DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
Prof. Pietro Gambarova

Objectives of the Doctoral Program

Structural, Seismic and Geotechnical Engineering - SSGE consists of the disciplines and techniques that allow to understand, model and control the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials and materials for micro-systems), (b) structural systems (from constructions to bio-mechanical systems and micro-systems), (c) soils, and (d) environment-construction interaction. Being deeply-rooted in Civil Engineering, which is – by its own nature – highly inter-disciplinary, SSGE focuses also on the environmental actions, either external (like earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction (like those caused by retained-earth thrust, landslides and water-table fluctuations). Because of their generality in materials and structural modeling, the methods developed within the domain of SSGE are very advantageous also in other technical-scientific domains, whenever understanding and controlling the mechanical aspects are necessary to guarantee both design reliability and structural safety, serviceability and durability. Many are the examples of the issues typical of SSGE: from tall buildings and bridges to industrial bio-mechanical and micro-electromechanical systems, from off-shore structures and dams to the rehabilitation of monumental buildings, from seismic design and structural dynamics to slope stability, tunnel behavior and foundations, not to quote many issues that are in common with several branches of Industrial Engineering. Within this context, the primary objective of this Graduate School is to favor the advancement of the knowledge, with reference to: (a) innovation in materials and structures; (b) building safety under highly-variable actions; (c) soil and surface/buried structure stability; and (d) biomechanics, that is a key aspect of industrial bio-engineering.

This objective is pursued by giving the PhD Candidates an advanced, research-oriented formation, based on the pivotal role of Structural Engineering and on the multi-disciplinary nature of Seismic, Geotechnical and Bio-Mechanical Engineering.

Contents of the Doctoral Program

The Candidates are offered several advanced courses on a variety of topics concerning materials and structural mechanics, computational and experimental methods, and structural reliability, the focus being always on both basic issues and engineering applications. As a consequence, great attention is given to many fundamental topics still highly-debated within the scientific community, and to many application-oriented topics, that are of direct interest for the public and private industry,

for the designers and for the institutions dealing with structural safety and reliability, and with the environmental impact of the structures.

The study plan includes courses and seminars given by scientists, experts and researchers active either in the Politecnico or in other Italian and foreign universities, research institutions and high-tech firms. The study plan (180 credits) is divided into 4 phases:

1. Propaedeutic formation (0-20 credits, 1st year), based on courses borrowed among the MS courses ("Laurea Magistrale"), with the objective of giving a common scientific basis to the PhD Candidates coming from different schools.

2. Basic, research-oriented formation (40 credits, 1st and 2nd years) consisting of 5-credit courses to be taken by the Candidates, to complete and enrich their scientific formation. These courses are focused on the most relevant topics debated within the scientific community, in the domains of materials and structural mechanics, structural dynamics and seismic engineering, soil mechanics and research management.

3. Specialized, research-oriented formation (10-30 credits, mostly in the 2nd year), based on a variety of opportunities offered to the Candidates: (a) short courses, and (b) series of seminars given by either internal or external faculty members, as well as by researchers from the industry, from the Society of the Engineers and from public institutions; and (c) short courses offered by well-known scientific institutions, like CISM - Int.

Center for Mechanical Sciences (Udine, Italy), IUTAM - Int. Union of Theoretical and Applied Mechanics (Summer Schools in different places in Europe), Rose School (Pavia, Italy) and JCR – Joint Research Center (Ispra - Varese, Italy). The Candidates are also suggested to attend the short courses organized by other Doctoral Schools, at the Politecnico or at nearby universities (Politecnico di Torino, Universities of Genoa and Brescia, ...).

4. PhD Dissertation (110 credits), whose preparation (in English) is a pre-requisite for being admitted to the final examination. The dissertation should contain original results concerning relevant and actual engineering problems, with reference to basic topics or to applications and technology. The preparation of the dissertation consists of different phases, whose results are presented by each Candidate at the end of the 1st, 2nd and 3rd year, in specific workshops, open not only to the Faculty and to the PhD Candidates, but also to the members of the Advisory Board and to all interested scholars.

To earn credits and to start or to refine their dissertation, the Candidates are highly suggested to spend a period abroad, in one of the universities or research centers that have systematic scientific relations with the Politecnico di Milano. At the same time, the PhD School favors the visit of foreign scholars, to give short courses in Milan. In this way, the Candidates are offered a number of opportunities to interact with the international community.

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ADHESION IN POLY-SILICON MEMS
Experimental Characterization and Numerical Modeling

Leonardo Baldasarre

STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

MEMS (Micro-Electro-Mechanical Systems) are mechanical transducers: they convert a nonelectrical signal, such as acceleration, magnetic field or pressure, into an electrical signal or vice-versa they transform an electrical signal into a mechanical work, such as movement, pressure or vibration, by means of a micro-scale coupled electro-mechanical mechanism. Very often a mechanical part is suspended and a large portion of free surface interacts at a very small separation distance. Otherwise negligible, in this situation the spontaneous adhesion forces are so strong that they can endanger the functionality of the device. This MEMS reliability issue, also known in literature as **stiction** (static-friction), is one of the main constraints for newer and/or smaller devices.

Adhesion is caused by different phenomena acting at the same time on the surface. In *poly-silicon* surfaces, the most relevant sources of adhesion forces are: **electrostatic**, **capillary** and **van der Waals**. Electrostatic force is caused by trapped charge on the silicon dioxide native layer on the surface, capillary force by the formation of water meniscus between the roughness

asperities, and van der Waals forces by electronic charge fluctuation on the bodies. The electrostatic force is a *long-range* force, *i.e.* its influence is still strong at large separations, and the capillary and van der Waals forces are *short-range*, *i.e.* their influence is negligible at large separation and dominates at small separation.

This research focuses at the same time on two issues: the **experimental characterization** and the **numerical modeling** of the adhesion phenomenon. First, the surface roughness is measured and the adhesion energy is evaluated on ad-hoc designed test devices. Second, to model the adhesion phenomena a numerical rough surface is generated and two different methods are developed respectively for the *short-* and *long-range* forces.

The measurement of the **roughness** in *poly-silicon* MEMS is of extreme importance for a precise characterization of the adhesion phenomenon in these devices. In this research, both *single-crystal* silicon and *poly-silicon* surfaces are measured by means of the **Atomic Force Microscope**. The measurements show a very small level of roughness of the *single-crystal surface* and a relevant level for the *poly-silicon* one. This latter

is characterized by a 9.39 *r.m.s.* and a correlation length of 298 *nm*. Moreover, the lateral surfaces, also called vertical, show a roughness of a different scale, hundreds of nanometers, due to the fabrication process.

The adhesion energy is measured directly **on-chip** with two ad-hoc designed devices: one for the *in-plane* contact that takes place on *vertical* surfaces and one for the *out-of-plane* contact that takes place on *horizontal* surfaces. This latter device is reported in figure 1: four springs keep suspended a structure that consists on two long electrostatic plates and a series of adhesion beams. During loading, the structure is moved *out-of-plane* by an electrostatic force acting on the plates in order to reach the contact between the beams and a lower adhesion pad. During the unloading, the electrostatic force is reduced and the structure remains stuck until a critical force is reached and the structure will unstuck. The adhesion energy can be evaluated by the energy difference between the stuck and the unstuck configurations. The **measured adhesion energy** per unit area are 13.4 ± 6.64% and 0.1675 ± 23.89% µJ/m^2 respectively for the *horizontal* and *vertical* surface.

The measured roughness
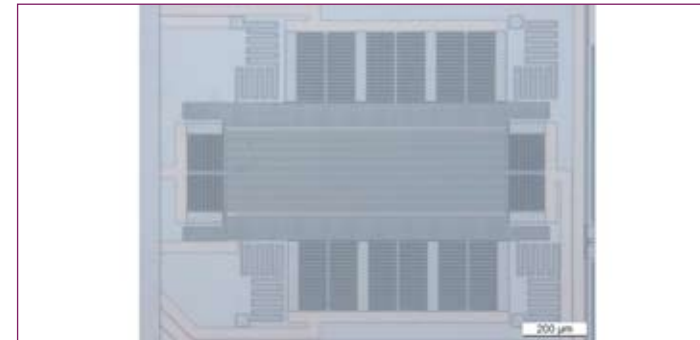
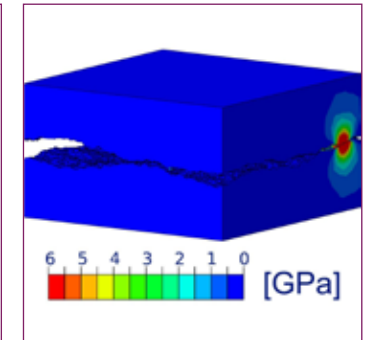**1. Optical image of the on-chip test device for the adhesion energy evaluation**

2. Von Mises stress contour plot of the two surfaces in the adhesion process simulation.

statistical parameters are taken as an input for the **numerical generation** of *horizontal* surfaces and then also manipulated to generate the *vertical* surfaces. The *Hu and Tonder* algorithm is used for the numerical rough surfaces generation. This algorithm is based on a **digital filter** that transforms a sequence of casual numbers into a rough surface with the imposed statistical parameters.

The purpose of the first developed numerical method is to **evaluate the adhesion energy for a generic rough surface**. To this aim, the adhesion process is simulated with a finite element model of two representative surfaces that, from a fully separated configuration, come into contact

and then separate again. The adhesion energy is evaluated by considering the work done to separate the surfaces, giving two evaluation of the energy: one for the loading an one for the unloading. The considered adhesion forces are the short-range forces, *i.e.* capillary and van der Waals forces. In these simulations the contribution of the electrostatic charge is not taken into account as it would prove irrelevant. *Short-range* forces are computed through the **Proximity Force Approximation**, *i.e.* depending only on the relative distance between material points. The constitutive model of the *poly-silicon* is *perfect elasto-plastic* to reproduce the observed surface plasticization in nano-indentation experiments. In figure 2 it is reported the von Mises stress

in the maximum contact position. The estimated loading adhesion energy are 23.74 and 25.66 µJ/m^2 respectively for the *horizontal* and vertical surface and the unloading energy are 480.9 and 506 µJ/m^2 respectively.

Finally, the **long-range** electrostatic force is modeled by means of the **boundary element method**. The main issue within this method for almost contacting surfaces is that the stiffness matrix become singular giving a wrong force estimation. In this research two methods to limit this issue are proposed based on a higher order integration and a fictitious surface approach. The methods are tested on benchmark cases showing good performances.

BIOMEMS FOR MICROSCALE FLUID TRANSPORT: DESIGN, SIMULATION AND PROTOTYPING

Emanuele Bertarelli

During the last two decades, within the well-established field of Micro Electro Mechanical Systems, the branch of Biological MEMS earned growing interest. BioMEMS development demands a strong multidisciplinary framework, which involves engineering, materials science, physics, biology, chemistry and medical sciences. Currently, a strong effort is being made by the research community to establish new paradigms for both modelling and manufacturing. To accelerate the technological transfer, an intense cooperation with the industry is required.

The final goal of this research was to design a device for microscale fluid transport to be used in the biomedical field, which exploits electrostatic actuation. Examples of target applications are drug delivery and biological fluid handling. The device has been conceived to be entirely realized through microfabrication techniques close to standard MEMS processes. Although founded on strong structural engineering basis, a continuos and fruitful interaction with disciplines such as fluid mechanics, materials engineering, physics and biomedical sciences created a complex environment that guided the investigation. The tools that have been developed, as well as the ideas

that have been introduced, are in general of broad applicability from an engineering standpoint. However, the underlying path is inherently treaded by the specific application in the biomedical field and by a careful evaluation of technological aspects from the material science perspective. Research has been primarily carried out at the Laboratory of Biological Structure Mechanics (LaBS) of the Department of Structural Engineering (DIS) of the Politecnico di Milano, Italy. A fundamental part of the activity has been performed at the Laboratory for Simulation of the Department of Microsystems Engineering (IMTEK) of the University of Freiburg, Germany. The expertise in the area of microsystems design and simulation of this research group greatly contributed to the definition of novel design ideas. Furthermore, the collaboration with the external partner STMicroelectronics represented an example of interaction of academics with a leader in ICT and MEMS design and manufacturing, with state-of-the-art microfabrication facilities. This is an important reference from a technological viewpoint, providing an origin for the definition of new technological processes suitable to realize a forthcoming generation of BioMEMS devices. As a first step, the full device
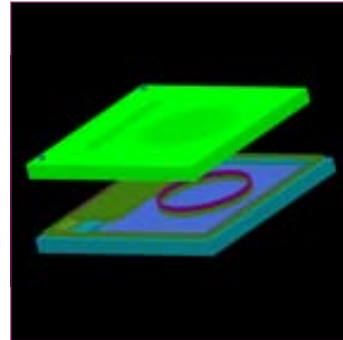
1. Rendering of a micropump actuator prototype. Stacking of polysilicon diaphragm (light green) on the substrate is represented. The pumping chamber is realized on the cap of the wafer, and placed above (not shown).

is studied by means of multiphysics numerical simulations in order to define and evaluate its fundamental characteristics in terms of working principle, actuation, geometry and overall performances. It is worth underlining that fully-coupled electro-fluid-mechanical dynamic simulations are proposed for the first time for electrostatic micropumps. Although some relevant simplifications are made to reduce the full problem to a 2D one, the proposed approach is an encouraging step in the direction of a complete Finite Element simulation of the electrostatic pumping mechanism. However, a fundamental improvement would be the simulation of the real 3D geometry, to adequately

represent the real device pumping mechanism and fluid flow inside the chamber. In this phase, a continuous interaction has been pursued with technology, aiming to set the key points for the development of a suitable technological platform for device manufacturing.

It has been evidenced that, to accelerate the technological transfer in BioMEMS research, an intense cooperation with the industry is crucial. A number of challenges has been faced to define a device design and a modified technological process compatible with existing microfabrication facilities. Undoubtedly, some technological and manufacturing issues represented relevant difficulties to be overcome. A preliminary design of the first prototypes is reported (Figure 1), while manufacturing is currently ongoing.

Attention is then focused on issues related to the device actuation. The actuator equilibrium in quasi-statics as well as in a dynamic damped framework has been modelled through Finite Element, Finite Difference and analytical methods. Among the different methods proposed and demonstrated for the study of electrostatic actuation, a one degree-of-freedom closed form solution obtained through Galërkin formulation is particularly interesting. In particular, a convenient load versus deflection relation is extracted for thin plates, but the method is suitable to be extended to different actuator geometries to study deformable MEMS electromechanics. In this direction, a novel design

strategy to achieve large strokes while avoiding pull-in occurrence is proposed, wich combines charge control with ring electrodes on a circular plate geometry. Indeed, the possibility to improve device performances and reliability by means of innovative electrostatic control methodologies is topical. The driving idea here is to extend the stable displacement range, aiming to realize efficient and reliable high stroke electrostatic diaphragm micropumps. An increase of the stable displacement range for the diaphragm actuator leads to various benefits: (i) a larger amount of fluid can be pumped at each stroke, increasing fluid transport capability; (ii) as a consequence, the ratio between stroke volume and dead volume is increased; (iii) for a target stroke volume, the initial capacitor gap can be reduced to achieve higher forces. However, the proposed control methodology can be in principle applied to a wide range of MEMS requiring extend travel ranges, such as optical devices.

This will allow to develop a new class of highly optimized and highly efficient actuators. As expected, charge control exhibits a stabilizing effect with respect to voltage drive, but not sufficient to achieve a full-range stability for the considered geometry. This is due to parasitic capacitance arising from non-uniform device deformation. When the electrode area is properly defined, stability range can be extended up to gap closure in the central part of the membrane. In this configuration, the increase in voltage required for full-range device drive

would be relevant, while in charge control the penalty is considerably lower. Loading conditions and geometrical parameters for an optimized actuation are suggested. Finally, design and modelling of ortho-planar microvalves suitable to be used for fluid flow rectification in the device under study has been performed. At this stage, laser rapid prototyping has been fruitfully exploited to realize stand-alone microvalves prototypes for a preliminary evaluation of various geometries.

The next steps of this research work will mainly involve the characterization of the first generation of prototypes. Furthermore, some of the aforementioned results represent a stimulating starting point for deeper investigations, in diverse directions, concerning multiphysics MEMS/BioMEMS modelling and simulation.

COMPUTATIONAL MODEL OF THE HEART

Elena Cutrì

Both the right and the left ventricular myocardium consists in a continuous muscle band spatially oriented as a helix. A key feature of this arrangement is the anisotropic organization which results from two contributions: local anisotropy due to the presence of obliquely oriented muscle fibers whose orientation varies from a right-handed helix at the subendocardium to a left-handed helix at the subepicardium and global anisotropy determined by the organization of these fibers in a twisted band of muscle which extends from the root of the pulmonary artery to the root of the aorta, with a helical configuration which defines two cavities, the right and left ventricles. The organization of the myocardium at a macroscopic level in a unique ventricular muscle band revealed the mutual coupling of anatomy and function in the ventricular myocardium in terms of electrical behavior, passive and active mechanical behavior, kinematical behavior. In addition, this peculiar architecture of the myocardial fibers is responsible for the torsional movement of the heart *i.e.* the mutual rotation of the cardiac base and apex around the ventricular long axis where counter-clockwise rotation is assumed as positive (when viewed from the apex). The cardiac torsion was proved
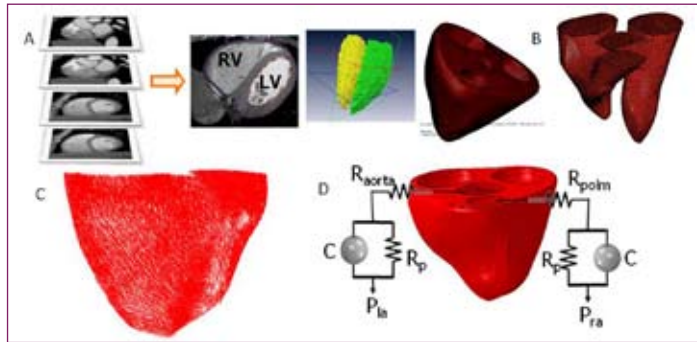
1. A) Anatomy based geometry; B) Geometry discretization;
C) Example of fibers orientation at the epicardium;
D) Biventricular model coupled to lumped parameters models.

to be a sensitive index of ventricular performance assessment.
In this Ph.D. thesis a 3-D Finite Element model of the heart was developed. The anatomy based geometry of the heart was reconstructed by segmentation using Amira® software which permits to process diagnostic images. Magnetic Resonance (MRI) images of the heart of an healthy patient at the end of the systolic phase were used. A parametric approach was adopted in order to model physiological or pathological hearts characterized by different anthropometric parameters (i.e. ventricle long and short axis length and wall thickness). The myocardium was modeled as an anisotropic hyperelastic material accounting for the contribution both of the matrix and the myocardial fibers. One family of fibers, each fiber

perfectly aligned to its direction, was modeled. Fibers orientation was defined by an ad hoc routine implemented in Matlab and was set according to literature studies: fibers orientation in the left ventricle varied from -60° at the level of the epicardium to +60° at the level of the endocardium with respect to the circumferential while in the right ventricle the orientation varied from -60° at the epicardium to +90° at the endocardium. Material parameters were identified using an univentricular model representing the left ventricle. In particular, material parameters were determined to address two requirements: the stress-like parameters of the matrix was identified to guarantee physiological end diastolic volume at physiological end diastolic pressure while fiber parameters were identified to obtain physiological cardiac

torsion and fibers contraction pattern. To replicate the active behavior of the myocardium the fibers stiffness was increased. This mechanism was aimed only at reproducing the macroscopic behavior of the myocardium. Variation of fiber stiffness was set according to concentration of free intracellular calcium, that characterizes the level of activation of a cardiac muscle cell. In order to simulate in vivo heart movement which is limited by the surrounding tissues, the ventricular base was anchored by means of a soft constraint modeled as a linear elastic ring anchored at its external circumference. The ring was assigned the same passive mechanical properties as the myocardial matrix. To evaluate the hemodynamic behavior of the heart, the FEM model was coupled with lumped-parameter models simulating cardiac afterload. The ventricular cavities were defined as fluid cavities by using hydrostatic elements to simulate physiological fluid flow from the ventricles to the outflow arteries. Fluid properties were assumed to be the same in both cavities. The fluid (blood) was modeled as an incompressible newtonian fluid with a density equal to 1060 kg/m3. The systemic and pulmonary circulations were modeled by three- element windkessel model. Each windkessel model consisted

of a resistance representing the outflow valves (i.e., aortic valve for the systemic circulation and tricuspid valve for the pulmonary circulation), a constant compliance accounting for systemic or pulmonary circulation compliance and a resistance representing the vascular resistance. A static stress/displacement analysis was performed consisting of two steps: cardiac diastole and systole. During the diastole, physiological flows to the two ventricles were defined to obtain the physiological end diastolic volumes. During systole, fluid flow between the two ventricular cavities and the two windkessel model was driven by the pressure fall between the LV and RV pressure and the aortic and pulmonary pressure, respectively. The model response was evaluated under different working conditions: physiological condition, systemic and pulmonary hypertension and aortic stenosis.
Realistic predictions of the LV and RV tensile stresses along the fiber direction were provided by the model. The stresses were higher during systolic peak than during the diastolic phases at the LV and RV free wall and at the interventricular septum, due to the cardiac fibers contraction. In the LV free wall and in the interventricular septum the stress peaks along the fiber

direction were located near the endocardial surface where the fiber orientation is almost circumferential. In the RV the maximum tensile stress is located at the epicardium where fibers orientation angle with respect to the circumferential direction is equal to 90°. Principal stresses were aligned with the fibers direction. The hemodynamic outcomes obtained from the simulation performed under physiological condition were within the physiological range. Simulation of pathological condition i.e., systemic and pulmonary afterload alteration and aortic valve stenosis showed realistic predictions of the hemodynamic behavior. In conclusion, the developed model accounting for an anatomy-based geometry, a realistic constitutive law and a fiber arrangement consistent with the histological findings represents a powerful tool for the comprehension of the heart behavior, proving that the cardiac function is strongly related to the anisotropic nature of the tissue. In addition, these features were fundamental to investigate the heart response under pathological conditions. Stress distribution, in fact, directly results from the geometry and from the fiber architecture.

STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

A NUMERICAL AND THEORETICAL ANALYSIS OF COMPACTION BANDING IN CEMENTED POROUS GEOMATERIALS

Giuseppe Dattola

Compaction banding is a particular kind of strain localization phenomena in which a plane compact zone forms perpendicularly to the maximum principal stress direction. Differently from shear bands, compaction bands are non stationary, that is the localized zone increases during the process (compaction band propagation). The study of compaction banding is relevant for oil engineering because the compaction band, reducing the material porosity and consequently the material permeability, slows down the oil extraction. The experimental results show that the possible mechanisms of compaction band formation are two: grain crushing and macro-voids collapse. In rocks, the mechanism of formation is the grain crushing as experimentally demonstrated by the increment of acoustic emission during localization. Consequently, in these types of materials the internal material length is a function of grain size. In high porous cemented materials, which are the object of this thesis, the mechanism of formation is due the macro-voids collapse. Indeed, a high porous cemented material is composed by a set of particles connected by bonds forming an internal structure characterized by macro-voids where the porosity is

concentrated. The macro-void collapse occurs since the bonds are elastic-brittle. Therefore, in a high porous cemented material the internal characteristic length is dominated by the size of macro-voids. Under oedometric conditions, the macroscopic response of high porous cemented materials when the compaction propagates is governed by the material characteristic length. In literature, only a general work proposed by Olsson (1999) about compaction band propagation is available, but this study does not include the material characteristic length. The aim of the present work consists in analyzing the influence of the characteristic length on the compaction band propagation and the instability phenomena that may occur in the global response of a sample under oedometric condition. To obtain this results the following steps was performed: (i) introduction of an analogical model (simple spring model); (ii) proof that the characteristic length of high porosity cemented materials is a property related to the macro-voids size; (iii) study of the effects of material characteristic length on the compaction band propagation under oedeometric condition, and consequently, study of the macro-response of a specimen subjected to oedometric tests; (iv) analysis of the connection,

due to the material characteristic length, between the local and global snapback during the compaction band propagation under oedometric conditions. The analogical spring model is based on the following idea: the compaction band propagation can be seen as compaction of a sequence of layer and so, the sample is idealized by superposed springs. Despite of its simplicity, the model is capable to reproduce the global behaviour of sample of high porous cemented materials under oedometric tests and, in particular, the model simulates the three phases that compose the response. By using this model, it is also possible to prove that by increasing the number of spring (or equivalently by reducing the material characteristic length) the number of oscillations on global response during the compaction band propagation increases and the length of the second stage depends on the material property. This analogical model was modified by introducing a softening response in the spring behaviour. The modified model was used to study the global snap-back problem that can arise during the compaction band propagation. The first conclusion of this study was that there are two possible types of snap-back, local snap

back, when it appears at the constitutive level, and global snap-back, when it appears at the global response of the sample. The second conclusion was that global and local snap-back are interconnected, and this interconnection depends on the material characteristic length. In particular two relevant cases are possible: the possibility to obtain the global snap-back when the material does not evidence any local snap-back, and its dual condition when the material evidences local snap-back while the global snap-back is not obtained. The second target of the thesis is obtained by using a distinct element method. This method is a numerical tool successfully used to describe a macroscopic response of a material by analyzing its internal structural. It is then suitable for the study of granular materials. Furthermore, the possibility to use the parallel bonds already implemented in the DEM codes allows the study of cemented materials. The DEM analyses were split in two parts: numerical simulations on honeycomb materials and numerical simulations on high porosity cemented materials. Honeycomb was analyzed, under uniaxial compression test, in order to understand the influence of the characteristic length in a material that exhibit a regular internal structure. In this way other geometrical effects are not considered. These simulations were performed by using two constitutive laws for the parallel bonds: the linear elastic model and an elastic perfectly plastic model. The results obtained by using the first model differs significantly with respect to the experimental evidence.

In particular, two drawbacks were evident: the localization mechanism was completely different than the experimental one and a detachment of the sample from the vertical walls was observed. This detachment generates a progressive reduction of horizontal forces because the lateral contact progressively disappears. By using the second model the results become more realistic if compared with the experimental tests. In particular, the mechanism of localization is captured and the global response exhibits qualitatively the same behaviour shown by the experimental results explaining, in this way, the global response of a sample. The second series of DEM simulations were performed on a high porous cemented material. To generate a sample with macro-voids and bonds, the following procedure was utilized. In the first stage two particle distributions were generated: the first particle distribution represents the particles of the material and the second one represents the macro-voids. After the generation, the second set of particles was deleted and consequently the macro-voids were generated. The final stage consists in the activation of the parallel bonds. The obtained numerical sample was subjected to odometric tests. The numerical results confirm, also in this case, that the internal characteristic length is a property related to the macro-voids, and that the instability phenomenon (snap-back) can be possible. In particular, the results confirm the analogical interpretation because, the reduction in height of the sample prevents the

global snap-back. To analyze a boundary values problem in presence of compaction banding the finite element method is the tool usually employed. Since the previous elastic-plastic models utilized to describe the material behaviour of cemented porous materials evidences some drawbacks, new expressions of the yield function, the plastic potential and the hardening rule were introduced. These new mathematical expressions overcome the previous drawbacks and this model reproduces satisfactorily the mechanical behaviour of common geomaterials as clays, sands and other geomaterials under mechanical degradation. The evolution of the yield function and the plastic potential in the deviatoric plane obeys the Matsuoka and Nakai criterion (1974). This model was implemented in a finite element code (Tochnog). The finite element simulations show also that the mechanical behaviour of sample during the compaction band propagation is governed by the material characteristic length and in particular the snap-back conditions are predicted.

PROPAGATION OF SEISMIC-SOURCE UNCERTAINTIES ONTO SEISMIC PERFORMANCE OF CLASSES OF BUILDINGS

Konstantinos Demartinos

This work investigates the matter of probabilistic seismic performance assessment at urban areas. The problem is characterized by a wide range of uncertainties, stemming principally from the difficulty in predicting the seismic excitation, especially in sites close to an active fault. Additional sources of uncertainty lie in the determination of structural capacity and the quantification of damage limit states in terms of engineering parameters, such as inelastic spectral displacement. The procedure of evaluating seismic performance is reviewed within the thesis, so that all physical processes involved are discussed, and underlying uncertainties recognized. From the fault rupture and the radiation of seismic energy, to the propagation of seismic waves on the Earth's crustal structure that causes ground shaking, and the eventual inelastic response of buildings. Furthermore, the theoretical background of state-of-the-art methodologies is presented in a critical fashion.

A variation of the probabilistic capacity-demand diagram method is presented, that enables the direct mapping of source uncertainties onto inelastic spectral displacement, on the basis of random rupture scenarios simulated through physics-based simulations

of seismic source and wave propagation (spectral element method, GeoELSE code). The Monte-Carlo integration scheme is then used to approximate the probability measures of seismic performance. In this context, the universal assumption of lognormality for the random variables involved is dropped, sources of uncertainty are separated and mostly treated in an explicit manner.

The resulting probability measures are treated as random variables, and estimates of the error in the probabilistic calculation are provided. The proposed formulation is adapted to facilitate the use of different representations of the seismic input, such as ground-motion intensity measures derived from empirical prediction equations. The direct probabilistic capacity-demand diagram is implemented for the evaluation of loss in the village of Pettino, struck by the 2009 M_w=6.3 L'Aquila earthquake. The availability of information on the physical damage suffered by the buildings in the village, motivated the simulation of 120 rupture scenarios to sample near-field ground motion variability and assess the reliability of the method. Further investigation has been carried out to draw conclusions on the convergence characteristics, the sensitivity of the probabilistic estimate

with respect to the sources of uncertainty considered and simplified methods of the evaluation of inelastic spectral displacement, and the comparative performance of methods based on intensity measures. The proposed method is shown to be able to produce realistic results, and it is shown to converge for sixty rupture scenarios. Neglecting the uncertainty stemming from the evaluation of structural capacity and the quantification of damage limit state, is not found to affect the probabilistic calculation, while the non-iterative method of equivalent linearization is shown to introduce a systematic error in the probabilistic calculation. Finally, it is found that ground-motion prediction equations can be used to produce results similar to the proposed method, in terms of the loss scenario. The analysis performed indicate that the use of the inter-event component of the ground-motion variability is more suitable for scenario studies.

Finally, the proposed methodology is implemented to evaluate the seismic performance and the losses in the town of Sulmona, for a M_w=6.4 scenario earthquake occurring in the vicinity. The number of rupture scenarios considered is limited to fifteen in this case, so that the probabilistic

calculation is characterized by an approximation error, attributed to the Monte-Carlo procedure. Moreover, the spatial variability of ground motion is accounted for, by subdividing the urban area into zones that are presumably subject to homogeneous ground shaking. The spatial variability of ground motion is shown to affect the probabilistic calculation, as the probability measures of seismic performance and the losses differ from one zone to another. Furthermore, an analysis is performed that verifies the negligible effect of uncertainties pertaining to the evaluation of structural capacity and the quantification of damage limit state. The range of reliability associated to the use of ground-motion prediction equations for this case of seismic performance assessment is also examined.

TUNNELS IN FIRE
Structural and materials behavior and modeling

Alireza Nafarieh

The increasing traffic congestion is becoming a very serious problem favored by the growing number of people living in urban agglomerations and – more generally – by the socio-economic development of many countries. One answer to this problem is offered by better infrastructures, which imply the construction of more roads, motorways, viaducts and tunnels.

As for tunnels (Figure 1), over the last years many new rail and road tunnels have been designed and built, bringing to the surface the issue of fire safety, which is a serious concern, fires are the worst possible accident in a tunnel.

Tunnels fire safety depends on the active and passive means devised to control and extinguish a fire or to prevent the activation of a fire. In the former case knowing the fire scenario and the consequences of the fire is a must. Furthermore, should the fire become incontrollable, knowing its effect on both the structural and materials behavior would be necessary for a proper design.

Hence, the Thesis is divided in two parts, one concerning some structural problems in fire and the other some materials problems at high temperature. The former part is devoted to modeling the fire in a road tunnel (to define the *fire scenario*) in order (a) to study the entity of the

thermal field and its propagation along the tunnel; and (b) to evaluate the static effect that the thermal field has on the tunnel lining. The car/bus/truck burning was simulated through realistic heat-release rate curves implemented firstly in a fire-zone model (CFAST) adapted to such a peculiar structure as that of a tunnel (where there are no compartments), and secondly in a more refined code (Pyrosim) based on computational fluid dynamics. Comparisons were made also with some real-vehicle fire tests.

Three major structural cases often found in modern road tunnels (lining, horizontal slab and vertical partition, as in the Frejus Tunnel) are examined. The lining (whose section is assumed to be circular) is investigated in both cohesive and soft soils by means of a simplified but effective model, while the horizontal and vertical plates are modeled by finite elements (Code ABAQUS), by introducing concrete nonlinearity at high temperature. The other part of the thesis is devoted to the mechanical characterization at high temperature of a somewhat special cementitious material, *shotcrete*, often used to consolidate the bore in blasted-off tunnels (*first-phase* lining). Since shotcrete has been recently proposed as a structural material to be used in the *final lining*,

its thermal and mechanical characterization at high temperature is badly needed (Figure 2). It is true that a lot of research activity has been devoted to shotcrete as a material to be used in provisional structures or to fill intentional/unintentional gaps in R/C structures or even to insulate fire-sensitive members, but very little attention has been given to shotcrete as a *structural material,* and practically no attention at all to its properties at high temperature, and during and past a fire.

Since in road tunnels fire is the most dangerous load condition, knowing shotcrete thermal and mechanical properties at high temperature and past a thermal cycle is preliminary to any safe use of this material, something that has never been done to date systematically.

The mechanical properties at ambient temperature, at high temperature and after cooling down to room temperature have been investigated by testing three shorcrete mixes.

The tests yield interesting results concerning the residual mechanical properties in compression and clearly show that the first mix (with an accelerating agent based on alkali silicates, fc = 15-20 MPa in virgin conditions) cannot be used for structural purposes, because of the time-increasing strength-loss after casting, not to mention its

high-temperature mechanical decay. On the contrary, the other two mixes (fc = 45-50 MPa in virgin conditions) behave similarly to vibrated concrete, and – as in vibrated concrete – steel fibers tend to marginally decrease both the strength and the elastic modulus in virgin conditions, while the thermal diffusivity
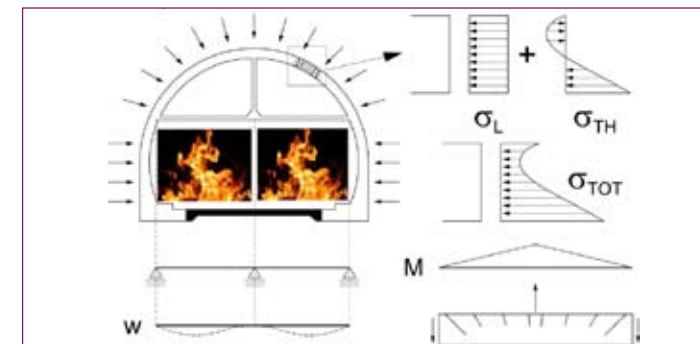
of shotcrete is definitely smaller than that of ordinary concrete (Figure 3).

The investigation on shotcrete, as a structural material exposed to high temperature, is accompanied by a similar investigation on three mortars (ordinary and high-performance mortars, fc = 5, 10 and 15

1. Thermal effects on internal forces of tunnel lining and partitions

2. Thermal decay test

3. Comparison of thermal diffusivity of the three shotcrete mixes with those given by EC2

MPa). In the Annex also the thermomechanical properties of three mortars are presented. Since mortars are often used for structural and non structural purposes (as – for instance – in the firewalls made of concrete blocks or hollow/solid bricks), a study on the high-temperature behavior of three mortars of different grade (cubic strength = 5, 10 and 15 MPa) is presented; the procedure is very similar to that adopted for the three shotcretes; the results show that mortars exhibit a much lower thermal diffusivity, but a mechanical decay close to that of ordinary concrete, unless alkali-based accelerating agents are used.

The motivation of this rather concise study on mortars is very simple: to Author's knowledge no evidence on mortar behavior at high temperature is available in the literature, while the design of firewalls made of bricks or concrete blocks requires the thermal and mechanical properties of mortars at high temperature to be well understood, even more since both the European Code and the national codes are introducing comprehensive and rather strict provisions concerning firewalls performance in fire. (Firewalls of different types are often found in the complementary structures of tunnels).
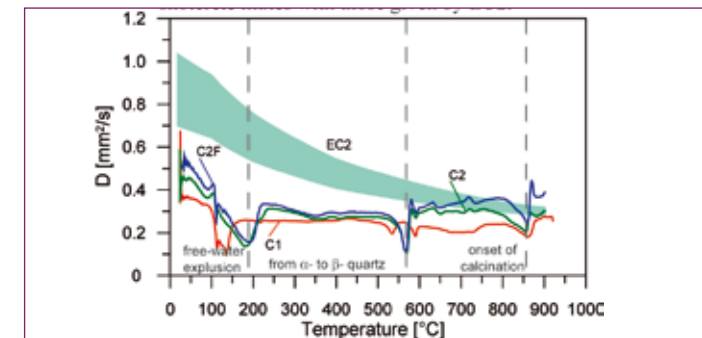
Summing up, this Thesis tackles some specific structural and materials problems concerning tunnels linings, and gives new information on the high-temperature behavior of two families of cementitious materials (shotcrete and mortars), whose structural use is on the rise.

SEISMIC PERFORMANCE OF INFINITE EARTH SLOPES: NUMERICAL MODELLING, CONSTITUTIVE ISSUES AND THEORETICAL CONSIDERATIONS

Federico Pisanò

Landslides are very frequent events in many areas of the world as part of the continuous evolution of landscapes. Case by case, the at rest conditions of slopes can be largely variable, ranging from amply to barely stable. Thus, the occurrence of even weak earthquakes can often be sufficient to trigger the collapse of sloping deposits, lying in slightly to moderately stable states before the seismic shaking.
Earthquake-induced landslides have been documented from as early as 1789 B.C. and represent, still nowadays, a major concern, since they can result in remarkable damage in terms both of economic and human losses. Suffice it to remind that, in many earthquakes, landslides have been responsible for as much or more damage than all other seismic hazards combined. It is therefore self-evident why the evaluation of seismic slope stability is one of the most relevant issues for geotechnical earthquake engineers.
The thesis is mainly focused on landslides occurring as a consequence of shear sliding mechanisms. In this context, the seismic analysis of slopes must be aimed at predicting whether, under a plausible input excitation, the slope will fail or not and, in the second case, whether excessive displacements from the standpoint of

serviceability requirements are developed.
For these reasons, predicting the displacement performance of slopes has become a topic of considerable interest in the Geotechnical Earthquake Engineering (GEE) community in the last 40-50 years, during which the state of practice has moved from simple pseudo-static analyses to increasingly more reliable displacement analyses. However, the GEE methods for slope displacement predictions – such as the so-called "stick-slip models" – usually rely on notable simplifying assumptions. From this point of view, the approaches employed in GEE do not seem to be up-to-date with respect to the enormous advances in Geomechanics in terms of modelling the mechanical behaviour of geomaterials, as well as numerically solving realistic 2D and 3D boundary value problems.
The motivation for this work stems from these premises. The thesis represents an attempt at building a "bridge" between GEE and Geomechanics on the issue of predicting the seismic performance of earth slopes. For this purpose, the simple but meaningful case of 1D numerical models for slope dynamic analyses is considered. A geometry reduction from 3D reality to the 1D ideal

scheme of "infinite slope" is commonly performed for practical applications, basically with the goal of reducing the computational costs. Besides, this is done with a further motivation, as a geometrically 1D model provides numerical results which are simpler to be mechanically interpreted. Indeed, when dynamic analyses involve highly non-linear materials (such as soils), the support both of physical insight and analytical solutions is essential to check the reliability of numerical results.
The work is in essence a theoretical/numerical study on the relationship between "modelling assumptions" and the results provided by 1D dynamic analyses. From this perspective, the most common assumptions adopted by the simplified GEE methods are critically discussed on the basis of more rigorous geomechanical theories.
The main contributions of the thesis are summarised hereafter:
a) the relevance both of structural redundancy and soil non-associativeness has been put in evidence, as long as the infinite slope is properly modelled as a special plain strain system (simple shear assumption). The use of bifurcation theory has clarified how the triggering of a failure sliding mechanism (strain

localisation) depends not only on the material frictional angle but also on its dilatancy, as well as on the previous loading history;
b) striking differences have been observed between the results of dynamic analyses obtained by employing the aforementioned simple shear (SS) approach and the so-called 1D shear (1DS) one. The latter is commonly assumed by the GEE methods and consists in modelling the slope problem only in terms of shear variables. In order to relate SS and 1DS models, a "condensation" procedure has been conceived to set up a "SS equivalent" 1DS hardening model, capable of matching the SS displacement predictions. The proposed procedure has been specialised for Mohr-Coulomb perfectly viscoplastic models, but represents a general and promising approach for deriving consistent predictions with low computational efforts;
c) the simpler 1DS approach has been employed to parametrically discuss the implications of certain constitutive factors. The influence both of soil time-sensitiveness and ductility has been numerically analysed. In particular, in the case of softening materials, it has been shown how the development of sliding planes (i.e. of strain localisation) can be in case inhibited when the material is sufficiently viscous. Moreover, even when localisation takes place, the number and the position of shear bands is not a priori predictable. These observations clearly conflict with the common GEE approaches, assuming the existence of a unique sliding plane at the bottom of the

system;
d) the influence of soil hysteresis on displacement predictions has been explored by means of a multi-surface kinematic hardening model. An interesting practical inference has been derived: in the case of dry slopes, isotropic hardening (single-surface) models overestimate the displacements derived through a multi-surface model, so that neglecting soil hysteresis seems to usually lead to conservative predictions.
At the same time, the work also provides some computational contributions, with emphasis on slope seismic analyses:
e) the use of an existing Taylor-Galerkin algorithm has been extended to seismic applications. The improvement of explicit algorithms for GEE applications is believed to be worthwhile, especially to simplify the numerical treatment of complex constitutive laws (e.g. multi-surface models);
f) in order to solve hydro-mechanical dynamic problems, the previous Taylor-Galerkin algorithm coupled with a fractional time-stepping has been improved and analytically validated;
g) the viscoplastic approach has been confirmed to be excellent to deal with dynamic localisation problems, often associated with a pathologic dependence of numerical results on space discretization. Viscoplasticity remedies this drawback by spontaneously introducing a material internal length as a consequence of rate-sensitiveness. Unfortunately, this beneficial effect tends to vanish as weakly viscous materials are considered. To overcome this difficulty, the

way of "regularised continua", and in particular of non-local viscoplasticity, has been followed. The non-local results are satisfactory from the viewpoint of objectivity, since the soil characteristic length can be reproduced even for nearly elasto-plastic materials. On the computational side, however, further work is needed to improve the efficiency of non-local FEM algorithms for demanding seismic analyses.
As is discussed throughout the dissertation, the description of localisation processes is still a major issue in seismic slope stability applications.
In conclusion, theoretical/numerical issues have been addressed, with the aim of highlighting some of the numerous factors affecting the slope seismic performance. In the light of modern geomechanical theories, it has been possible in some cases to go deep into the interpretation of the numerical results; in other cases, unsolved problems have been put in evidence, in order to stimulate further discussions within both the scientific and the technical communities. The thesis is believed to contribute to build that "bridge" between theory and practice, leading the way for increasingly rational approaches to the solution of seismic slope stability problems.

COMPUTATIONAL METHOD FOR THE DESIGN OF INNOVATIVE MATERIALS FOR HEART VALVE PROSTHESES

Adriano Zaffora

Heart valve replacement consists of the substitution of the diseased natural heart valve with an artificial device, the Heart Valve Prosthesis (HVP). Currently, surgeons can implant two typologies of HVP: mechanical HVP or bioprosthetic HVP. Mechanical HVPs that are made from synthetic hard materials, assure good reliability but require daily anticoagulant treatment to avoid blood cells damage. Bioprosthetic HVPs, which are made from animal or human tissues, display better hemocompatibility but significant risk of failure due to tissue degradation. Currently, the biomedical research is seeking innovative solution to the heart valve disease treatment: the main goal is to merge the advantages of the mechanical and biological HVPs into a single biomorphic device. Polymeric HVP are of particular interest in clinical practise. Soft polymeric materials can be used to build up biomorphic leaflets assuring better hemodynamics than mechanical heart valves. Many biocompatible soft polymers are available giving rise to potential standardisation and reduction of the manufacturing cost that are collateral disadvantages of the bioprostheses. Despite several authors contributed to the development of polymeric heart valves, their use is limited

to some pulsatile Ventricular Assist Devices (VAD) because the reliability of the material is not sufficient for long lasting implantation mainly due to degradation in blood.
The technological challenge in polymeric heart valve prostheses construction is in the production of synthetic materials capable to withstand the cyclic solicitations, which are typical of the heart cycle, for long time. In order to pursue such objective, the design of a heart valve has to optimise both the geometry of the device and the mechanical properties of the material. Biomorphic heart valve shapes demonstrated the reduction of thrombogenic risk secondary to poor haemodynamic performance. Experimental and computational studies about natural or bioprosthetic heart valves confirmed the functional role of the anisotropy of the biological tissue in the reduction of the stresses in the leaflets and the stabilisation of the motion of the valve.
New emerging technologies in material science, such as the block copolymers technology, made it possible to build up custom materials from chemical bonding of blocks of other polymers. In particular, styrene based block copolymers have been proposed as promising biomaterial for cardiovascular applications: they demonstrated

biocompatibility, chemical stability in biological environment and good fatigue resistance. Among the characteristics of such polymers there is the possibility to tailor their mechanical response by modifying just the volume fraction of styrene. Moreover, it was demonstrated that thermomechanical treatment can modify the morphology of the material passing from macroscopically isotropic to oriented, with mechanical behaviour analogous to the natural tissue.
The optimisation of the design of Polymeric Heart Valve Prosthesis (PHVP) involves several geometrical and material variables such as thickness and local orientation.
The computational mechanics provides useful tools to approach the design problem. The dissertation aims at the identification of suitable materials for heart valve prosthesis applications.
The development of a numerical tool for the design of the heart valve was pursued to describe the mechanical behaviour of such material, define the design of the valve and enhance the mechanical response of the material adopted for leaflet construction. Block copolymer based on styrene are thermoplastic elastomers, rubber-like materials.
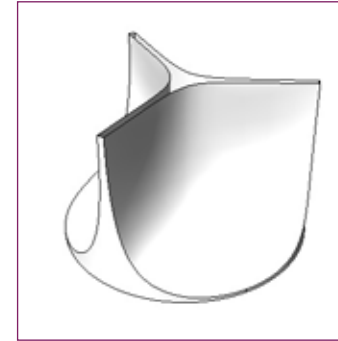
1. Geometrical NURBS model of a biomorphic heart valve prosthesis made from block copolymers
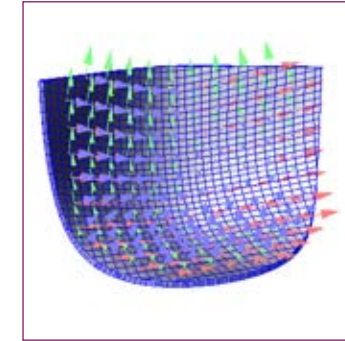
2. Model of a single leaflet with local orientation of the material set by mean of local reference frames

Two commercially available block copolymers were selected and mechanically tested. The isotropic and oriented morphology of the materials were achieved by thermomechanical treatments and studied: the effect of thickness, loading-unloading cycle, viscoelasticity was quantified. On the basis of the outcomes, a constitutive model was formulated. Being thermoplastics, the mechanical behaviour of the block copolymers was described by a hyperelastic constitutive model. A microstructural description of the material was included and used to model the transversal isotropy of the material: the cylindrical architecture of the material is accounted by a unit vector, being the descriptor of the direction of principal orientation of the material fibres. After the verification of the constitutive model, a finite element formulation was implemented as subroutine in the commercial code Abaqus (Simulia).
The geometry of symmetric trileaflet heart valve prostheses was drawn by means of Non Uniform Rational Basic Spline

(NURBS) modelling.
A parameterisation of the leaflet was set and an automatic procedure for the drawing was developed.
The geometric model was used in a finite element procedure capable to simulate the mechanical behaviour a biomorphic heart valve leaflet made from the studied material. Proper boundary conditions were set to simulate the presences of the surrounding structures. To account for the mechanical effect of a change in the material orientation, a reorientation algorithm was developed: the procedure updates, iteratively, the orientation of the material in order to align the material fibres with the maximum principal stress. An optimisation of the orientation of the material was performed and the results analysed in order to identify the most effective configuration. The computational model resulted useful for the identification of the structural parameters such as the correct thickness the material should have to withstand the loading conditions when shaped as heart valve prostheses. In addition,

the effect of the orientation of the materials within the leaflet was investigated. The results pointed out that block copolymers can be used for heart valve prosthesis applications. The most relevant result is that the oriented morphology of block copolymer material, whereas required, should be tailored to enhance the structural performance of the leaflets. The optimisation of the material orientation offers functional advantages. It is also noticed that the orientation maps can guide the manufacturing of the heart valve leaflets: a proper positioning of the material source in addition to a sapient constraint of the polymer flow may allow the construction of proper oriented raw material from which a heart valve prosthesis prototype can be obtained.