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Abstracts are in the order of the presentations

Fracture Performance of Annealed Additively Manufactured Structures

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Polymeric structures fabricated using Fused Filament Fabrication (FFF) suffer from poor inter-laminar fracture toughness. As a result, these materials exhibit only a fraction of the mechanical performance of those manufactured through more traditional means. Here we present a simple thermal annealing technique which dramatically increases the inter-laminar toughness of structures manufactured using the FFF technique. Single Edge Notch Bend (SENB) fracture specimens made from a variety of common FFF feedstock polymers (Acrylonitrile (ABS), poly-carbonate (PC), and ABS/PC blend) annealed across a range of times and temperatures were used to quantify the critical elastic-plastic fracture toughness of annealed structures. For all polymers tested, thermal annealing increased the inter-laminar toughness by at least an order of magnitude. In the best cause, the inter-laminar toughness was increased by a factor of approximately 30 over a non-annealed sample. Void coalition and migration during the annealing process was analyzed using X-Ray Computed Tomography and provides insight into the toughening mechanisms provided by the annealing process.

Investigation into Post Constrained Recovery Properties of Nickel Titanium Shape Memory Alloys

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In recent experimental investigation, Shape memory alloys (SMAs) exhibits a phenomenon wherein the material can be actuated, constrained from returning to its original geometry, and upon ceasing actuation, the Nickel Titanium (NiTi), the most widely used SMA, will continue to generate post constrained recovery residual stresses (PCRRS) which provides a new way for the material to be used as an actuator that may be beneficial to previous applications like self-healing material and could support new applications like using a dispersion of NiTi particles to inhibit fatigue cracking in material structures. This research aims to provide a detail experimental analysis of NiTi wire beyond its post constrained recovery residual stress (PCRRS) state by validating that this PCRRS can be generated in multiple NiTi formulations, by investigation of properties by straining NiTi from residual stress state to understand the stability of the phenomena and by analyzing the properties in cyclically loaded trained NiTi samples. As for both untrained and trained samples, NiTi displayed a reduction in residual stress magnitudes in each small strain cycles, however, this research pioneered the process of regeneration of residual stress from diminishing states by triggering the full thermal cycling. Regeneration of residual stress has the potential to stimulate new engineering design and applications.

Phononic metastructures as ultrasonic filters for nondestructive evaluation measurements

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Non-linear ultrasound, a nondestructive evaluation method that correlates micro-scale damage to second harmonic frequency generation, is plagued by high frequency noise present in experimental set up and signal generation. This project aims to eliminate noise around the second harmonic frequency using a phononic metastructure as an ultrasonic filter in non-linear ultrasound measurements. A Titanium structure with ultrasonic band gaps was designed using Finite Element simulation. The structure was additive manufactured and tested using contact transducers. Experimental and simulated results are compared. Applying ultrasonic filters to non-linear ultrasound measurements to improve early damage detection in metals is discussed.

Fundamental understanding of ultrasonic waves generated by shear-mode piezoelectric transducers

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Ultrasonic structural health monitoring methods present an opportunity to improve safety while reducing maintenance cost in engineering structures. Shear-mode (d35) piezoelectric transducers were used to generate and detect ultrasonic waves on thin plates and laminates. Finite element analysis were employed to explore the characteristics of propagating wave modes.

Vortex Dynamics of an Oscillating Hydrofoil for Energy Harvesting at High Reynolds Numbers

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A viable option for hydrokinetic energy harvesting is the use of an oscillating foil. To generate power during its sinusoidal stroke, a foil heaves vertically with an angle of attack relative to freestream that produces a vertical force positive power. It then repeats the the same energy generation mechanism on the downstroke, with a pitch reversal at the top and bottom of the stroke. The energy extraction potential from this sinusoidal heaving and pitching motion of an elliptical hydrofoil is explored through direct numerical simulations (DNS) at a Reynolds number of 1,000 and large eddy simulations (LES) at a Reynolds number of 50,000. The LES is able to capture the time-dependent vortex shedding and dynamic stall properties of the foil as it undergoes high relative angles of attack. At a reduced frequency of fc/Uinf = 0.1 the high Reynolds number has a 1.4-3.6% increase in power compared to the low Reynolds number. The vortex formation and shedding downstream have a major role in the power generation as both are directly affected by the frequency, pitch angle and heaving amplitudes of the oscillating foil. These organized vortical structures of the wake in terms of vortex location and strength are analyzed for future multiple-foil array configurations via a vortex tracking algorithm.

Numerical and Experimental Investigation of Ice Adhesion using the Blister Test

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A fracture mechanics based approach is proposed for in situ characterization of the interfacial fracture energy of ice on different substrates. This presentation summarizes the development of the experimental and analytical framework to measure the ice adhesion energy. The testing configuration utilizes a shaft-loaded blister test to produce stable crack propagation, from a well-defined pre-crack at the interface of the ice layer and the substrate. The developed analytical framework to estimate the ice deformation configuration and the adhesion energy are verified and calibrated via finite element numerical simulation of the proposed geometric configuration and employing cohesive surfaces along the interface to simulate the crack nucleation and propagation process. Several different phenome were observed including the transition from adhesive to cohesive fracture and the formation of surface cracking.

Quantitative Evaluation of Bonding Strength of Thin Films Using Peel Test

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Bonding strength of thin films is mostly evaluated qualitatively through assessment of failure mode of bonding. This work is focused on the measurement of bonding strength of thin films using a precise peel test design. To perform the experiment, a thin layer of plastic paint is attached to Teflon (PTFE) substrate.

Utilization of Asymmetric Beam Test for Characterization of Ice Adhesion

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Aircraft and Wind turbine operating in a cold environment are challenged with icing which unfavorably affects their aerodynamics and degrades their safety. Precise characterization of the ice adhesion is crucial for the effective design of ice protection system. In this paper, a fracture mechanics-based approach incorporating asymmetric single cantilever beam test is used to characterize the interfacial fracture of a typical ice/aluminum interface with different surface roughness. The measurements showed adhesion/cohesive interfacial fracture energy values between 0.16 and 1.1 J/m 2. In this asymmetric beam test, a thin film of ice is formed between a fixed and elastically deformable beam subjected to the applied loading. The inspection of the interfacial ice fracture surface using fracture surface replication technique highlighted the association of the fracture mode with the measured macroscopic fracture toughness. The higher level of fracture toughness was associated with cohesive interface failure. While the lower level of fracture toughness on smoother surfaces was associated with adhesive interface failure.

Atomistic-Continuum model for 2D multi-layer materials

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2D nanomaterials exhibit surface corrugations (wrinkles and ripples) and crumples either during manufacturing or while using them. These corrugations can modify their electronic structures, band gap, photo luminescence intensity and other electrical and optical proper-ties. Moreover, reversibility of these properties on undoing the mechanical deformations has also been seen. This research focuses on providing a qualitative prediction of configurations of these 2D materials under different loading conditions. A combination of highly desirable properties made mono and multi-layer graphene a wonder material and has also inspired numerous and diverse applications. Recently, other 2D materials and their compounds

have also gained attention, with special focus on transition metal dichalcogenides (TMD). Despite tremendous growth in research activities both in experiments as well as in small-scale simulations on two-dimensional multi-layer materials (2DMMs), still there is no predictive modeling framework at the experiment or device level. The proposed model which acts as a bridge between atomistic and continuum physics can fill this gap and provide more insight to understand the behavior of 2DMMs. Already existing purely atomistic models (DFT, MD) are highly reliable but highly computationally demanding. This restricts length scale of simulations. Whereas, continuum models which are extremely fast, disregard the atomistic physics in these 2DMMs. Proposed atomistic-continuum model obtain energy potentials from bond stretching and change in bond angles in terms of continuum variables. The objective here is to develop a predictive model for 2D multi-layer Materials by deriving crystal elasticity based constitutive relations through Cauchy-Born rule of 2D films for single (graphene) and multi atom thick (MoS2) single layer 2D materials. This model then will be used to predict and understand the deformations of 2D multi-layer materials.

Effects of Cut Boundary Location on Finite Element Submodeling: The Case of a Deformable Block

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Large or complex structures such as gas turbine engines pose challenges when computational solutions are desired. This is due to the costs associated with creating complex models to obtain accurate results. Luckily, there are methods to alleviate this; one such method is submodeling. To utilize submodeling, a model of the entire structure with a coarse mesh is first solved. This is called the “global” model. Then, a super-refined model is created just of the feature of interest (e.g. the contact interface on a turbine blade). This is called the “submodel”. Boundary conditions extrapolated from the global model are applied to the cut boundaries of the submodel and the submodel is then solved. Where the cut boundaries are located can drastically affect the solution of the submodel. This work looks at how the locations of the cut boundaries affect the solution of an elastic, “deformable” block pressed onto a rigid half plane where the feature of interest is the contact interface between the structures.

Temperature effects and matrix-scale material properties of an elastomeric open-cell foam

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Elastomeric polymer foams are often used for impact protection in field equipment that experiences a wide range of temperatures. We have recently conducted experimental work and developed a material model for the quasi-static response of a novel polyurethane-base open-cell foam (Poron XRD, Rogers Corp.). To measure the effect of temperature variations akin to those experienced in practice, we now report macro-scale indentation experiments conducted in temperatures ranging between -10 degrees C and 55 degrees C, which will be used to include temperature as a model parameter. In addition, we describe room-temperature nanoindentation-based experiments to quantify the material properties of the matrix polymer. This data serves as secondary calibration data for the continuum-scale material model mentioned above and input for computational experiments to follow.

Poroviscoelastic (PVE) Damping Tuned by Interfaces: Application to Passive Vibration Absorbers

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Passive damping mechanisms employed in traditional methods of vibration attenuation lack broadband effectiveness. Fluid exudation and associated viscous dissipation is one of those damping mechanisms effective in various damper designs such as squeeze-film dampers and fluid-swollen open-cell foams. In those common dampers, the amount of dissipation is proportional to the strain rates, and hence the bandwidth of optimal damping is restricted to high frequencies. This study is an effort to extend this bandwidth to lower structural frequencies. This is achieved through localizing the fluid-exudation in poroviscoelastic (PVE) materials, and tuning diffusion time-constant to the structural modes of a passive host-absorber system. In particular, punch-like indenters are used to confine the diffusion to the vicinity of the interface with reticulated polyurethane and polyethylene foams swollen with various liquids. By adjusting the interfacial length scales, the diffusion time-constants of these PVE dampers are tuned to the modes of the host-absorber system within 100 Hz. The PVE dampers designed this way exhibit optimal damping performance, and enable vibration suppression of the structural modes. These results confirm that bandwidth of optimal viscous dissipation can be tuned through interfacial lengths. This tuning method could passively achieve desired damping variations within a frequency range of interest. When combined with semi-active methods, the same tuning methodology can yield unprecedented bandwidth of optimal damping.

Highly tunable dynamic response of vertically aligned carbon nanotube foams

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The vertically aligned carbon nanotube (VACNT) foams are synthetic hierarchical materials with unique gradient functional properties that makes them excellent candidates to be used in extreme applications where energy or impact absorption is needed. When compressed, they exhibit strain localization and sequentially progressive buckling that result in a nonlinear hysteretic stress-strain response. They also have the ability to recover near-completely from large strains upon unloading. Though numerous studies have examined their quasistatic behavior, the mechanical properties of VACNT foams subjected to continuous harmonic excitations remains elusive. We study the dynamic response of VACNT foams under harmonic excitations at amplitudes up to 1.5 μm for the linear regime and up to 45 μm for the non-linear regime, over a broad frequency range (1 to 2,000 Hz). We observe a non-linear increase in damping and dynamic modulus with increasing excitation frequency that is a result of the density gradient and progressive buckling in the samples. Their response is also amplitude dependent, with a decrease in stiffness as the excitation amplitude is increased. We also show that their dynamic properties are nonlinearly tunable as a function of an applied static precompression. Values observed for tan δ at different frequencies exceed those observed in common materials such as rubbery polymers or closed cell foams at the same frequencies while maintaining values of stiffness several orders of magnitude higher than these materials. The highly tunable damping and stiffness of the VACNT foams will enable potential applications in active damping and energy absorption.

Application of Multiscale analysis techniques in continuous and discontinuous fiber-reinforced composite materials to investigate the failure induced by microscopic instability phenomena

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Failure induced by fiber microbuckling is a frequent failure mode in continuous and discontinuous fibers composite materials subjected to compression along the fibers direction. As a matter of fact, this failure mechanism may lead to a notable decrease of the compressive strength of composite materials, especially in presence of multi-axial loading conditions which may provide destabilizing effects, and may also induce the initiation and propagation of cracks at the micro-structural level, which, in coupling with buckling instabilities effects, may leads to a premature collapse of composite materials. In some recent studies the combined effects of different microscopic failure modes (fracture, damage, instability, for instance) on the overall response of a composite material under large deformations have been analyzed, showing that a detailed microscopic continuum analysis with an appropriate representation of different sources of nonlinearities is usually required, at the expense of a very large computational effort. In order to avoid a direct modeling of all microstructural details of the composite solid, at least in areas where no collapse mechanisms are incipient, multiscale techniques can be adopted. As a matter of fact, multiscale techniques, also used in coupling with first-order homogenization schemes, may overcome some limitations characterizing first-order homogenization approaches but additional investigations are required, however, in order to accurately analyze the influence of different (and eventually interacting) microscopic failure phenomena on the macroscopic behavior of a composite solid in practical applications, where the hypotheses of scale separation and of a periodic arrangement of microstructural failure mechanisms (instability, localization, fracture) cannot be assumed and boundary layer effects may arise. To this end, in the present work, two multiscale approaches to predict the instability-induced failure behavior of locally periodic composite solids subjected to large deformations are proposed and their effectiveness is investigated. This aspect is particularly important since, in many practical applications of composite materials, perfect periodicity does not hold and the composite solid can be assumed only locally periodic, namely micro-to-macro scale length ratio may be considerably larger than zero.

Instabilities in Hyperelastic Fiber Composites

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Fiber reinforced soft composites are of great interest because of their desired properties- high strength, large deformation levels and light weight. Instabilities and failures associated with fiber reinforced composites (FCs), sets a threshold on the application of the compressive strains. In particular, the phenomena of local buckling or loss of stability is considered on par with the failure due to delamination in FCs. In the presentation, I will discuss the effect of strain stiffening of fiber on the instability parameters. I have used Bloch-Floquet analysis to determine the onset of instabilities in periodic FCs with hyperelastic constituents. Critical strains, wavelengths and buckling modes are observed to be highly tunable by variation in strain stiffening parameter of fiber, at given material composition. This investigation can have a potential use in the design of FCs with controlled switching of geometric properties.

A generalized superelliptic void microstructure mapping for topology optimization

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There has been a recent interest in High-resolution Topology Optimization (HTO), enabling unprecedented details in the design. However, the computational cost in HTO can be massive. An alternate approach is to rely on Multiscale Topology Optimization (MTO) where microstructures are optimized at a smaller scale, while simultaneously optimizing the structure at the macroscale. The two scales are linked through homogenization theory. In MTO, instead of optimizing microstructures along with macroscale optimization, we use parameterized single-void Vigdergauz-like microstructure and homogenize it for various values of these parameters first. Later, these parameters and a rotation variable are used for optimization of the structure for stiffness. This work is similar to the rectangular-void microstructure optimization but the difference lies in the parameterization of the void. Instead of having a rectangular void, here we use a generalized superelliptical void which encapsulates the possibility of a rectangular void as well. To ensure connectivity, microstructures are mapped over an auxiliary field dictated by the optimized rotation variable. Finally, the analysis is carried out over mapped microstructures. Numerical experiments are performed for both 2D and 3D design domains to show the merit of the proposed parameterized microstructure. Various advantages along with existing challenges and future research will be discussed.

A coupled chemo-mechanical theory for high temperature oxidation in polymers

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High temperature oxidation in polymers is a strongly coupled, highly nonlinear and complex process which limits the use of polymeric materials in several aerospace and defense application as it causes significant performance degradation. The coupled diffusion-reaction process that occurs during thermo-oxidation together with the macromolecular network behavior and finite viscoelasticity of a polymer require a time, temperature and oxidation dependent constitutive law to predict the mechanical response of the material. Therefore, a thermodynamically consistent thermo-chemo-mechanically coupled constitutive model is formulated in this work and implemented in finite element method by writing a user element subroutine in ABAQUS/Standard (2017).

Elastomer Cutting: Radius, Constitutive Response, and Rate (Keynote)

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Materials that exhibit crack-blunting during tearing-induced failure have a higher-than-expected strain energy release rate for a given modulus. Thus, though local failure response governs crack propagation, non-linearity modifies its effect. To understand the consequences of this interplay, we take the approach of controlling crack tip geometry through cutting. However, no quantitative link exists between cutting and traditional far-field tearing energies. Using a unique, friction-eliminating cutting test, we demonstrate the separability of cutting and tearing contributions as a step toward relating cutting and tearing failure modes. We apply both experimental and finite element approaches; the latter results in an ABAQUS method to compute the J-integral for a loaded crack front.

We utilize a Y-shaped cutting geometry first introduced by Lake & Yeoh (1978). In this geometry, we translate a pre-`notched' sample toward hold a load-cell-mounted razor blade. The 'legs' forming the notch are held clear of the razor blade by hanging weights that constant angle between—and load on—the legs. Increasing the leg angle induces a tearing force on the crack tip. We calculate cutting energy using the maximum value of the cutting force within the steady-state response.

Several key results follow. We find that strain-stiffening, a material parameter governing blunting during tearing, qualitatively scales with cutting energy's sensitivity to blade radius for blunter blades. Conversely, for sharper blades the shear modulus scales with an 'intrinsic' cutting energy value that emerges as a plateau in the cutting energy at small radius. We explore the origins of the latter using low-defect silicone elastomers and samples with tunable interfacial bond density. We also construct a new J-integral calculation method to demonstrate the separability of cutting and tearing energy contributions in simulated tests. We compare these simulations to experiments. Through this work, we aim to provide insight and stimulate discussion on soft fracture.

Characterization of Shear Wave Speed-Stress Relationship in Collateral Ligaments

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About one in five patients are not satisfied after total knee arthroplasty (TKA). With current predictions for the number of TKAs performed annual in the United States, this amounts to around 700,000 patients per year that are not satisfied. Overly tight collateral ligaments, which can contribute to pain and stiffness, are one complication linked with patient dissatisfaction. We are investigating the use of shear wave tensiometry, a non-invasive approach for gauging axial stresses in soft tissues, to identify and correct overly tight ligaments. The purposes of this study were to (1) determine whether the shear wave speed-stress relationship, which has been demonstrated in tendons, extends to ligaments, and (2) compare load-dependent wave speeds between the lateral and medial collateral ligaments (LCL and MCL), which exhibit substantially different cross-sectional geometries. Three LCLs and three MCLs were subject to cyclic loading between 30 and 300 N and wave speeds were computed using the time delay in wave arrival measured using two laser vibrometers. There were moderately strong linear relationships between squared shear wave speed and stress in both the LCL and MCL (R2 = 0.67 and 0.65, respectively). The slope of the linear fit was significantly greater in the MCL (2.15 m2/s2/kPa) than in the LCL (1.87 m2/s2/kPa), ($p < 0.0001$). The findings of this study suggest that the shear wave speed-stress relationship may vary between the LCL and MCL. Moving forward, results from this study can be used to better interpret stresses in collateral ligaments from in situ shear wave speed measurements. Overall, these findings motivate the further development of an intraoperative sensor to guide ligament balancing in total knee arthroplasties with the ultimate goal of improving surgical outcomes and patient satisfaction.

Modeling ACL constitutive behavior with full-field methods

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Anterior cruciate ligament (ACL) tears are associated with the development of osteoarthritis and typically require surgical reconstruction. Computational models provide a valuable platform for evaluating potential injury risk factors and reconstruction techniques, but constitutive models currently lack the fidelity necessary to predict three-dimensional material deformation. My work has shown why standard constitutive modeling methods (e.g. curve-fitting global stress-strain curves) are inadequate for accurate material characterization, and how full-field displacement mapping in conjunction with full-field inverse methods overcome the limitations of standard techniques.

Comparison of mechanical parameters in the lean and obese type II diabetic rat urinary bladder

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Diabetic patients experiencing symptoms of neuropathy can develop a neurogenic bladder, also known as diabetic cystopathy. Loss of connection between the urinary bladder (UB) and nervous system dulls the sensation of fullness in the UB, leading to chronic over-distension. This type of volume overload has been shown to cause an increase in compliance and elastin content, thinned walls, and inflammation. In order to characterize how this remodeling affects the mechanical behavior of UB tissue, uniaxial ring tests and histological analyses were performed on both lean and obese type II diabetic rat UB's. Specifically, we used Goto-Kakizaki (GK, lean diabetic, Wistar as control) and Zucker diabetic fatty (ZDF, obese diabetic, lean littermate as control) rat models. Stress-strain data from these tests were then fitted to an isotropic, exponential material model to compare parameters across the groups. Our results show that in both the lean and obese models, there is an increase in compliance in the diabetic, compared to the control. Namely, parameters specific to compliance at low stresses were higher in the diabetic samples. Additionally, the ZDF bladders showed increased compliance compared to the GK's in both the control and diabetic cases. Ongoing histological analyses show a potential increase in elastin content, changes in collagen structure, and increase in mast cell activation in ZDF diabetic bladders compared to controls. Both lean and obese (GK and ZDF) type II diabetic models show signs of UB remodeling, but changes seem to be exacerbated in the obese.

Rate-dependent crack nucleation in cartilage

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Rate-dependent crack nucleation in cartilage under microindentation was investigated with a poroviscoelastic framework and nano/microscopic images. Localized crack failure was created at known locations and at different loading rates via microindentation with an axisymmetric sphero-conical indenter. Finite element modeling was used to reproduce results of microindentation tests. Scanning electron microscopy was used to investigate nano- and microscale structural features of crack surfaces. Results indicated that the solid matrix in the vicinity of the tip underwent relatively large relaxation at the slow loading rate in comparison to the fast loading rate, delaying crack nucleation.

Length Scale Effects in Fibrous Materials

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Physical cues from a cell's environment, such as stiffness, affect cell migration, proliferation, and gene expression. The extracellular environment is composed of many fibrous constituents, the most common being collagen I. At the scale of bulk material, the environment can be modeled as a nonlinear continuum. At scales approaching that of a cell, mechanics caused by fiber rotations and realignment cannot be accounted for by classical elasticity. Here, we propose using Micropolar Elasticity to model the behavior of such networks. The micropolar model accounts for local rotations of fibers by including characteristic length scales, which are typically related to an inherent length of the materials such as the average fiber length. Classical elasticity does not account for any length scale effects. We primarily investigate bending of fibrous networks under small strain and linear assumptions. We observe the material stiffness increasing by an order of magnitude as scale decreases, consistent with micropolar theory. The characteristic length in bending is found to be similar in magnitude to that of the average fiber length of a network. Additionally, we investigate torsion and Hertzian contact of fibrous networks also under small strains. Both display similar trends of stiffer networks at length scales approaching that of a fiber length. We argue that a micropolar model can explain mechanical response of random fiber matrices in this linear range. These mechanics would affect the mechanosensing of cells within them and ultimately, the cell's response.

Quantifying Mechanical Strain in CPVT Stem Cell Derived Cardiomyocytes

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Catecholaminergic polymorphic ventricular tachycardia (CPVT) is characterized by an arrhythmogenic mechanism involving disruption of calcium handling. This genetic disease can result in arrhythmia leading to sudden death in children and young adults during physical exercise or emotional stress. Prior CPVT studies have focused on calcium handling, but mechanical functionality has rarely been investigated. Using a patient iPSC line with RyR2-H2464D mutation and control line from the patient's mother, contractile functionality was quantified by evaluating contractile strain. Engineered culture substrates with stiffnesses ranging from 5 kPa to 50 kPa were used in conjunction with microcontact printing to control placement of ECM proteins into defined patterns. Brightfield videos of spontaneous contractions were captured and evaluated using Digital Image Correlation. The contractile strain of the patient line was found to be higher across the range of stiffnesses, and the difference was statistically significant on 30 kPa and 50 kPa substrates.

A diffuse interface framework for modelling the evolution of multi-cell aggregates as a soft packing problem driven by the growth and division of cells

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We present a model for biological cell growth, division and packing under soft constraints that arise from the deformability of the cells as well as of a membrane that encloses them. Understanding the processes underlying the formation of these aggregates is central to many phenomena in cellular biology and physiology, including embryogenesis, regeneration, wound healing, tissue engineering, and the growth and metastasis of cancerous tumors .Our treatment falls within the framework of diffuse interface methods, under which each cell is represented by a scalar phase field and the zero level set of the phase field represents the cell membrane. A key feature is the implementation of a free energy density function which captures cell-cell contact and adhesion. In order to properly represent cell packing and this associated free energy, we include a simplified representation of the anisotropic mechanical response of the underlying cytoskeleton and cell membrane through appropriate penalization of the cell shape change. Numerical examples are presented to demonstrate the evolution of multi-cell clusters, and the total free energy of the clusters as a consequence of growth, division and packing.