FOM - 16.0172

Annual report 2015

FOM programme nr. 143
'Marginal soft matter: leveraging the mechanics of responsive networks'

Foundation for Fundamental Research on Matter
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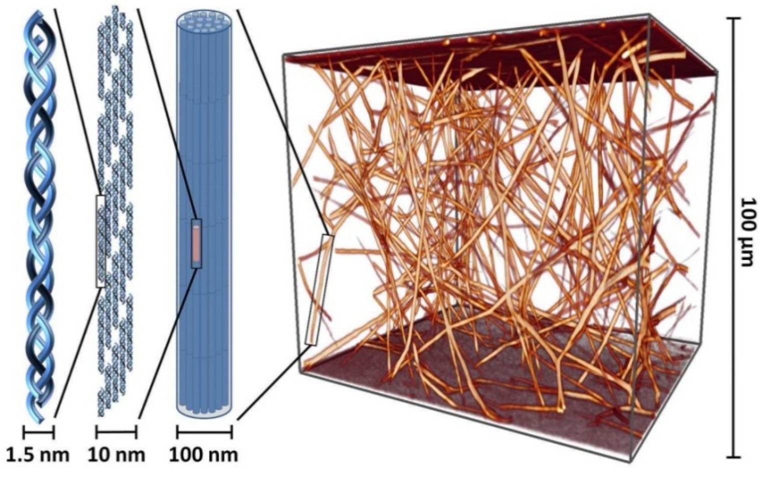

A 3D confocal image of a reconstituted collagen type I network shows a highly branched local geometry (right). On the left, the multiscale organization of this network; collagen fibers are hierarchically assembled of fibrils (diameter: 10nm) which in turn consist of staggered collagen molecules (diameter: 1.5nm). In this PNAS paper, a direct confrontation between mutliscale models and experiment confirms the central role of stresses in controlling the mechanical response of hierarchical biomaterials.
Figure A.J. Licup, et al, Stress controls the mechanics of collagen networks PNAS, 112: 9573 (2015).

May 2016

Content

1. Scientific results 2015

The programme is roughly midway and is at full steam. 2015 has been a very productive year in terms of scientific output, with close to 20 papers - many of which involving several programme groups - either directly from or closely related to the efforts in the programme published. Some in high profile outlets such as Nature Communications, PNAS, and Phys. Rev. Lett. Although collaborative work is carried out in several combinations of participating groups, I will highlight this year in particular the progress made along the VU-AMOLF axis.

At AMOLF, Gijsje and her group have focused on the mechanical properties of fibrin, comparing the response of fibrin networks to an applied mechanical compression, tension, or shear. Under shear, they measure strong strain-stiffening and large negative normal stress. The negative normal stress contrasts with the positive normal stress developed by elastic solids such as metals, rubbers and polymer gels. By systematically varying the network pore size (in collaboration with the group of D. Bonn at the UvA), they discovered that the sign of the normal stress switches from positive to negative at a characteristic time scale controlled by the network porosity. AMOLF closely collaborated with the MacKintosh group, who developed a quantitative model based on a two-fluid model to unify the opposite behaviours encountered in semiflexible gels versus standard elastomers. In this description, dense networks are impermeable to solvent flow, making them incompressible and resulting in positive normal stress, while open networks are compressible on long time scales, resulting in the anomalous negative normal stress. Thus, the geometry of the network may be used to control nonlinear elastic response – one of the objectives of our programme. Under cyclic shear, they also find evidence of network remodeling, whcih is even stronger under cyclic compression, and results in strong stiffening. To interpret these findings, we hypothesize that fibrin fibers adhere and form new bonds when brought into contact. This hypothesis was tested using optical tweezer manipulation in combination with fluorescence microscopy. This showed, that fibrin fibers indeed spontaneously adhere when brought into contact. The VU group (Fred MacKintosh and coworkers) has been making good progress on the effects of axial strain in subisostatic systems. This is largely with experiments (in joint work with external partner Paul Janmey) and has resulted in two papers published/submitted so far. They are also working on the marginal, 'jammed' limit for networks with soft inclusions (cells, particles) under compression. Programme PD Mahsa Vahabi has also been key to a new collaboration with Daniel Bonn and Gijsje Koenderink on normal stresses in subisostatic networks (fibrin). The jointly disicered 'smoking gun' that it (in)compressibility and fluid coupling determine the sign and magnitude of normal stresses, has been a true highlight of our programme this year.

The Eindhoven project has made important steps in the speed, stability and reliability of the numerical code we employ to study the nonlinear response of networks and composites. In addition, the features needed to study stiff inclusions in a soft background network (to model e.g. a rod-inforced hydrogel) have been added to the code, and a tool to tune the connectivity of the network during its generation. These aspects of numerical toolkit-development have slowed down our plans concerning producing publishable results on the questions relevant to the programme goals, but the more powerful code will certainly be very beneficial in the coming two years.

Meanwhile, the Leiden projects (Van Hecke and Vitelli) are currently focusing on designing one degree of freedom origami structures. Traditionally, these are designed by complex computer aided design, but have discovered a simple combinatorial approach to a design vast number of distinct origami patterns. Interestingly, and unique to origami, is that despite the one continuous degree of freedom, these mechanisms have a varying number of discrete folding motions, which can either be finite (2) or extensive in the size of the folding pattern. Leiden is currently finishing the classification these systems, and in the next year will move towards endowing these structures with mechanical functionalities by including elastic interactions.

2. Added value of the programme

This continues to be a rather close-knit programme, with frequent (organized and impromptu) meetings and significant collaborative output. This community-building aspect, in my opinion, is one of its greatest added values. To further emphasize this, over the last year the programme leader (Storm) has taken over the organization of the Soft Matter Meetings (jointly with Daniela Kraft in Leiden), and part of the steering budget (with FOM approval) is used to ensure its continued success. We have also supported an Aspen workshop that many of us attended.

3. Personnel

Nothing major to report – all positions are filled, all PhD's on track. A point of some concern is the imminent departure for the US of Fred MacKintosh in 2016, whose theoretical input has been central to our programme. At this point, it appears that Fred will remain sufficiently present and connected to the NL to 'serve out' his commitment to the programme, but I will continue to monitor this. A previous change of plans – the departure (before the start) of Leunissen from science – has been resolved this year by assigning part of the intended research to Koenderink's group (Amolf) and the start of a new collaboration with the group of Manoharan at Harvard to begin exploring the DNA-functionalized colloidal routes towards marginality.

4. Publications

<u>Project 12CSM06 'Marginality in tunable microscopic fibrin networks' (AMOLF)</u>

- A. Sharma, A.J. Licup, K.A. Jansen, R. Rens, M. Sheinman, G.H. Koenderink, F.C. MacKintosh, Strain-controlled criticality governs the nonlinear mechanics of fiber networks. Nature Physics, DOI: 10.1038/nphys3628 (2016) and arXiv:1506.07792.
- Nicholas A. Kurniawan, Jos Grimbergen, Izabela K. Piechocka, Karin A. Jansen, Fred C. MacKintosh, Jaap Koopman, Gijsje H. Koenderink, Unraveling the Link between Nonlinear Mechanics, Microstructure, and Molecular Packing of Fibrin, Biophys. J. 108, 40a (2015).

<u>Project 12CSM02 '3D printed macroscopic marginal networks' (Leiden)</u>

- Pedro M. Reis, Heinrich M. Jaeger, Martin van Hecke (2015) Design Matter: A perspective, Extreme Mechanics Letters, 5, 25-29.
- Scott Waitukaitis, Rémi Menaut, Bryan Gin-ge Chen, and Martin van Hecke (2015) Origami Multistability: From Single Vertices to Metasheets, Physical Review Letters, 114, 055503.

<u>Project 12CSM03 'Cellulose and cellulose-composite networks' (UU)</u>

- Microstructure and rheology of microfibril–polymer networks S.J. Veen, P. Versluis, A. Kuijk, K.P. Velikov Soft matter 11 (46), 8907-8912.

<u>Project 12CSM04 'Theory of tunable marginal networks and thermal paradox materials' (VU)</u>

- A.J. Licup, S. Muenster, A. Sharma, M. Sheinman, L.M. Jawerth, B. Fabry, D.A. Weitz and F.C. MacKintosh, Stress controls the mechanics of collagen networks PNAS, 112: 9573 (2015).
- R. Rens, M. Vahabi, A.J. Licup, F.C. MacKintosh, A. Sharma Nonlinear mechanics of athermal branched biopolymer networks J Phys Chem B, DOI: 10.1021/acs.jpcb.6b00259.

Project 12CSM01 'Two-fiber composites, thermal marginal matter and the response to global driving' (TU/e)

- W.G. Ellenbroek, V.F. Hagh, A. Kumar, M.F. Thorpe and M. Van Hecke, Rigidity loss in disordered systems: Three scenarios, Phys. Rev. Lett. 114, 135501 (2015).
- C. Vrusch and C. Storm, Curvature-induced crosshatched order in two-dimensional semiflexible polymer networks, Phys. Rev. E 92, 060602 (2015).

Project 12CSM05 'Nonlinear effects in driven networks with thermal fluctuations' (Leiden)

- Selective buckling via states of self-stress in topological metamaterials, Jayson Paulose, Anne S. Meeussen and Vincenzo Vitelli, Proceedings of the National Academy of Sciences 112(25):7639-7644, (2015).
- Topological modes bound to dislocations in mechanical metamaterials, Jayson Paulose, Bryan Gin-ge Chen and Vincenzo Vitelli, Nature Physics 11:153-156, (2015).

5. Valorisation and outreach

Nothing to report.

6. Vacancies

None.

FOM – 13.0226/3
datum: 01-01-2016

APPROVED FOM PROGRAMME

Number	143.
Title (code)	Marginal soft matter: leveraging the mechanics of responsive networks (CMA)
Executive organisational unit	BUW
Programme management	Dr. C. Storm
Duration	2013-2018
Cost estimate	M€ 1.7

Concise programme description

a. Objectives

In our programme we seek to create and probe a novel class of functional soft materials, focusing on fibrous networks. The objective of our programme is to *create, control and characterize* real-life marginal soft materials.

b. Background, relevance and implementation

Our programme centers around three specific themes to achieve this objective:

1) **Architecture**: we will establish a fundamental understanding of how network connectivity and fiber bending, in other words, the network architecture, affect marginality and the ensuing mechanics. Experimentally, we manipulate these properties in soft micro- and macroscopic networks – ranging from networks created by 3D printing, to microscopic fibrin networks, cellulose networks and DNA hydrogels, created through self-assembly. We extend the celebrated mechanical theory of Maxwell to include polymeric and persistent meshwork's.
2) **Thermal fluctuations**: most soft matter is ruled by energies of the order of thermal energy, kT. Yet, little is known about the interplay between marginality and thermal fluctuations because the focus to date has largely been on marginality in athermal jammed particle packings. The intrinsic softness and range of relevant length scales in our materials offer a unique opportunity to exploit thermal fluctuations. Our preliminary theoretical work shows that signature marginal properties survive thermal fluctuations - and are, in fact, enriched by them. We will control the extent of fluctuations by varying the rigidity in fibrin and cellulose gels, probe their role for the mechanical response, explore them numerically and develop the theory of thermal marginal networks.
3) **Driven networks**: Our materials are exquisitely sensitive. To take advantage of this sensitivity, we will drive our architectures by internal and external forces, actively and passively generated. We will explore the roles of mechanical frustration, prestresses, instabilities and activity, manipulating near-marginal fibrous architectures to reach novel functionalities, and develop the theory of driven marginal materials.

Each of these themes is addressed both theoretically and numerically.

Funding

salarispeil cao tot 01-01-2016

bedragen in k€	≤ 2015	2016	2017	2018	2019	2020	≥ 2021	Totaal
FOM-basisexploitatie	537	337	337	337	-	-	-	1.548
FOM-basisinvesteringen	135	-	-	-	-	-	-	135
Doelsubsidies NWO	-	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-	-
Totaal	672	337	337	337	-	-	-	1.683

Source documents and progress control

a) Original programme proposal: FOM-12.1323
b) Ex ante evaluation: FOM-12.1491
c) Decision Executive Board: FOM-13.0221

Remarks

The final evaluation will be based on the self-evaluation report initiated by the programme leader and is foreseen for 2019.

vH par. HOZB

Subgebied: 100% FeF

Historical overview of input and output

Input	personnel (in fte)				finances* (in k€)
	WP/V	WP/T	PhD	NWP	
2013					3
2014	-	1.3	2.3	-	192
2015	-	2.8	4.0	-	398

Output	PhD theses	refereed publications	other publications & presentations	patents
2014	-	3	10	-
2015	-	3	21	-

* After closing the financial year.

PhD defences

2014
None.

2015
None.

Patents (new/changes)

2014
None.

2015
None.

Overview of projects and personnel

Workgroup FOM-E-10

Leader	Dr. C. Storm
Organisation	Eindhoven University of Technology
Project (title + number)	Two-fiber composites, thermal marginal matter andthe response to global driving (12CMA01)

FOM employees on this project

Name	Position	Start date	End date
M.F.J. Vermeulen	PhD	1 April 2014	31 March 2018

Workgroup FOM-L-07

Leader	Dr. V. Vitelli
Organisation	Leiden University
Project (title + number)	Non linear effects in driven networks withfluctuations (12CMA05)

FOM employees on this project

Name	Position	Start date	End date
D. Banerjee	WP/T	1 September 2014	31 August 2016
J.J. Paulose	WP/T	1 September 2015	31 August 2016

Workgroup FOM-L-25

Leader	Prof.dr. M.L. van Hecke
Organisation	Leiden University
Project (title + number)	3D printed macroscopic marginal networks (12CMA02)

FOM employees on this project

Name	Position	Start date	End date
P. Dieleman	PhD	15 May 2014	14 May 2018

Workgroup FOM-U-09

Leader	Prof.dr. A. van Blaaderen
Organisation	Utrecht University
Project (title + number)	Cellulose and cellulose-composites networks (12CMA03)

FOM employees on this project

Name	Position	Start date	End date
S. Mohan	PhD	1 May 2014	30 April 2018

Workgroup FOM-V-13

Leader	Prof.dr. F.C. MacKintosh
Organisation	Vrije Universiteit Amsterdam
Project (title + number)	Theory of tunable marginal networks and thermalparadox materials (12CMA04)

FOM employees on this project

Name	Position	Start date	End date
M. Vahabi	WP/T	1 September 2014	14 September 2016

Group Koenderink

Leader	Dr. C. Storm
Organisation	FOM Institute AMOLF
Project (title + number)	Marginality in turnable microscopic fibrinnetworks (12CMA06)

FOM employees on this project

Name	Position	Start date	End date
A. Boire	WP/T	1 May 2014	30 March 2015
B.E. Vos	PhD	16 October 2014	15 October 2017
A. Aufderhorst-Roberts	WP/T	1 December 2015	30 November 2017