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Computer-aided design, simulation and manufacturing of (modular) materials, mechanisms, and structures

Jan Zeman

Faculty of Civil Engineering, CTU in Prague

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Robotics and Advanced Industrial Production
CZ.02.01.01/00/22_008/0004590

RA4: Computer-aided design, simulation and manufacturing of modular materials

- Group G4: Three departments at FCE, CTU in Prague
  - Department of Mechanics [DM]
  - Department of Physics [DP]
  - Experimental Centre [EC]

- RO 4.1 - **Simulations** (M. Jirásek [DM], J. Zeman [DM])
- RO 4.2 - **Optimal design** (M. Kočvara [DM], J. Zeman [DM])
- RO 4.3 - **Manufacturing and validation** (J. Novák [EC], V. Nežerka [DP])

RA4/GA4 Team: FCE CTU

prof. Jan Zeman (GL)

prof. Milan Jirásek (ex. T)

prof. Michal Kočvara (ex. T)

doc. Jan Novák (ex. TT)

doc. Václav Nežerka (ex. TT)

Marek Tyburec (PD)

Martin Doškář (PD)

Michael Somr (PD)

RA4/GA4 Team: FCE CTU

Lukáš Supik (PhD student)

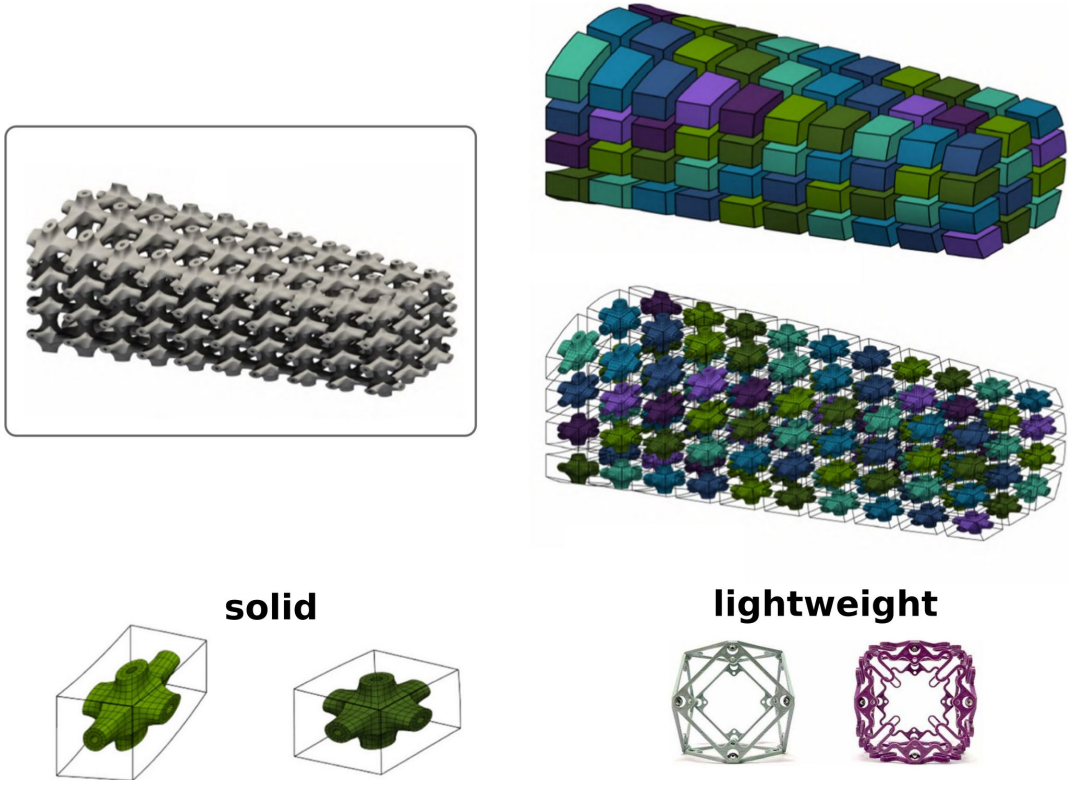
Matěj Porubský (PhD student)

Slávek Zbirovský (PhD student)

+2 positions (acquiring)

RA4: Computer-aided design, simulation and manufacturing of modular materials

What we mean by “modular”

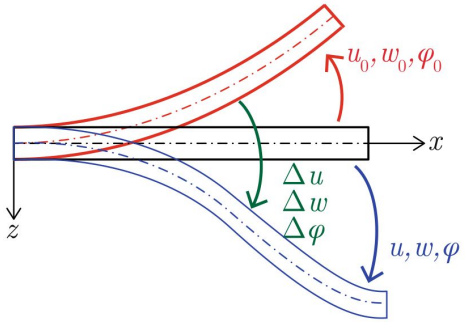


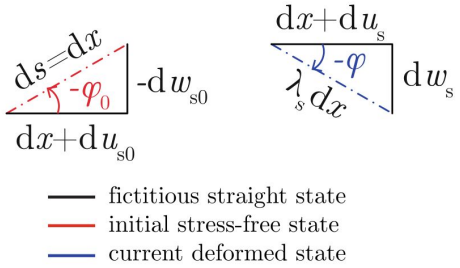
adapted from: Hirschler, T., Antolin, P. & Buffa, A. *Fast and multiscale formation of isogeometric matrices of microstructured geometric models*. Comput Mech **69**, 439–466 (2022); Jenett, B. et al. *Discretely assembled mechanical metamaterials*. Sci Adv **6**, eabc9943 (2020).

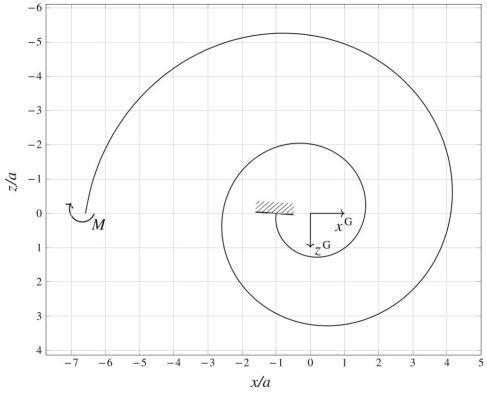
RO 4.1: Simulations

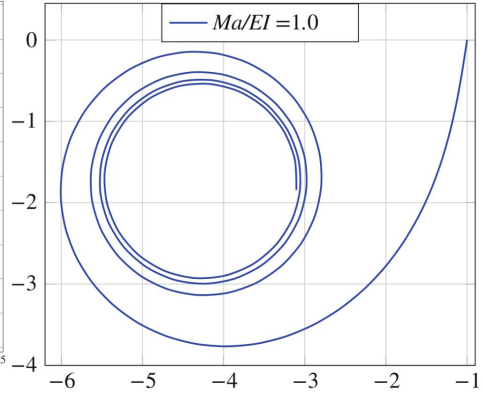
Geometrically exact nonlinear beam formulation[lightweight]

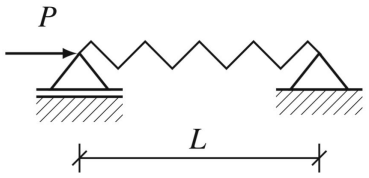
- novel approach based of the shooting method
- exact and flexible description of curved geometries
- captures geometrically non-linear behavior and instabilities
- (almost) analytical accuracy with a single element

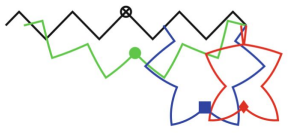


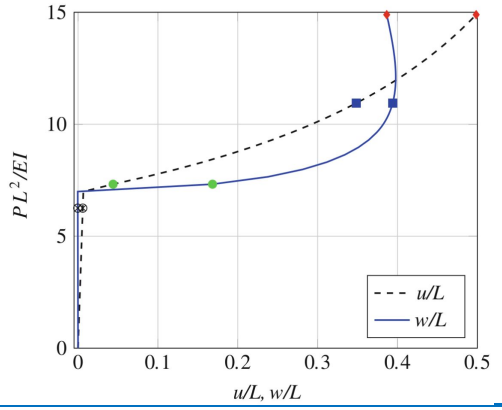






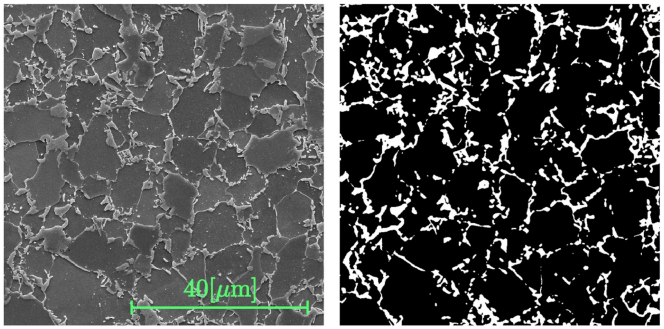






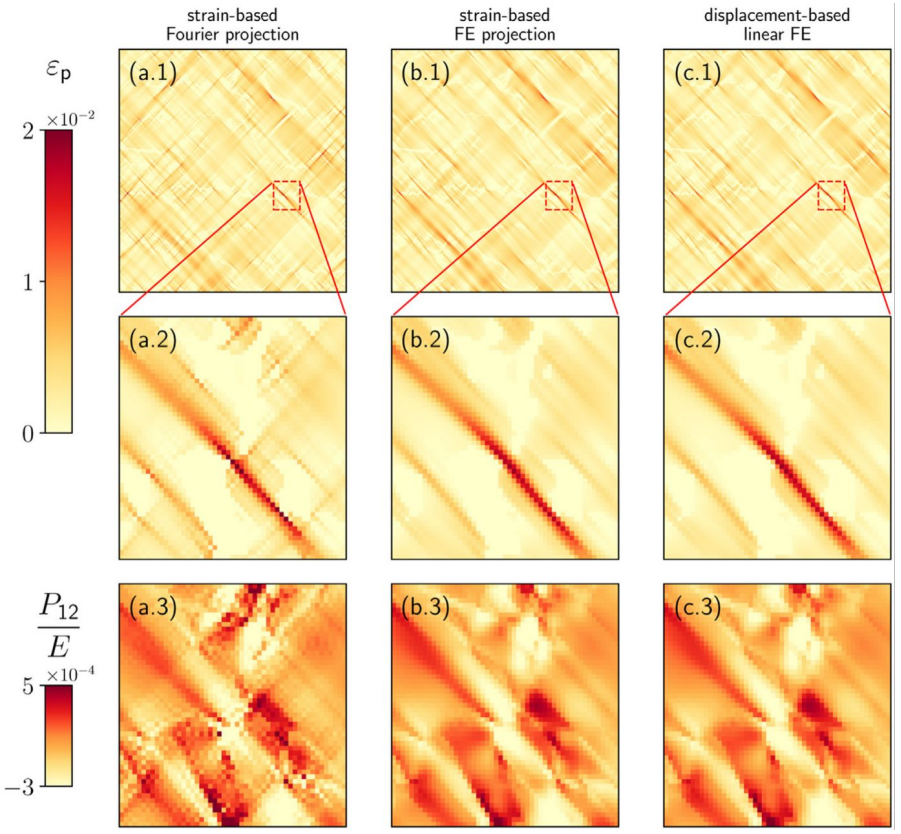
Horák, M., La Malfa Ribolla, E. & **Jirásek, M.** *Efficient formulation of a two-noded geometrically exact curved beam element.* Int J Numer Methods Eng **124**, 570–619 (2023)

RO 4.1: Simulations



Efficient solvers for image-based homogenization[solid]

- high-fidelity simulations of heterogeneous materials
- computationally- and memory-efficient
- arbitrary material constitutive laws
- theoretically supported
- removes parasitic modes present in conventional approaches

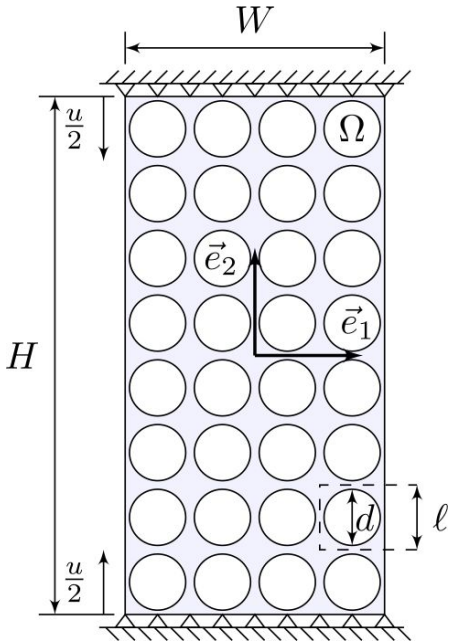


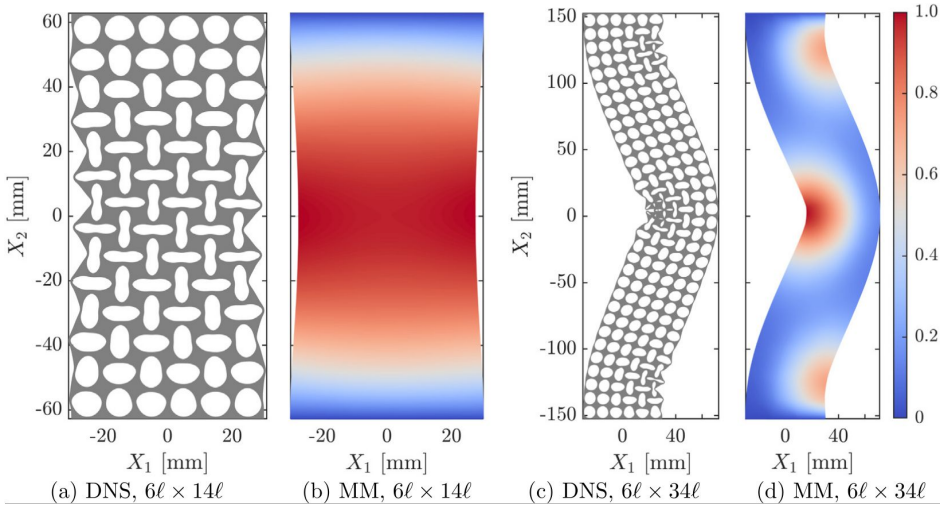
Ladecký, M., Leute, R.J., Falsafi, A., **Pultarová, I.**, Pastewka, L., Junge T., **Zeman, J.** *An optimal preconditioned FFT-accelerated finite element solver for homogenization.* Appl Math Comput **446**, 127835 (2023).

RO 4.1: Simulations

Multi-scale solver for patterning architectured materials[solid]

- materials exhibiting sub-scale instabilities
- description by generalized homogenized continuum model
- non-linear solver based on the Newton method
- instabilities at both scales are predicted adequately





van Bree, S., **Rokoš, O.**, Peerlings, R., **Doškář, M.** & **Geers, M.G.D.** *A Newton solver for micromorphic computational homogenization enabling multiscale buckling analysis of pattern-transforming metamaterials.* Comput Methods Appl Mech Eng **372**, 113333 (2020).

RO 4.1: Simulations

- **What we aim for:**
  - developing dedicated simulation techniques for problems with modular structure
  - extending the existing beam formulation to additional (mechanical) effects
  - utilizing the extended formulation for efficient simulations of modular lightweight structures

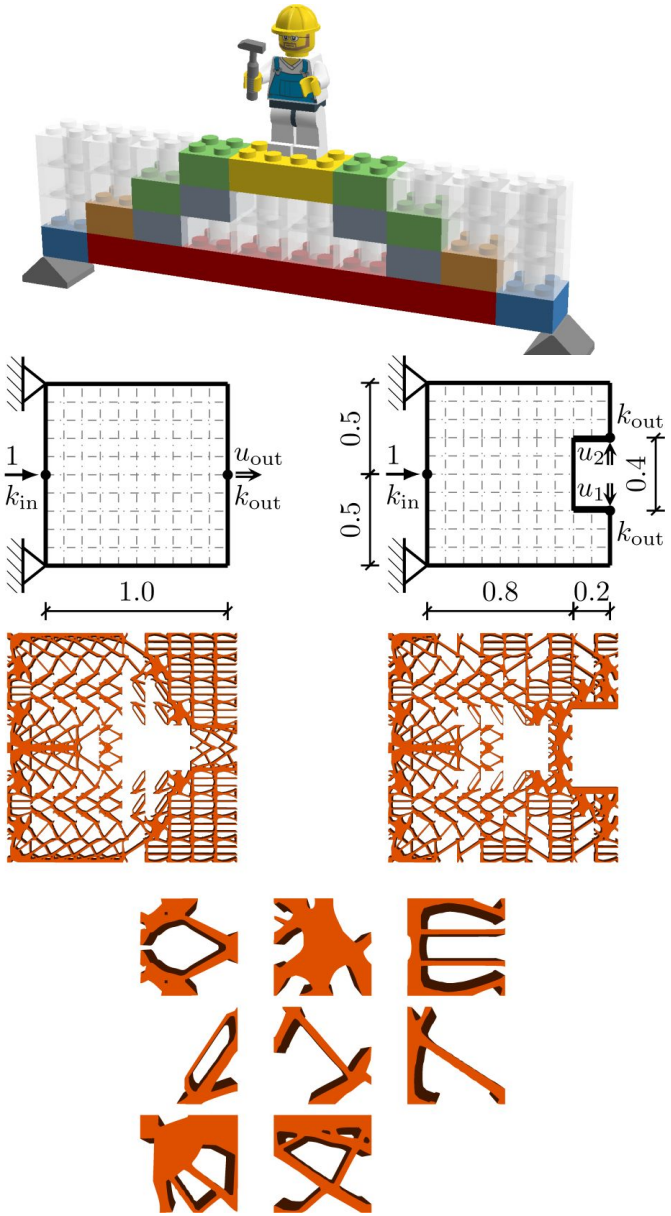
- **International collaboration:**
  - Dr. Ondřej Rokoš, Prof. Marc Geers (Eindhoven University of Technology, the Netherlands): joint Ph.D. student

- **Cooperation with other RAs:**
  - J. Zemánek - RA2: modeling aspects required in control problems

RO 4.2: Optimal design

Design of modular mechanisms[solid]

- involves **(1)** determination of module placement, **(2)** their design for optimal performance
- **(1)** solved with semidefinite optimization + clustering heuristics
- **(2)** solved using topology optimization technology
- accounts for manufacturing imperfections and module connectivity



Tyburec, M., **Doškář, M.**, **Somr, M.**, Kružík, M., **Zeman, J.** *Modular-topology optimization for additive manufacturing of reusable mechanisms* (2023) preprint. doi:10.13140/RG.2.2.29545.26724

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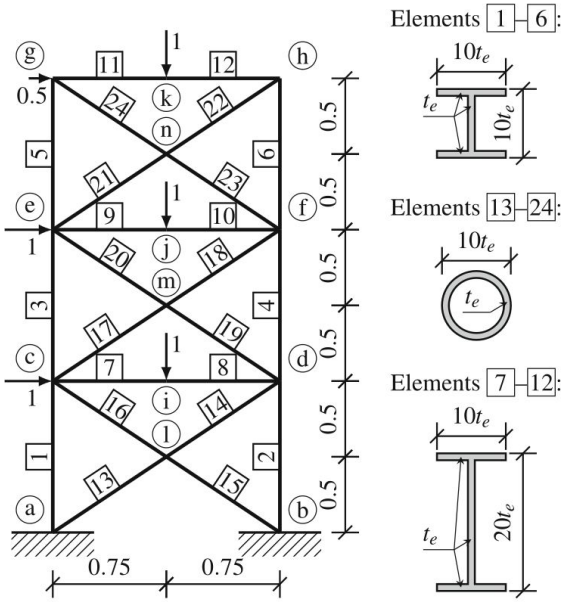
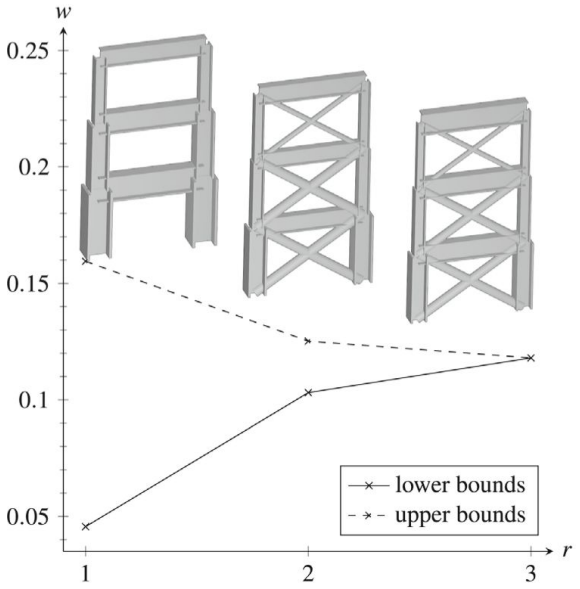
RO 4.2: Optimal design

Optimal design of bending-resistant structures[lightweight]

- leads to Polynomial Optimization Problems
- solved with the Lasserre hierarchy
- mechanics-based guarantees of global optimality and solution extraction
- minimum weight and maximum stiffness versions available
- theoretically supported algorithm





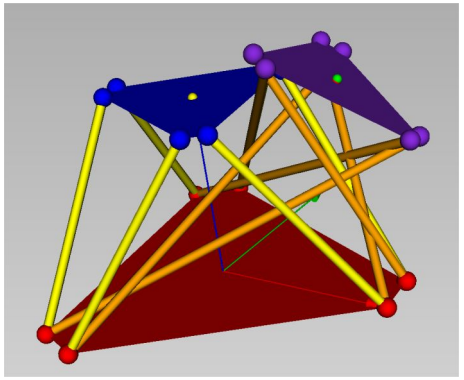
Tyburec, M., **Kočvara, M.** & Kružík, M. *Global weight optimization of frame structures with polynomial programming*. Struct Multidisc Optim **66**, 257 (2023).

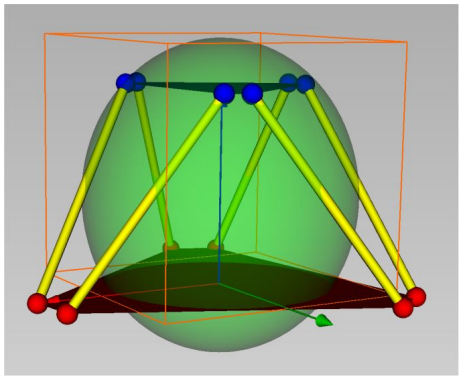
RO 4.2: Optimal design

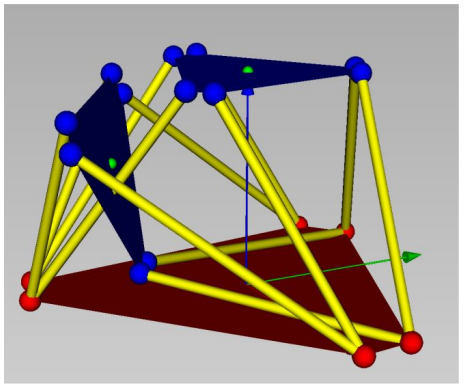
Low-rank semidefinite solver

- large-scale semidefinite problems with sparse solution or data
- specific preconditioner exploiting sparsity
- suitable, e.g., for
  - structural optimization problems
  - sensor localization
  - robot kinematics
  - enclosing ellipsoid of robotic workspace
- open-source code in MATLAB or Julia

Habibi, S., **Kočvara, M.** & Stingl, M. *Loraine – an interior-point solver for low-rank semidefinite programming*. Optim Methods Softw, 1–31 (2023).







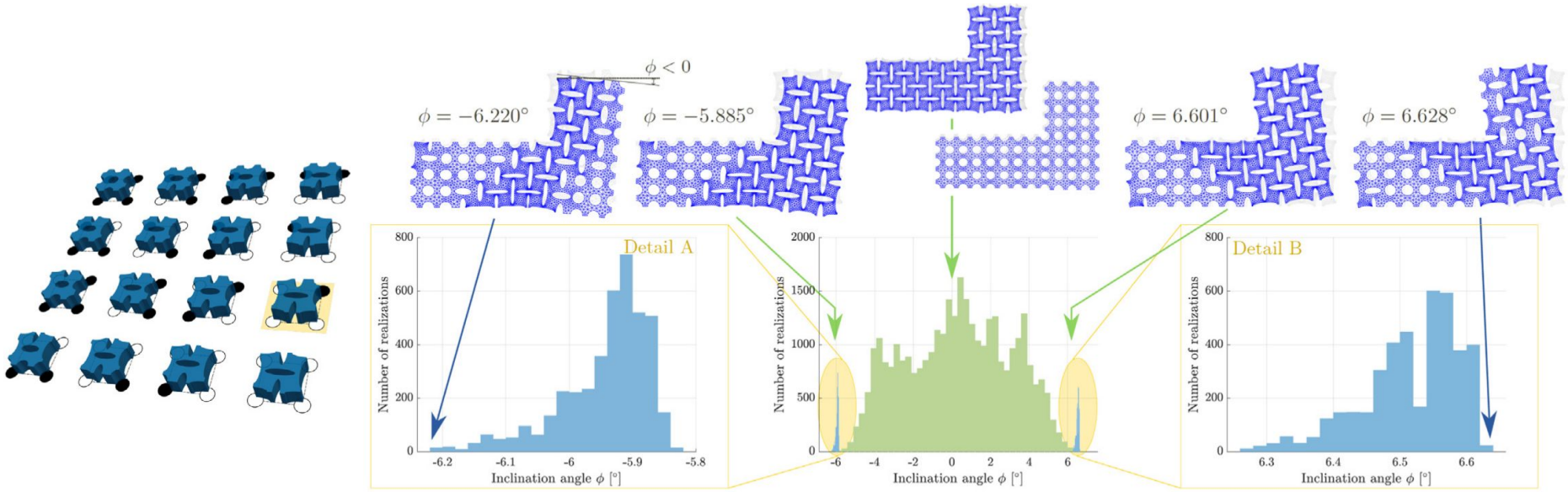
RO 4.2: Optimal design

- **What we aim for:**
  - extending the existing modular-topology optimization framework to other (physical) phenomena
  - incorporating additional relevant constraints into the frame optimization design
  - exploring the application of polynomial optimization to design modular structures
  - improving solution efficiency

- **International collaboration:**
  - Prof. Michael Stingl, Dr. Giovanni Fantuzzi (FAU Erlangen-Nürnberg)
- **Cooperation with other RAs:**
  - D. Henrion - RO 3.2: better scalability of the moment-SOS hierarchy
  - Z. Hanzálek - RA11: suitable alternatives to clustering heuristics

RO 4.3: Manufacturing and validation

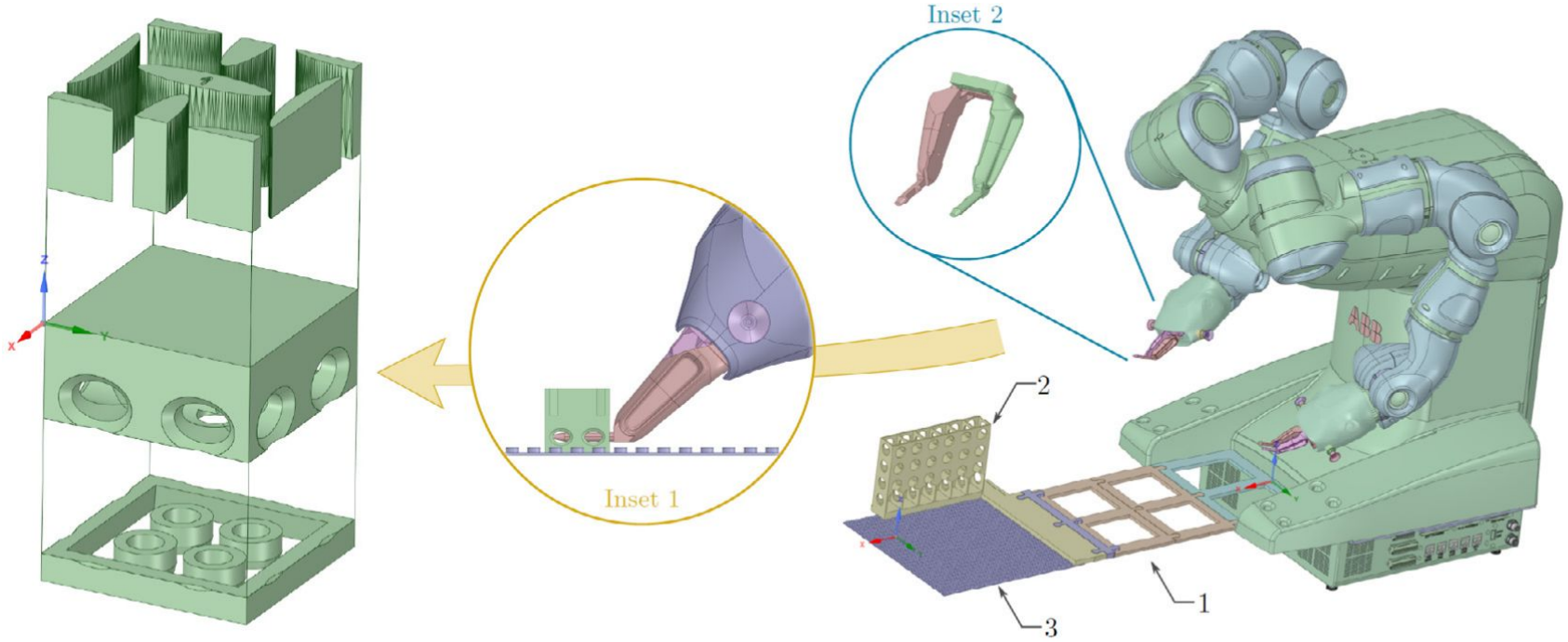
Combinatorial design and robot-assisted manufacturing of modular materials[solid]



Doškář, M. Somr, M., Hlůžek, R., Havelka, J., **Novák, J.**, **Zeman, J.** *Wang tiles enable combinatorial design and robot-assisted manufacturing of modular mechanical metamaterials.* Extreme Mech Lett **64**, 102087 (2023).

RO 4.3: Manufacturing and validation

Combinatorial design and robot-assisted manufacturing of modular materials[solid]



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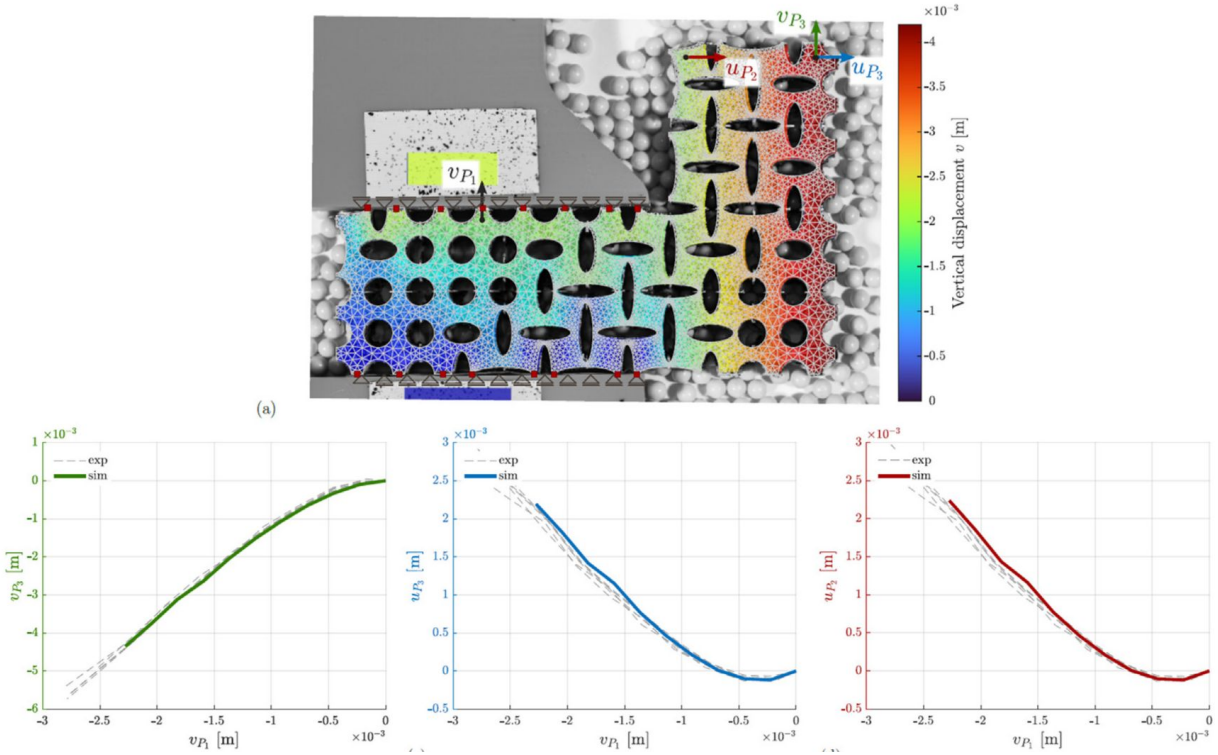
RO 4.3: Manufacturing and validation

Combinatorial design and robot-assisted manufacturing of modular materials[solid]



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RO 4.3: Manufacturing and validation

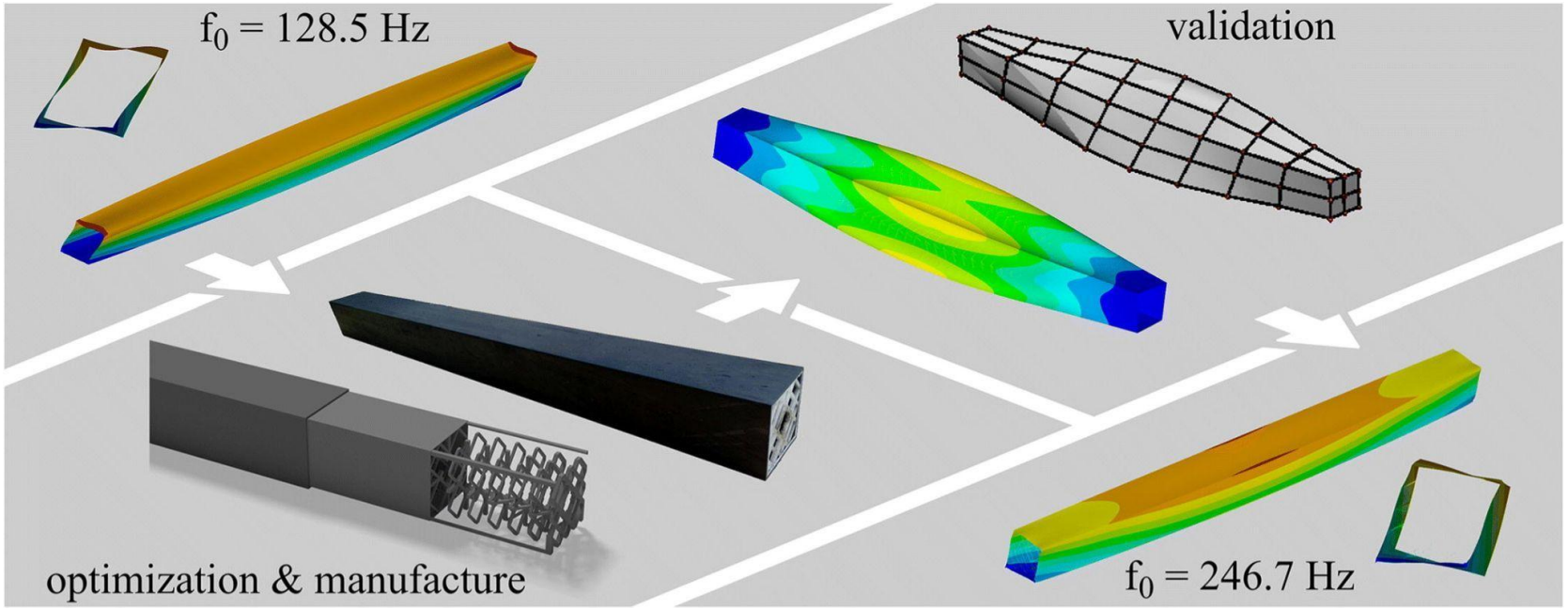
Optimal modular internal reinforcement

- vibration suspension in high-performance carbon composite tubes
- reinforcing core of 3D-printed trusses
- optimized minimum weight under compliance and eigenfrequency constraint
- large-scale linear semidefinite problem

Tyburec, M. et al. *Designing modular 3D printed reinforcement of wound composite hollow beams with semidefinite programming.* Mater Des **183**, 108131 (2019).

RO 4.3: Manufacturing and validation

Optimal modular internal reinforcement[lightweight]

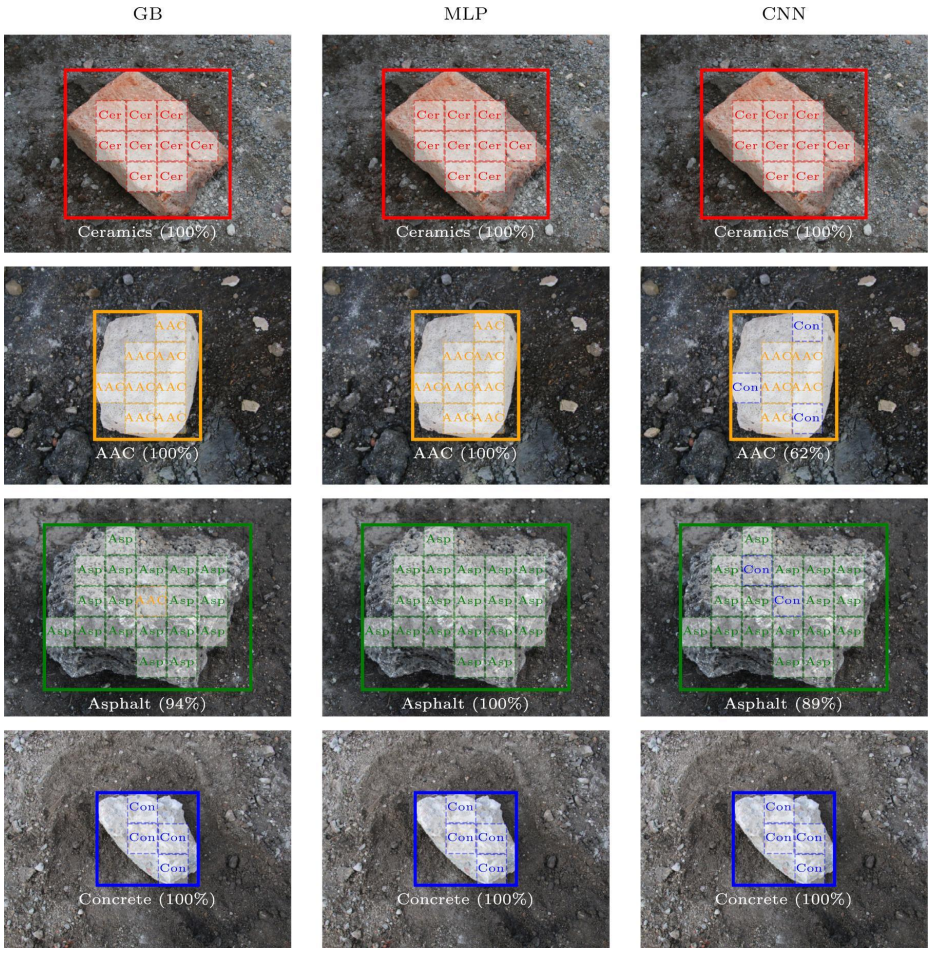


Tyburec, M. et al. *Designing modular 3D printed reinforcement of wound composite hollow beams with semidefinite programming.* Mater. Des. **183**, 108131 (2019).

RO 4.3: Manufacturing and validation

Automatic classification of waste fragments

- genuine Civil Engineering application
- testing of three classifiers
  - convolutional neural network
  - gradient boosting trees
  - multilayer perceptron
- combined procedure proposed
- overall accuracy up to 92.3%



Nežerka, V., Zbíral, T. & Trejbal, J. *Machine-learning-assisted classification of construction and demolition waste fragments using computer vision: Convolution versus extraction of selected features*. Expert Syst Appl **238**, 121568 (2024).

RO 4.3: Manufacturing and validation

- **What we aim for:**
  - extending the robot-assisted manufacturing study to 3D (porous) modules
  - validating the designs produced in remaining ROs
  - (valorizing consortium experience for Civil Engineering applications)

- **International collaboration:**
  - Dr. Viacheslav Slesarenko (Cluster of Excellence livMatS, University of Freiburg)

- **Cooperation with other RAs:**
  - Z. Hurák, J. Zemánek - RO 2.1: module manipulation by magnetic field
  - we are open to collaborations

Potential international collaborations

- **Dr. Heiko Andrae**, Fraunhofer Institute for Industrial Mathematics, Kaiserslautern, Germany; **Dr. Robin Oval**, Delft University of Technology, the Netherlands
  - expressed interest in collaborating on modular-topology optimization problems
- **Dr. Alexander Heinlein**, Delft University of Technology, the Netherlands
  - expressed interest in domain decomposition methods for modular problems
- **RECONMATIC**: Automated Solutions For Sustainable And Circular Construction And Demolition Waste Management
  - international resource of Civil Engineering applications

Potential industrial collaborations

- **bimproject.cloud**

- **IOTEE s.r.o.**

- **Tecnalia**

- **Strabag**

- **Knauf Insulation**

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Thank you for your attention!

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