Materials

Technische Universität Berlin, Germany

February 18-19, 2016

Organizers
Prof. Dr. Ivan Argatov and Prof. Dr. Valentin Popov

Location

The Workshop will take place at the TU Berlin
Building M, Room M 123
Straße des 17. Juni 135, 10623 Berlin, Germany
(see attached campus plan of the Berlin Technical University)

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Program

February 18

13:30-14:00	Registration
14:00-14:10	Opening: **Valentin L. Popov**
	Chair: **Gennady Mishuris** ***Keynote lectures***
14:10-15:00	**Marco Paggi** Multi-scale and multi-field modelling and testing of photovoltaic modules
15:00-15:10	Short break
15:10-16:00	**Feodor M. Borodich** Evaluation of adhesive and elastic properties of materials by non-spherical indenters
16:00-16:30	Coffee break
	Chair: **Mariusz Kaczmarek** ***Testing of anisotropic and textile materials***
16:30-16:50	**Gennady Mishuris**, Ivan Argatov and Michael Paukshto Indentation testing of thin anisotropic collagen scaffolds
16:50-17:10	**Julia Orlik** and Vladimir Shiryaev Simulation and optimization of textile membrane via homogenization and beam approximations
17:10-17:30	L. Heepe, A.E. Kovalev, S.N. Gorb and **Alexander E. Filippov** Testing of soft textured tapes by study of wave propagation and friction
	Workshop dinner

February 19

09:00-09:30	Registration
	Chair: **Marco Paggi** ***Multi-scale testing of materials***
09:30-09:50	**Christian Liebold** and Wolfgang H. Müller Mechanics on the microscale – AFM experiments and generalized continuum theories
09:50-10:10	**B. Emek Abali** and Wolfgang H. Müller Size effect and its computational explanation by using strain gradient theories
10:10-10:30	**Ivan Argatov** Multi-scale indentation testing of composite materials
10:30-11:00	Coffee break
	Chair: **Alexander E. Filippov** ***Testing of biological materials and tissues***
11:00-11:20	**Mariusz Kaczmarek** and Waldemar L. Olszewski Estimation of hydromechanical parameters of lymphedematous tissue of limb using single or two chamber test
11:20-11:40	**Gennaro Vitucci** and Gennady Mishuris 3-D contact problem of a transversely isotropic, transversely homogeneous biphasic cartilage layer
11:40-12:00	Sebastian Björklund, Tautgirdas Ruzgas and **Vitaly Kocherbitov** Testing the effect of humidity on properties of polymer and surfactant films: advantages and challenges of QCM-D approach
12:00-12:10	**Photo in front of the Institute of Mechanics**
12:10-13:30	Lunch break

	Chair: **Feodor M. Borodich** ***Method of Dimensionality Reduction***
13:30-13:50	Ivan Argatov, Qiang Li, Roman Pohrt and **Valentin L. Popov** JKR adhesive contact for a toroidal indenter — Application of the Method of Dimensionality Reduction
13:50-14:10	**Markus Heß** A simple but precise method for solving axisymmetric contact problems involving elastically graded materials
14:10-14:30	**Emanuel Willert**, Valentin L. Popov and Yakov A. Lyashenko Quasi-Static Elastic Impacts: The Influence of Friction, Adhesion and Viscosity
14:30-15:00	Coffee break
	Chair: **Ivan Argatov** ***Multi-physics problems in material testing***
15:00-15:20	Choon Yeol Lee and **Young Suck Chai** Simulations of fretting wear for steam generator environment
15:20-15:40	**Aleksey V. Pichugin** Coupled thermoelasticity and micro-scale elastodynamics
15:40-16:00	**Nikolai Gorbushin** and Gennady Mishuris Effect of non-local interactions on steady-state crack propagation in one-dimensional lattice
16:00-16:10	Closing

KEYNOTE LECTURE

Evaluation of adhesive and elastic properties of materials by non-spherical indenters

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Usually contact problems are considered without taking into account adhesive forces. Indeed, the chemical bond distances are within sub-nanoscale and due to surface roughness of contacting surfaces, these bonds can arise only between small amount of surface atoms, while the interaction free energy between molecules varies with the inverse sixth power of the distance at small and intermediate distances of nanoscale. Hence adhesion between contacting bodies has usually a negligible effect on surface interactions at the macro-scale, whereas it becomes increasingly significant as the contact size decreases.

In spite of considerable efforts applying to studies of adhesion, the mechanics of adhesion is well established only for the classical theories of adhesive frictionless contact between spheres that include the JKR, DMT and Maugis theories. Although the validity of these theories is mainly attributed to molecular adhesion, other physical and chemical interactions can be also taken into account by including their actions into the work of adhesion. However, the work of adhesion between interacting surfaces is not a well-known quantity for many modern materials and existing direct methods are not stable. Using the connection between depth-sensing indentation by spherical indenters and mechanics of adhesive contact, a macro-scale method (the BG method) for non-direct determination of adhesive and elastic properties of contacting materials was proposed by Borodich and Galanov [1,2]. The method is based on a simple idea that at low loads the force-displacement curves reflect not only elastic properties but also adhesive properties of the contact and, therefore one can extract from the experiments both elastic characteristics of contacting materials (like the reduced elastic modulus) and characteristics of molecular adhesion (like the work of adhesion and the pull-off force).

Here the further developments of the JKR theory and the BG method are discussed: (i) the JKR theory is developed for the case of the non-slipping boundary conditions because it is more natural to assume that a material point that came to contact with the punch sticks to its surface [3]; (ii) the frictionless JKR model is generalized to arbitrary convex, blunt axisymmetric body, in particular to the case of the punch shape being described by monomial (power-law) punches of an arbitrary degree $d \geq 1$; (iii) it is shown that regardless of the boundary conditions, the solution to the contact problems for monomial punches is reduced to the same dimensionless relations between the actual force, displacements and contact radius; (iv) the results are extended for tested samples whose materials can be described by linear or linearized models having rotational isotropy of its mechanical properties [4, 5]; and (v) the BG method is extended to nanoindentation tests when the shape of the indenter can be described by monomial (power-law) function.

References

[1] Borodich, F.M., Galanov, B.A. (2008) *Proc. Roy. Soc.* A, **464**, 2759–2776.
[2] Borodich, F.M., Galanov, B.A., Gorb, S.N., Prostov, M.Y., Prostov, Y.I., Suarez-Alvarez, M.M. (2013) *Macromol. React. Eng.*, **7** (10) 555–563.
[3] Borodich, F.M., Galanov, B.A., Suarez-Alvarez M.M. (2014) *J. Mech. Phys. Solids*, **68**, 14–32.
[4] Borodich, F.M., Galanov, B.A., Keer L.M., Suarez-Alvarez M.M. (2014) *Mech. Mater*., 75, 34–44.
[5] Borodich, F.M. (2014) *Adv. Appl. Mech*., **47**, 225–366.

KEYNOTE LECTURE

Multi-scale and multi-field modelling and testing of photovoltaic modules

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Photovoltaics (PV) is one the most growing technology in the World for renewable, sustainable, non-polluting, widely available clean energy sources. To make it further sustainable and durable, unconventional simulation tools and experimental methods are required to effectively characterize and optimize the performance of PV systems subject to mechanical and environmental loadings. This is the main focus of the IDEAS Starting Grant "Multi-field and multi-scale Computational Approach to design and durability of PhotoVoltaic Modules" (CA2PVM) supported by the European Research Council.

The present lecture will present relevant project results regarding the development of a novel multi-physics computational tool integrating: (i) advanced structural mechanics models to compute the stress and deformation fields in PV laminates; (ii) geometrical multi-scale numerical schemes to solve thermal and moisture diffusion problems; (iii) nonlinear fracture mechanics formulations to simulate crack propagation in the solar cells; (iv) electric models to quantify the electric output of the device, also in the presence of Silicon cracks. Both traditional technologies based on mono- and poly-crystalline silicon semiconductors and innovative semi-flexible PV modules are targeted. The insight gained from the application of the proposed computational methods is validated in relation to selected experimental tests.

Size effect and its computational explanation by using strain gradient theories

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Mechanical response of a material is given by a material equation relating stress to strain for any geometries in any length-scales. Hence, materials behaviour is believed to be the same in macro- and micrometer length scale. Interestingly this assumption fails to be correct even for the engineering materials, like copper, aluminum, and steel. The change in mechanical response depending on the length-scale is called a "size effect". Various attempts in the literature exist to explain this phenomenon. We present a continuum mechanical formulation by using strain gradient theories and perform a variational formulation in order to generate a weak form. This weak form is then solved by using finite element method in space and finite difference method in time. Such a simulation allows us to comprehend the occurring size effect in a computational environment.

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Multi-scale indentation testing of composite materials

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Indentation technique has been proved very useful in testing mechanical properties of small material samples and, in particular, thin films. In recent years, the AFM indentation tests have been also applied for characterizing composite materials, for which new identification methods should be developed to take into account the effect of material inhomogeneity. In order to model the indentation test, the axisymmetric frictionless unilateral contact problem for a rigid indenter pressed against an elastic sample of finite size is solved by the method of matched asymptotic expansions. The first-order asymptotic solution is obtained in explicit form under the assumption of relatively small contact radius size. The influence of the sample shape on the incremental indentation stiffness is described in terms of the so-called asymptotic constant (extracted from the corresponding Green's function), which possesses information about the size of the sample and its geometry. By modelling the sample configuration as an elastic layer or a spherical inhomogeneity bonded to a rigid base or to an elastic substrate, one can study the corresponding thickness effect or the substrate effect.

JKR adhesive contact for a toroidal indenter — Application of the Method of Dimensionality Reduction

Ivan Argatov, Qiang Li, Roman Pohrt, and Valentin L. Popov*
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Contact mechanics, friction and adhesion play a key role in many technological and biological systems. Due to the non-linear nature of unilateral contact, the analytical treatment of associated contact problems proves to be difficult. The Hertz-type three-dimensional frictionless JKR (Johnson, Kendall, and Roberts) adhesive contact problem with a single controlling parameter is considered through a prism of the method of dimensionality reduction (MDR). In particular, the normal axisymmetric contact problem between a smooth toroidal indenter and a transversely isotropic elastic half-space is transformed to an equivalent problem of the indentation of a rigid punch with the equivalent profile into an elastic Winkler foundation. In the case of axisymmetric contact with a circular contact area, the equivalent profile is given by the MDR integral transformation. For all other shapes, including a generalized toroidal one, the equivalent profile is deduced from the solution of the elastic contact normal problem, which can be obtained numerically or approximately. A special case of a concave indenter, which produces an annular area of contact, is considered in detail.

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Testing the effect of humidity on properties of polymer and surfactant films: advantages and challenges of QCM-D approach

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The relative humidity (RH) of the air sets up the level of water activity in materials that are able to interact with water. The changes in water activity can cause phase and glass transitions in the non-porous materials and capillary condensation in porous materials. These changes strongly affect physical properties of the materials, including their mechanical properties and the ability to act as a barrier for diffusion of molecules present in the environment.

Quartz crystal microbalance with dissipation monitoring (QCM-D), including its humidity scanning modification (HS QCM-D), is an efficient method to study the effects of humidity on properties of materials. In the experiments, the materials are deposited on QCM-D sensor as thin films and the resonance frequencies of the sensors together with the dissipations are monitored as functions of relative humidity. Depending on film thicknesses and their rheological properties, different dependencies of frequencies and dissipations on overtone numbers are observed. From these dependencies, the film mass and the rheological properties can be derived. For example, in case of viscoelastic films in air, the negative normalized frequency shift is proportional to the square of the overtone number. In that case, using the procedure of extrapolation to zeroth overtone one can assess the size and rheology of the film and monitor their changes upon hydration. In many cases however, the frequency - overtone number dependencies are more complicated, influenced by film roughness, deposition technique and other factors. For the cases when the hydrated films exhibit more liquid-like than viscoelastic behavior, the established methods of film mass calculation do not work. In order to elucidate the effect of roughness on the resonance frequencies, we used ink-jet printing for depositing the material films on QCM-D sensors with specific geometrical patterns. The results show that the frequencies are dependent on the type of the patterns and their dimensions, which can be used to improve the accuracy of QCM-D experiments. The mathematical description of the resonance frequencies on the properties of the patterns is however not developed at the moment.

References

[1] Björklund, S., Kocherbitov,V. (2015) *Rev. Sci. Instrum*. **86**, 055105.
[2] Graf, G., Kocherbitov, V. (2013). *J. Phys. Chem*. B. **117**, 10017−10026.

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Effect of non-local interactions on steady-state crack propagation in one-dimensional lattice

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Various properties of materials arise from their structure on different scale levels. The application of a certain material might require the mathematical model that may grasp the qualities of material at the scale level and be suitable for making some predictions.

Being a complicated task for solids the problem of crack propagation is even more challenging if the material has a particular structure at some scale level. The technique to study steady-state crack propagation in a structured media was developed by Slepyan [1]. The results showed highly oscillating behaviour of energy release rate at low values of crack speed.

The present work shows theoretical results for the steady-state crack propagation in one-dimensional chain of oscillators with non-local interactions. The neighbouring oscillators are connected by linear springs while the non-local interactions are presented by linear springs between next to closest neighbour interactions. The analysis was based on the recent works of Slepyan and his colleagues [2-3].

The obtained results demonstrate that there are low values of crack speed that may provide its steady-state movement for some values of parameters of the model. That is different in comparison with the classic homogeneous model with local interaction. Moreover, for some parameters of the model the energetic characteristics of fracture process are qualitatively different from the case when the non-local interactions are absent. This, in turn, leads to the intermediate values of crack speed when it moves unstable.

The present work shows that the problem of steady-state crack propagation in structured media requires further study for the understanding of fracture process in solids in general.

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References
[1] Slepyan, L.I. (2012) *Models and phenomena in fracture mechanics*. Springer.
[2] Slepyan, L.I., Movchan, A.B., Mishuris, G.S. (2010) *Int. J. Fract*. **162**(1–2), 91–106.
[3] Mishuris, G.S., Movchan, A.B., Bigoni, D. (2012) *Multiscale Model. Simul*. **10**(3), 936–953.

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Testing of soft textured tapes by study of wave propagation and friction

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The motivation of this study was as follows. Last few years microstructured elastomer surfaces have received considerable attention from various fields of science due to their interesting adhesion, friction and wetting properties. In the context of friction, microstructured elastomer surfaces have become model systems due to their well-defined material and surface properties to understand the basic physical interactions and processes involved in the relative motion between two solid surfaces. Understanding friction of such soft, rubber-like materials is of great importance also for many technological applications such as the road-tire contact, windshield wipers, rubber seals, joint prostheses, climbing robots, industrial pick-and-place processes, but also for the understanding of e.g. animal locomotion, cell mechanics and skin friction. Microstructured surfaces usually show strongly reduced stick-slip behaviour during sliding friction if compared with an unstructured control surfaces made from the same material. Moreover, orientation-depended friction could be achieved by anisotropic microstructures and under lubricated conditions the space between surface microstructures can effectively act as drainage channels allowing for controllable friction in wet environments. However, not only surface microstructures can affect friction behaviour (such as precursor dynamics, transition from static to kinetic friction, and sliding friction), but also the subsurface material (e.g. elastic coupling between individual surface microstructures and subsurface architecture) and the actual experimental conditions. This may include, for example, the probe geometry during friction experiments and the detailed loading condition such as friction tests under fixed normal displacement or load. Even the stiffness of the experimental setup may influence friction behaviour. So far, during friction tests microstructured elastomer surfaces were usually fixed onto a rigid substrate, which allows only for shear deformations of surface microstructures and the backing layer, but not for stretching of the whole sample. In our study we present friction experiments soft microstructured tapes, which were adhered to a smooth and rigid substrate without any further constrain and subsequently one side of the tapes were pulled parallel to the substrate. This allows, in principle, the tapes to be stretched during shear motion, which is assumed to change the friction dynamics. Three different types of microstructured tapes were tested and their friction behaviour compared to results from numerical simulations of a simple block-spring model similar as introduced earlier.

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A simple but precise method for solving axisymmetric contact problems involving elastically graded materials

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The technological progress requires the development of high-technology materials. This class includes Functionally Graded Materials (FGMs) whose area of application ranges from biomechanics, tribology and optoelectronics to nanotechnology. Due to their optimized properties FGMs are associated with considerable cost. Therefore, mathematical models are needed as a basis of numerical simulations to predict the behaviour of FGMs. The spatial variation in the material properties is usually described by an exponential or a power law.

In this lecture we present an efficient method for solving axisymmetric, frictionless contact problems between a rigid punch and an elastically non-homogeneous, power-law graded half-space. One field of its application are contact problems involving the above-mentioned FGMs. Provided that the contact area is simply-connected profiles of arbitrary shape can be considered. Moreover, adhesion in the framework of the generalized JKR-theory can be taken into account. The method uses the fact that three-dimensional contact problems can be mapped to one-dimensional ones with a properly defined Winkler-foundation; hence, the method is to be understood as an extension of the method of dimensionality reduction (MDR). All the necessary mapping rules are presented and their ease of use explained by solving contact problems based on actual examples and up to now unsolved problems.

Estimation of hydromechanical parameters of lymphedematous tissue of limb using single or two chamber test

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Rational and effective application of mechanical therapeutic modalities (massage bandaging, elastic socks, etc.) for lymphedematous tissues (subcutaneous tissue under the skin) requires diagnosis of stage of lymphedema and knowledge of properties of the tissues. Moreover, the development of advanced therapy such as the intermittent pneumatic compression (IPC) requires this knowledge before appropriate parameters of IPC are determined.

The very basic hydromechanical characteristics of lymphedematous tissue treated as two-phase material composed of tissue matrix filled with interstitial fluid are parameters of elasticity of matrix and permeability [1]. From practical point of view simple and reliable methods which can be useful to identify such properties in vivo are needed. The large group of techniques which are developed for such studies are indentation or suction methods, however the drawback of these local techniques (techniques applied on relatively small area) is that the skin may play equally important role as subcutaneous tissue and separation of the influences is not a straightforward task. An alternative clinical technique which has been recently developed [2] in order to set IPC parameters is the two chamber inflation-deflation method. The important feature of such technique is limited role of skin. The aim of this work is to present a simple technique based on single or two chamber inflation-deflation method of testing circumferential changes of limb in time in order to estimate undrained elastic modulus and hydraulic permeability of lymphedematous tissue. The methodology is also useful in order to observe recoil effect, which is characteristic for tissue with edema.

References

[1] Kaczmarek, M., Olszewski, W.L., Nowak, J., Zaleska, M. (2015) The hydromechanics of edema fluid in lymphedematous lower limb during intermittent pneumatic compression. *Lymphat. Res. Biol*. **13**(4), 260–267.
[2] Zaleska, M., Olszewski, W.L., Durlik, M., Kaczmarek, M. (2015) A novel clinical test for setting intermittent pneumatic compression parameters based on edema fluid hydromechanics in the lymphedematous calf. *Lymphat. Res. Biol*. **13**(3), 208–214.

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Simulations of fretting wear for steam generator environment

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Fretting is understood as a special wear process that occurs at the contact area between two materials under load and subject to small relative motion by vibration or some other force. In nuclear power plant, fretting wear due to a combination of impact and sliding motions of the U-tubes against the supports and/or foreign objects caused by flow induced vibration, can make a serious problem in steam generator. In this research, the development of a test rig — fretting wear simulator — is demonstrated for the purpose of elucidating the fretting wear behaviour under actual conditions of steam generator in nuclear power plant, qualitatively and quantitatively. The realistic condition of steam generator of high temperature up to 300ºC, high pressure up to 15 MPa, and water environment could be achieved. The fretting wear simulator consists of main frame, control unit, and water loop system. Actual contact region under a realistic condition of steam generator was isolated using autoclave. Effects of various parameters such as the amounts of impact and sliding motions, applied loads and initial gaps and so forth are considered in this research. After the experiment, wear damage was measured by a three-dimensional profiler and the surface was also studied by SEM microscopically. Initial results show that the area of wear damage grows with an increase of normal loading, which means a qualitative agreement with actual situation.

Keywords: Fretting wear, steam generator, wear test rig, impact and sliding

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Mechanics on the microscale – AFM experiments and generalized continuum theories

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In the context of the static theory of elasticity for isotropic and non-simple materials, higher order continuum theories are widespread in modern continuum mechanics in order to model size-dependent deformation behavior that is experimentally verified. (Modified) Strain gradient-, micropolar-, couple stress- and surface theories [3, 4, 5] are used and constitutive relations are derived by following a cascade of principles of rational mecha-nics. Analytical solutions in the context of Bernoulli beam theory, as well as numerical im-plementation in terms of a finite element formulation is presented and solved with the help of the open-source Finite Element code FEniCS.

The engineering polymer materials epoxy and SU-8 have been investigated corresponding to the method of size effect described by LAKES (1995) [1]. Experiments with Atomic Force Microscopy (AFM) are presented and higher order material parameters, i.e. the material length scale parameter were obtained. Force and deflection data is recorded in order to measure bending rigidities of micro-sized beams of rectangular cross-sections. Forces F, deflections w, and thicknesses T are in the range of $0.5\ \mu N < F < 250\ \mu N$, $0.05\ \mu m < w < 8.0\ \mu m$, and $7.9\ \mu m < T < 170\ \mu m$, respectively.

As a result, positive and negative size effects are observed depending on the thickness and additional material parameters are extracted by the method of least squares between analytical solutions and corresponding experimental data. Whenever possible, a comparison to existing values from the literature, e.g. [2], is given.

Acknowledgments
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References

[1] Lakes, R.S. (1995) Experimental methods for study of Cosserat elastic solids and other generalized continua. In: Mühlhaus, H. (ed.) *Continuum Models for Materials with Micro-Structure*, pp. 1–22. Wiley, New York.
[2] Lam, D., Yang, F., Chong, C.M., Wang, J., Tong, P. (2003) *J. Mech. Phys. Solids* **51**, 1477–1508.
[3] Eremeyev, V.A., Lebedev, L.P., Altenbach, H. (2013) *Foundations of micropolar mechanics*. Springer.
[4] Bertram, A. (2013) *The mechanics and thermodynamics of finite gradient elasticity and plasticity*. Preprint, Univ. Magdeburg.
[5] Javili, A., McBride, A., Steinmann, P. (2013) *Appl. Mech. Rev*. **65**, 010802 (31 pages).

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Indentation testing of thin anisotropic collagen scaffolds

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Typical method to determine elastic properties of biological and other samples is based on micro-and nano-indentation procedures using the atomic probe microscope. Cantilevers equipped with hard indenters serve as sensitive tools allowing local testing of small and inhomogeneous samples like cells or tissues. To calculate the parameter of interest various models are used, but most of them are based on the Hertz model and extended to match the experimental conditions concerning the indenters' shape or the thickness of the sample. The existing models use isotropic approximation of the sample and typically allow measuring the averaged elastic modulus. But actual biologic samples like, for example, tissue samples or extracellular matrices (ECMs) are often highly anisotropic.

The typical indenters used for micro- and nano-indentation have axisymmetric (e.g., spherical or conical indenters) or centrally symmetric (e.g., pyramidal indenters like the Vickers indenter) shape therefore they measure effectively averaged elastic response in the contact plane. In order to obtain data about individual elastic modules of anisotropic material one should use an indenter which can sense the sample anisotropy, for example, cylindrical indenters with the axis parallel to the contact plane or ellipsoidal indenter (e.g., the Knoop-like indenter) with the large axis parallel to the contact plane. These examples are not limiting the possible shape of a suitable indenter.

Since indenter is sensing the substrate anisotropy then the force indentation curve depends on the angular position of the indenter. Thus, one can obtain the force indentation curves for several angular positions for each scanning point of the sample. In general, indenter may have several parameters and for each of them the force indentation curves may be determined. Of course, the sample angular position can vary with respect to the indenter. In this case one would have several force indentation curves for each chosen angular position but these curves may correspond to different points at the sample surface which is not an issue for a homogeneous material.

An indentation testing method, which utilizes lateral contact of a long cylindrical indenter, is developed for a thin transversely isotropic elastic film deposited onto a smooth rigid substrate. The so-called cylindrical lateral indentation test can be approximately modelled in the framework of the two-dimensional contact model for an orthotropic elastic strip. It is assumed that the material symmetry plane is orthogonal to the substrate surface, and the film thickness is small compared to the cylinder indenter length. The presented testing methodology is based on a least squares best fit of the first-order asymptotic model to the depth-sensing indentation data for recovering three independent elastic moduli, which characterize an incompressible transversely isotropic material.

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Simulation and optimization of textile membrane via homogenization and beam approximations

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The talk consists of two parts. In the first part we consider a new model for simulation of textiles with frictional contact between fibers and no bending resistance. One-dimensional computational model for hyperelastic string structures with Coulomb friction modeled by the Capstan equation are combined. The connection of this model with conventional hyperelasticity and Coulomb friction models is shown. Then, the model is formulated as a problem with the rate-independent dissipation, and proofs that the problem possesses proper convexity and continuity properties are provided. The talk concludes with a numerical algorithm, based on the Newton's method and provides numerical experiments along with a comparison of the results with a real measurement.

The second part of talk deals with optimization of the same textile-membrane, however in a framework of the linear elasticity with the linearized contact, modeled by Robin-(or Winkler-)type boundary conditions. The structures possess certain quasiperiodicity properties. Several research topics are combined in the talk: the homogenization approach together with beam models is applied to the problem of optimization of effective properties. The homogenization method is used to represent the structures as homogeneous elastic membranes and is essential for formulation of the effective properties optimization problems. Existing results for problems with Robin-type boundary conditions for thermal conductivity are extended to the case of elasticity. Some additional results, e.g. Korn's inequality for such structures and continuity of the effective coefficients w.r.t. the geometry design parameters were obtained. Further, optimization of the effective stress profile is considered. A beam approximation is used to reduce the cell problems to algebraic equations and obtain the derivatives of the effective properties symbolically. The adjoint approach is exploited for the PDE-constrained optimization problem resulting from the homogenization.

The theoretical results are illustrated on an example of a knitted membrane, used as a material for medical compressible stocking. The optimal micro-structure pattern along the leg is found to reach a target pressure profile on the leg.

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Coupled thermoelasticity and micro-scale elastodynamics

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It is known since the pioneering work of Danilovskaya in early 1950s that disregard of the thermal coupling can lead to distorted representation of the elastodynamic response, both qualitatively and quantitatively. Nevertheless, the relative weakness of the thermoelastic effect, awkward analytical structure of the coupled equations as well as their dual hyperbolic/parabolic nature meant that the work with coupled equations is scarce and mostly unconfirmed experimentally. This talk will be focussed on performing dimensional analysis of the classic coupled equations of the thermoelasticity with the Fourier conduction law. Natural small parameters will be identified and allow to perform an asymptotic analysis of the coupled equations in the stationary case. In the bulk all motions within a wide range of practically-relevant parameter values turn out to be approximately adiabatic. This allows one to formulate an asymptotic correspondence principle that relates a coupled thermoelastic problem to a simpler viscoelastic problem for an effective Voigt material. The associated dissipation is controlled by the natural small parameter that is vanishingly small at the microscale, but becomes important at micro- and nano-scale. Interestingly, we also demonstrate that in many practically-relevant situations the thermoelastic dissipation is actually not dominated by the bulk, but is mostly produced near the material boundaries due to the interaction with a strongly oscillatory thermoelastic boundary layer. The asymptotic modelling of the boundary layer is demonstrated using a variety of simple 1D model problems.

3-D contact problem of a transversely isotropic, transversely homogeneous biphasic cartilage layer

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The thin cartilage tissue which covers the diathrodial joints plays a central role in articular mechanics. The highly heterogeneous material by which it is constituted allows the bones to exchange forces with a substantial absence of friction and an advantageous distribution of stresses. The rapid solicitations to which the articulation undergoes are carried, in the short term, mainly by the self-pressurized fluid phase. Such constraint of the interstitial fluid and the shear stresses are instead ascribed to a structurally complicated solid matrix. The latter appears inhomogeneous both in stiffness and permeability.

Given the thinness of the cartilage layer with respect to the contact surface dimensions, solutions for the biphasic deformation problem have been traditionally obtained by means of asymptotic analysis. The closed-form analytical solutions for a homogeneous isotropic linear elastic solid matrix was studied by [1, 4], transverse isotropy was introduced later by [2]. Finally the effects of the complex microstructure composed of collagen fibrils and distributed porosity were taken into account through in-depth exponential inhomogeneity in [3].

Following the three-dimensional generalization of the axisymmetric contact problem by [5] which was applied to a homogeneous cartilage layer in [6], we study the integral characteristics for a transversely isotropic, transversely homogenous biphasic layer based on the constitutive equations provided in [3]. The cartilage is firmly attached to a rigid substrate shaped as elliptic paraboloid, the fluid phase is not allowed to flow through the confining surfaces.

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References
[1] Ateshian, G. A., Lai, W. M., Zhu, W. B., Mow, V. C. (1994) *J. Biomech.*, **27**(11), 1347–1360.
[2] Argatov, I., Mishuris, G. (2015) *Contact Mechanics of Articular Cartilage Layers*. Springer.
[3] Vitucci, G., Argatov, I., Mishuris, G. (2015) arXiv Preprint arXiv:1511.09379.
[4] Wu, J. Z., Herzog, W., Epstein, M. (1997) *J. Biomech*. **30**(4), 371–375.
[5] Argatov, I. I. (2004) *J. Appl. Mech. Tech. Phys.*, **45**(1), 118–123.
[6] Argatov, I., Mishuris, G. (2011). *J. Biomech.*, **44**(4), 759–761.

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Quasi-Static Elastic Impacts: The Influence of Friction, Adhesion and Viscosity

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The talk will deal with quasi-static oblique elastic impacts of spheres and their application in testing methods. The main task shall be the determination of both the normal and tangential coefficients of restitution as the solution of the impact problem. All three plain degrees of freedom are taken into account. However, rolling is only considered kinematically, i.e. its influence on the contact configuration is neglected. Also the influences on the contact/impact problem of plastic deformation, elastic dissimilarity and the change of the sphere position during the impact are considered negligible.

The influence of friction, adhesion and viscosity on the impact problem is studied both numerically and by comparison with experimental results. The numerical model is based on the Method of Dimensionality Reduction (MDR), for which the exact mapping of the axisymmetric contact problem with coupled elastic degrees of freedom (DOF) onto a plain problem with uncoupled DOF is possible for frictional or adhesive contacts with arbitrary loading histories, provided the validity of a local Coulomb friction law and the JKR-theory of adhesion can be assumed for the contact problem. The numerical model also easily adopts for viscoelastic material properties. Here, as an example, the standard solid as a model of the sphere material is studied in detail.

Due to the massive reduction of the problem's numerical and analytical complexity, achieved by the MDR, it is possible to give comprehensive solutions of the described impact problems for the complete parameter space. It is shown, that the solution of the impact problem, written in proper dimensionless variables, depends only on very few governing dimensionless parameters.

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