Final Report Summary - BIOMECH (Nonlinear solid biomechanics: theory, experiments, computations, applications.)

Project objectives, work performed, main results, and expected final results

The overall scientific aim of the Project was to improve understanding of the nonlinear mechanics of soft biological tissue such as arterial wall tissue, brain stem, or skin, with particular reference to the influences of residual stress, of inhomogeneity, of anisotropy, and of external fields (e.g. electromagnetic) on the mechanical response and on stability. More specifically, the initial project had identified five explicit objectives.

(i). Develop elastic and viscoelastic anisotropic constitutive laws to model a variety of biological soft tissues, including arterial walls, brain matter, and skin;
Much effort was devoted to the derivation of reasonable models. We conducted a series of experiments, coupled to theoretical developments, to test the validity of existing constitutive laws. First, we disputed the physical soundness of the model used by the commercial Finite Element software package ABAQUS for nonlinear viscoelasticity. We wrote a paper highlighting that flaw [Rubber Chemistry and Technology]. We also contacted the company (now SIMULA, Dassault Systèmes); they subsequently changed their model of nonlinear viscoelasticity, see below. This very concrete consequence of our research puts all the former simulations relying on ABAQUS into question, especially when we appreciate that, presumably, many public decisions of civil or biomedical engineering relevance may have been taken based on a model which is now obsolete. In the emerging field of elastography, nonlinear elastic models are in great demand, especially in respect of biological soft tissues. They usually rely on the so-called weakly nonlinear elasticity theory. However, the modelling of soft tissues requires the inclusion of the constraint of incompressibility, which is not well developed in that theory. Using the framework of Finite (Exact) nonlinear elasticity, we wrote three papers on the effect of incompressibility on the weakly nonlinear results of acoustoelasticity, anisotropic laws, and elastic constants [Journal of the Acoustical Society of America]. The major applications in this area are in medical imaging, where current ultrasonic devices rely on algorithms based on simple linear models. The inclusion of incompressibility into models of weak non-linear elasticity will lead to a better resolution and contrast between soft (healthy) and stiff (tumour) tissues. A new project is currently underway to carry out experiments on human skin and phantom gels based on this new knowledge, see Objective (v) below.

(ii). Analyze the influence of residual stress in soft tissues on their mechanical, and design simple experiments to quantify residual stresses;

Residual stresses were studied in great depth. First, we established results for the existence, uniqueness and stability of deforming a sector of a circular cylindrical tube into an intact tube. This deformation is often used to quantify residual stresses in an artery, through the so-called opening angle method (when an artery is sectioned, not only does it shrink in length and diameter, but it also opens up). We designed simple experiments with soft silicone sectors, and obtained good agreement with the theory, see picture [Int. J. Engineering Science]. Next, we studied theoretically the propagation of mechanical acoustic waves in residually stressed solids, with a view to assess the residual stresses through the measurement of wave speeds. This work will have serious repercussions in biomedicine as until now, the evaluation of residual stresses has relied on destructive methods of testing. Experimental work is under way to measure the speed of surface waves in brain matter and skin, see also Objective (v) below.

(iii). Model and test experimentally the response of biological soft tissue adaptation due to changes in an applied electro-magnetic environment;

The coupling of Maxwell laws with the equations of continuum mechanics poses a challenging and sophisticated problem. We managed to reconcile the Lagrangian approach used to describe the mechanical fields in a deformable solid with the Eulerian approach favoured for the description of the electric and magnetic fields. We also considered wave propagation in finitely deformed magneto-sensitive elastomers [Mathematics and Mechanics of Solids]. It is planned to test the hypotheses against calibrated and repeatable experiments at Tufts University. The long-term objective is to provide a sensible model for
the sensitivity of brain matter to applied external electro-magnetic fields, with obvious public policy implications.

(iv). Formulate and solve prototype boundary-value problems and elastic stability problems and compare the predictions with available and acquired experimental data;

An early focus of the project was on the mechanics of bending, because it is such an ubiquitous mode of deformation for biological soft tissues. Experimental, numerical, and theoretical advances were reported in four publications, and contact was made with Professor A.E. Wood from the National Center for Cardiothoracic Surgery, a specialist in homograft heart valve replacement. He is very interested in testing the mechanical properties of human heart valves, for which he would have ethical approval. A testing machine was devised during a Final Year Project at UCD, and it is now part of a MSc project. We plan to test the mechanical properties of cling film soon, and then porcine and bovine heart valves, before we go back to Prof. Wood. The results coming out of this blend of theoretical and experimental research could prove crucial to heart valve surgery. Another prototype problem concerns the buckling of a thick column, where we obtained explicitly the nonlinear correction to Euler formula in the hinged-hinged configuration [Proc. Roy. Soc. A] We were also interested in torsion instability, with a view to model the tortuosity of veins and the torsional buckling of arteries. A Final Year Engineering student worked on this problem and devised a rig for the force/moment/twist measurements of silicone rods.

(v). Analyze the response of skin to puncture, using theoretical, experimental, and numerical approaches, with a view to applications in forensic science.

For this Objective, a doctoral funding was secured, jointly supported by the Irish Research Council for Science, Engineering and Technology and by the Irish Department for Justice, Equality, and Law Reform. This is the first time that such a joint effort is put in place by these two independent governmental bodies. Moreover, strong links were developed with a research laboratory in Lyon, France, with several visits and planned experiments taking place. The modelling of the mechanical behaviour of human skin and of porcine skin advanced at a very good pace. The Irish State Patologist Prof. Marie Cassidy is a high-profile public figure in Ireland, and is deeply involved in the project, which aims at providing a way to quantify the amount of force used in a blade wound. Moreover, the research undertaken by the PhD student has received national exposure with an article in the Irish Independent; has received dual agreement from University College Dublin and from Université Pierre et Marie Curie-Paris6 for the deliverance of a Joint PhD diploma; and has been awarded a Pierce Malone Scholarship in Engineering from the National University of Ireland. There is also an ongoing collaboration with the Department of Physics at the University of Limerick, to use Optical Coherence Tomography in order to visualize in vivo and in real time the mechanical response of the human skin to acoustic wave propagation, see also Objectives (i) and (ii).

Related documents

Microsoft Word - periodic-report-IEF-destrade.doc