EUROPEAN MECHANICS SOCIETY

FINAL REPORT

EUROMECH COLLOQUIUM 634

MULTI-PHYSICS OF FIBROUS NETWORKS AND FIBRE-COMPOSITE MATERIALS

1. General information

Location: Eindhoven, the Netherlands

Date: 19/21 June 2023

Chairperson: Emanuela Bosco

Co-chairs: Artem Kulachenko, Catalin Picu

Conference fee:

- Regular fee 350 Euros (380 Euros for non-members)
- Student fee 325 (355 Euros for non-members)

The registration fee included:

- Welcoming reception on Monday 19/06;
- Two daily coffee breaks and five lunches;
- Social dinner at Kazerne Restaurant (Eindhoven) on Tuesday 20/06.

2. Participants

In total, 46 participants joined the colloquium. Among these, 22 were already Euromech members. The list of participants, the full program and the book of abstracts are provided in a separate document. The distribution of the participants per country is illustrated below.

Country participant distribution	
Sweden	12
Netherlands	9
Germany	5
Italy	5
Switzerland	4
Austria	2
UK	2
USA	2
France	2
Finland	1
Spain	1
Denmark	1

3. Scientific content

This Euromech colloquium focused on recent developments in computational multi-scale models and experimental methodologies for the analysis of fibres, fibrous networks and fibre-composite materials. The program included 41 oral presentations. A key-note lecture was given by Prof. G. Holzapfel, from Graz University of Technology.

Materials based on fibrous network structures play a significant role in many different physical and technical systems. These include both natural materials, such as biological networks and manufactured materials, such as paper, packaging, non-wovens, metamaterials, and composite network materials. In contrast to the conventional composites, the fibre network in these materials acts as the main load-bearing component, which singles them out into a separate category of fibre-based materials. Considering this large variety of applications, one of the key objectives of this EUROMECH colloquium was to identify the commonalities between the different classes of fibrous materials, to identify common issues encountered with such materials in different applications, and to bring together the corresponding research communities.

The presentations covered a wide range of topics related to the grand challenges in the field of fibrous networks and composite materials, including the behaviour of biological networks (collagen-based tissues and structures), cellulose networks, composite networks and classical composites with network reinforcement. Both numerical and experimental works were presented. Recurring issues addressed in the talks and discussed were:

- *Advanced multi-scale methods for fibrous materials*

Multi-scale mechanics methodologies play a crucial role for the accurate modelling of fibrous materials. All fibrous materials have multi-scale structures, and their macroscopic material response is governed by the interaction between fibres, their constitutive behaviour, the inter-fibre bonding properties, the fibre geometric features, morphology and orientation, and the typical random nature of the network. Identifying the structure-property relationships controlling the response of fibrous materials is thus a challenging task, particularly since the fibres are typically characterized by non-linear and time-dependent material behaviours, which are dependent on the ambient humidity and temperature. In addition, the presence of moisture or temperature fields induces deformations on the fibre and at the bond level. Further, failure commonly initiates at the scale of individual fibres, which makes it crucial to understand and predict how fracture phenomena propagate through the different length scales. In the colloquium, different homogenization approaches were discussed. These include asymptotic homogenization for the analysis of hygro-chemo-mechanical degradation of paper; computational homogenization for the analysis of the fracture response of fiber-reinforced composite materials; an homogenization strategy based on a localized orthogonal decomposition method for the modelling of paper networks; an homogenisation strategy based on describing the statistical distribution of stretch among the fibres in a random network, particularly applicable for the analysis of biological tissues; a multi-scale methodology based on numerical homogenization for the simulation of damage mechanisms in long-fiber-reinforced thermoplastics.

- *Continuum models capturing micro- and meso-mechanical phenomena*

The stiffness and strength of fiber-based materials are primarily influenced by the micro-scale structure, encompassing the mechanical properties of individual fibers, their morphology, orientation, the number of inter-fiber contacts, bonding characteristics, and the disordered nature of the fiber network. Consequently, it is crucial to address questions pertaining to the mechanics of fiber network structures at a length scale that considers these essential components. Simultaneously, it is necessary to incorporate information from the micro-scale into engineering-scale models, accounting for relevant climate conditions, in order to ensure the practical relevance and applicability of scientific findings. Failure mechanisms often originate at the scale of a few fibers, while quality parameters are typically defined using continuum mechanics principles, resulting in properties that are essentially independent of size. By understanding and bridging these scales, researchers can gain valuable insights into the behavior of fiber-based materials, enabling the development of tailored and reliable applications. In different talks within the colloquium, continuum mechanics strategies were presented. These include elastoplastic models for the damage response of paper, with focus on the creasing and folding of paperboard; a large deformation continuum model for an isotropic visco-plastic matrix reinforced by a distribution of fibres applicable to biological tissues; a macroscopic phase-field model capturing the emergence of anisotropy in contractile cells that reorganize fibrous extracellular matrices and form dense tracts of aligned fibers; a phase-field model for ductile fracture in orthotropic paperboard materials; a statistical mechanics model considering a statistical population of fibers, whose key parameters are identified from experiments.

- <u>Parameter identification from experiments</u>

The experimental characterization of material parameters of fibrous systems is a challenging task, especially when consideing small-scale properties. Consequently, the development of reliable and robust experimental methodologies becomes essential to accurately evaluate the mechanical, hygroscopic, and diffusive properties of fibrous materials across various length scales—from individual fibers and fiber bonds to the engineering level. Additionally, advanced in-situ observation techniques are necessary to understand the underlying deformation and damage mechanisms. During the colloquium, diverse experimental methodologies were presented, with a particular focus on cellulose-based materials. These methodologies encompassed the characterization of local mechanical response through in-situ micro-profilometry of micrometric fibers, measurement of the elastic stiffness tensor of cellulosic fibers using Brillouin light scattering, and assessment of fiber-fiber contact behavior via Mode I and Mode II experiments. Discussions revealed that obtaining individual properties for biological materials like collagen remains an ongoing challenge. However, some of the proposed methods within the context of cellulose fibers hold great relevance for the biological network community as well.

- <u>Moisture effects in cellulose networks</u>

Understanding the impact of moisture on the mechanical properties of cellulose-based network materials represents a significant challenge within the field of paper mechanics. This topic was explored across various length scales, including both experimental and modeling approaches. A continuum model capable of capturing the transport of liquid and swelling phenomena in paper sheets was discussed, providing insights into macroscopic moisture-related behavior. Additionally, a multi-scale experimental study was proposed to investigate the moisture-induced swelling, or hygro-expansion, of paper. This study aimed to examine the effects at different scales, including single fibers, inter-fiber bonds, and sheets

The talks at the colloquium frequently addressed issues related to these aspects. It can be concluded that significant progress has been made in both continuum and network models in recent years, but there are still numerous critical questions that require attention. It is emphasised that there was ample time for informal discussions among the participants during coffee breaks, lunches and social activities, which was highly appreciated by everyone involved. These extensive discussions also facilitated the identification of common features shared among different classes of fibrous materials, which are often overlooked and underutilized. This provided an opportunity to leverage and benefit from advancements made in various research communities, while also fostering stronger connections among researchers focused on paper mechanics, biological tissues, and composites. The community has agreed to plan another meeting in approximately 2 to 3 years, potentially with broader participation from outside Europe. Many participants expressed their high regard for the colloquium, which successfully achieved its intended objectives.

We would finally like to thank EUROMECH for all the financial and, not the least, organisational support.

Emanuela Bosco, Artem Kulachenko, Catalin Picu

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