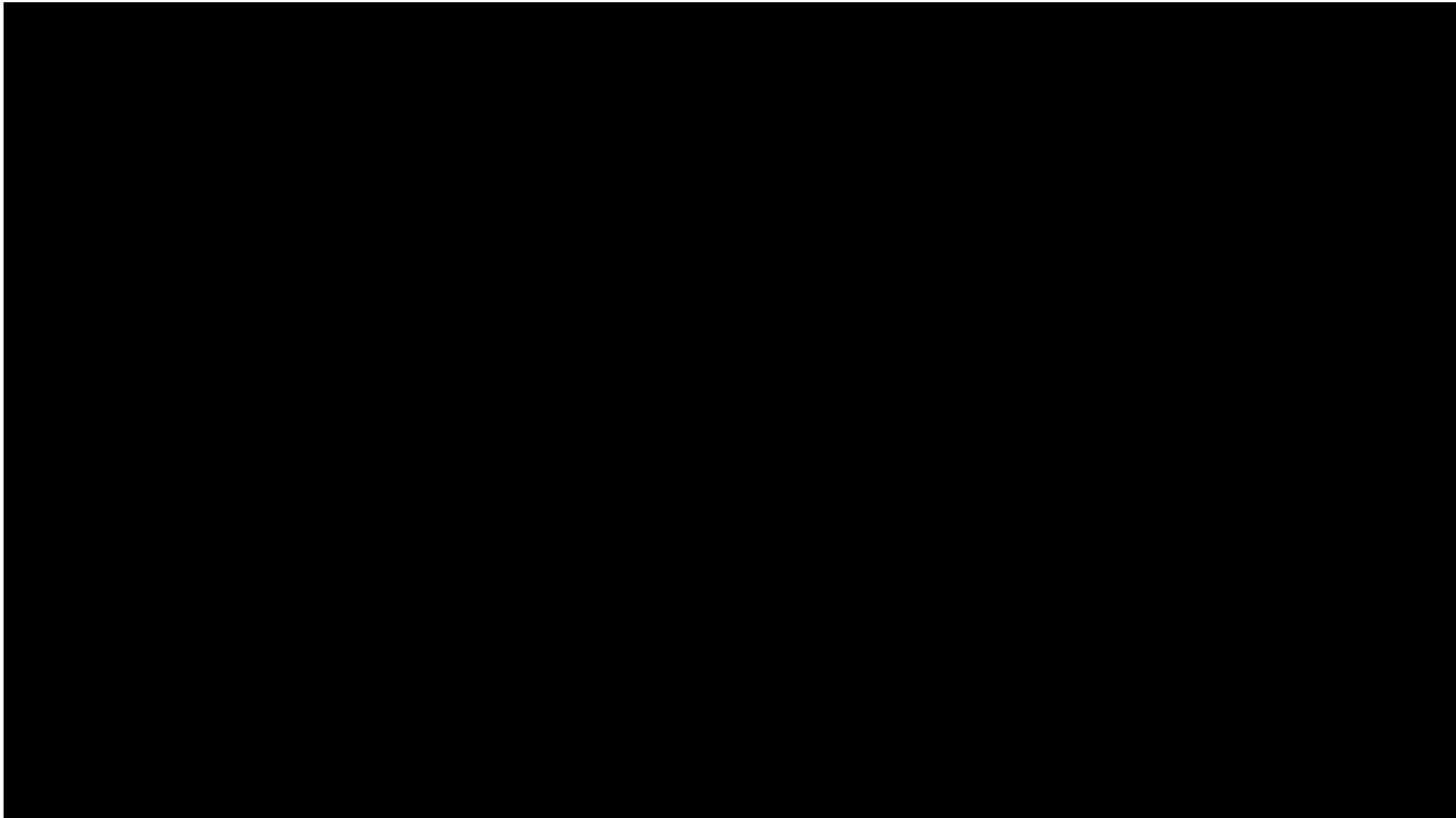
University of Stuttgart
Institute for System Dynamics

Ultralightweight and Adaptive Structures

A Technology for Tomorrow's Telescopes and Instruments?

Michael Böhm

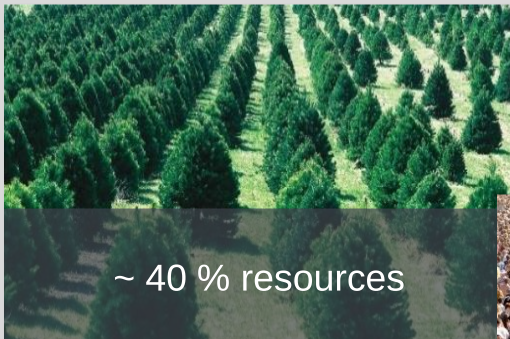
Video Excellence Cluster

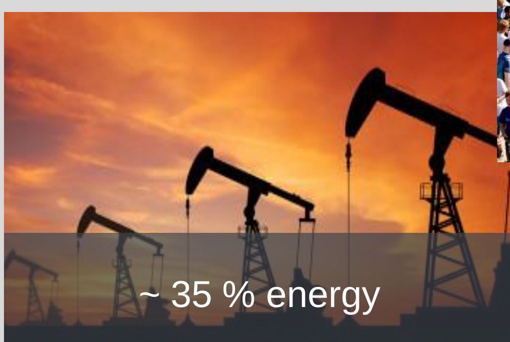


Adaptive Skins and Structures for the built envirnment of the tomorrow

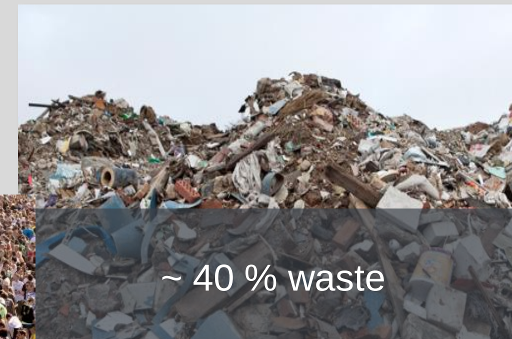
construction sector accounts for:

consumption





production



UNEP, 2011; OECD, 2015; UN, Department of Economic and Social Affairs, 2017

CRC 1244 – Cluster Overview

Lead principal investigators

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Lead principal investigator

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Managing director

Associated institutes

Baustatik und Baudynamik

KTD

ito

IMA

IFB

ILEK

isys

IIS

IFF

zirius

Zentrum für Interdisziplinäre Risiko- und Innovationsforschung

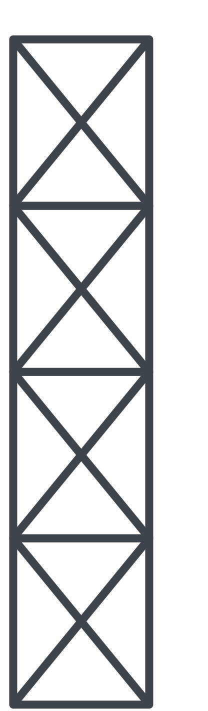
LBP

ipoc

ICD

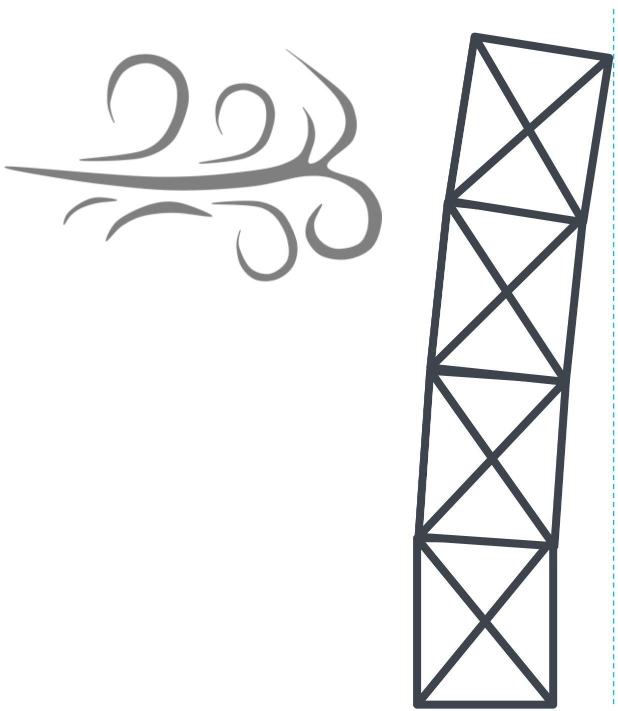
Fraunhofer IBP

Ultralightweight design



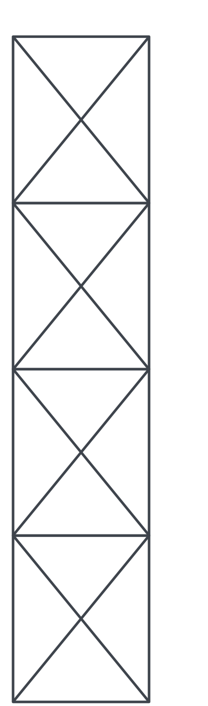
- High stiffness necessary for comfort

Ultralightweight design



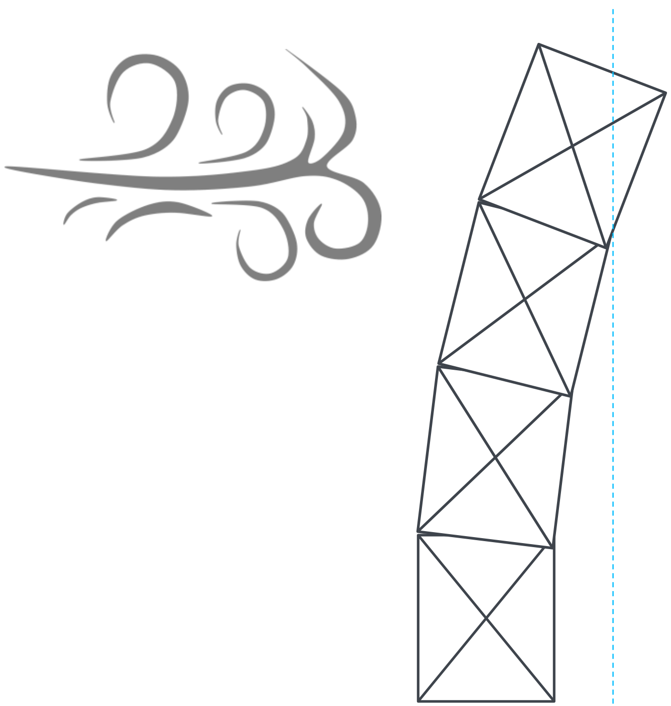
- High stiffness necessary for comfort

Ultralightweight design



- High stiffness necessary for comfort
- Lower stiffness remains safe, but excitations are outside of usability bounds

Ultralightweight design



- High stiffness necessary for comfort
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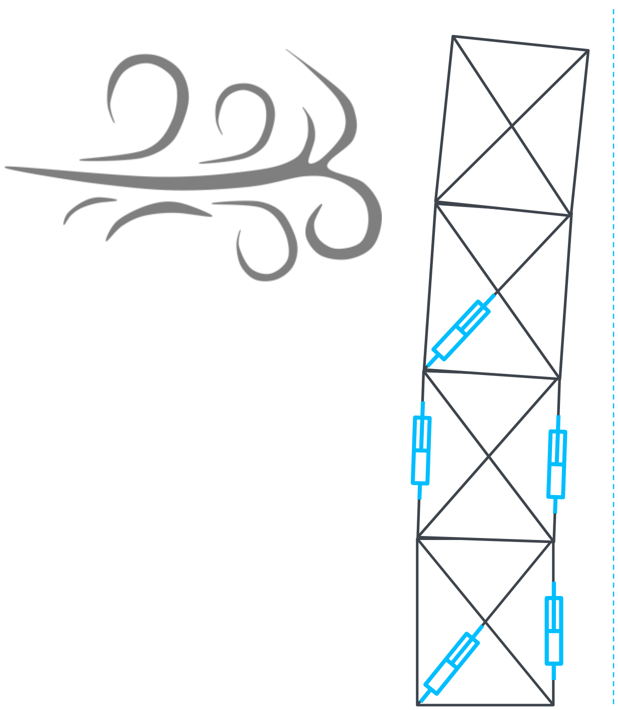
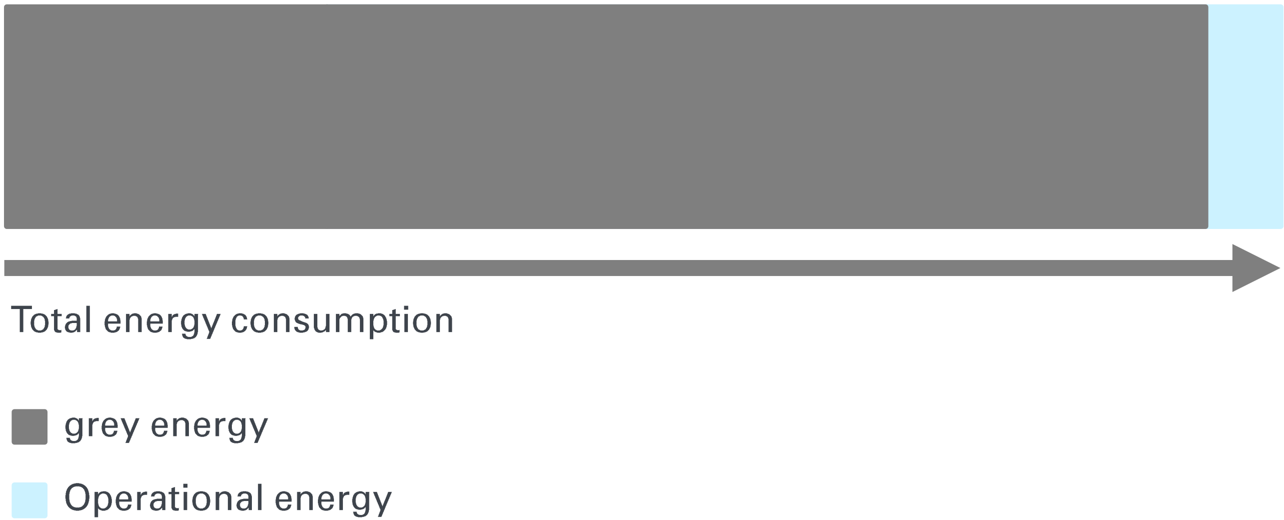
Ultralightweight design



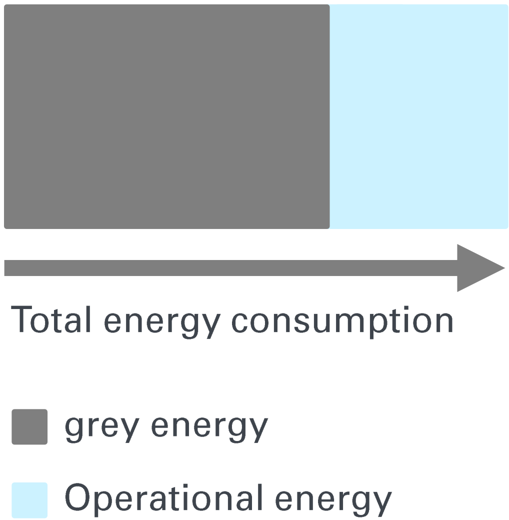
- High stiffness necessary for comfort
- Lower stiffness remains safe, but excitations are outside of usability bounds
- Active structures can stay within usability bounds despite ultraleightweight design

Save up to 50% in total mass

Less Grey Energy



Less Grey Energy



CRC 1244 – Goals

The CRC's research is focused on the potential of adaptive structures, envelopes and interior fittings

The work of the CRC will lead to a transformation from

high tech to low tech

and from

high cost to low cost,

such that the comprehensive results can be utilized for a broad variety of applications.

Classic lightweight design, (non-adaptive) concrete shell

Betonschale am Rastplatz Deitingen/CH
Architekt and Ingenieur: Heinz Isler

Form determining load case: dead weight

Ultralightweight design – Adaptive (Wood-) Shell

The Stuttgart SmartShell is a large-scale demonstrator in the project HIKE (Image: Bosch Rexroth)

Manipulation of tension and/or displacement fields

Increasing the life-time of (existing) bridges

Active load compensation leads to a stress range reduction

Adaptive Facade

- Vertical cable facades very common:
  - Kempinski Hotel, Munich
  - Foyer, University of Bremen
  - Aviation Center Lufthansa, Frankfurt

- Pneumatic actuators

Adaptive Facade

Goals:

- Reduce facade element displacements
- Damping of vibrations

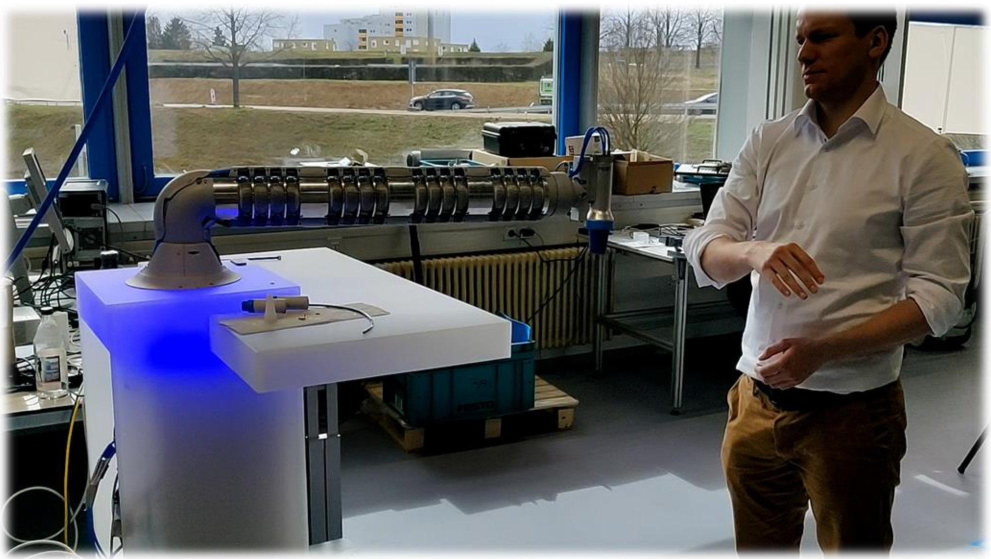
- Input: $u(t)$ – Actuator position
- Output: $y(t)$ – Maximum displacement of the facade
  - But: Measurement of cable strains and accelerations (IMU)
- Desired value: $y_d(t) = \min y(t)$
- Disturbances: wind

Adaptive Facade

Adaptive Facade

Examples for lightweight design

- Extensive use of new and improved materials
  - CFRP
  - High-tensile steel
- Next steps:
  - lower mass
  - high artificial stiffness due to control software

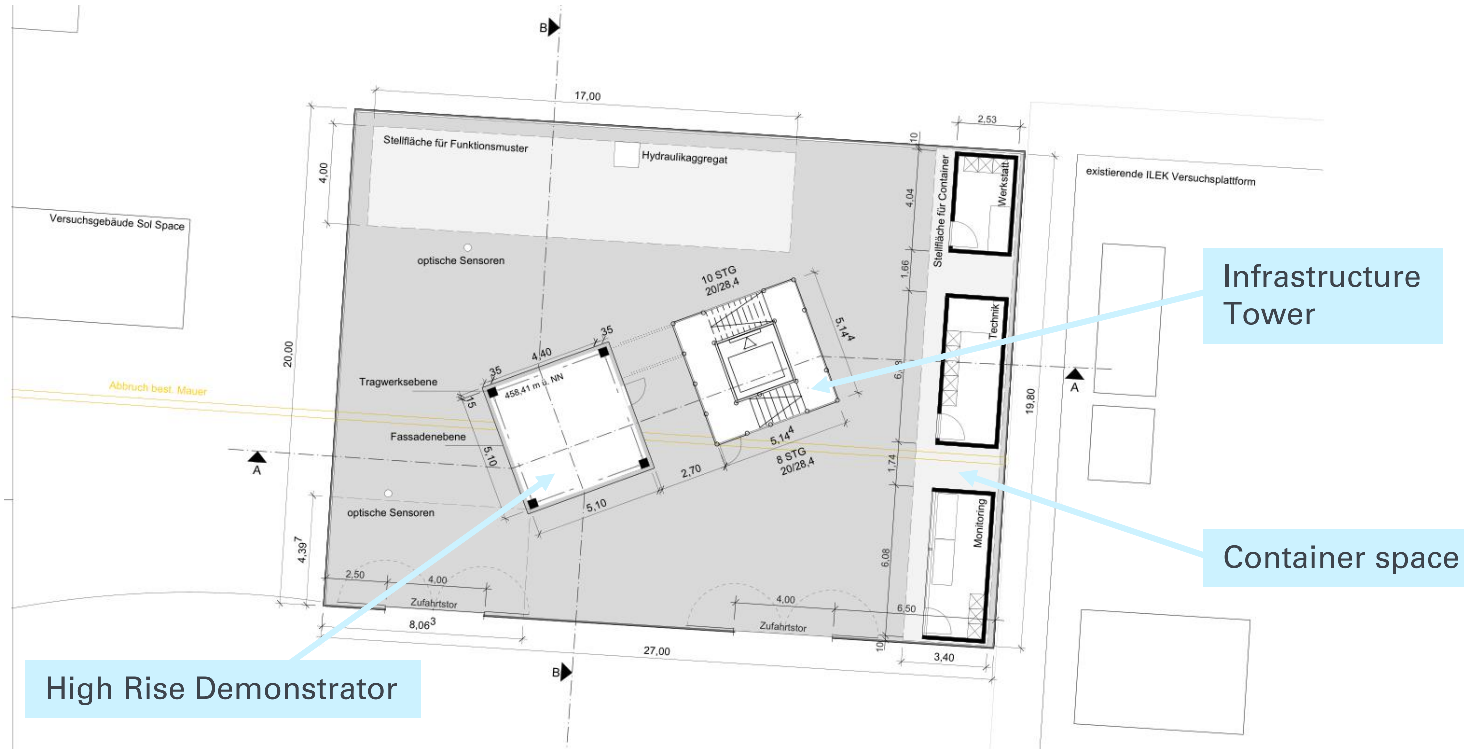


CRC 1244 – First adaptive high rise building of the world

Site

CRC 1244 – First adaptive high rise building of the world

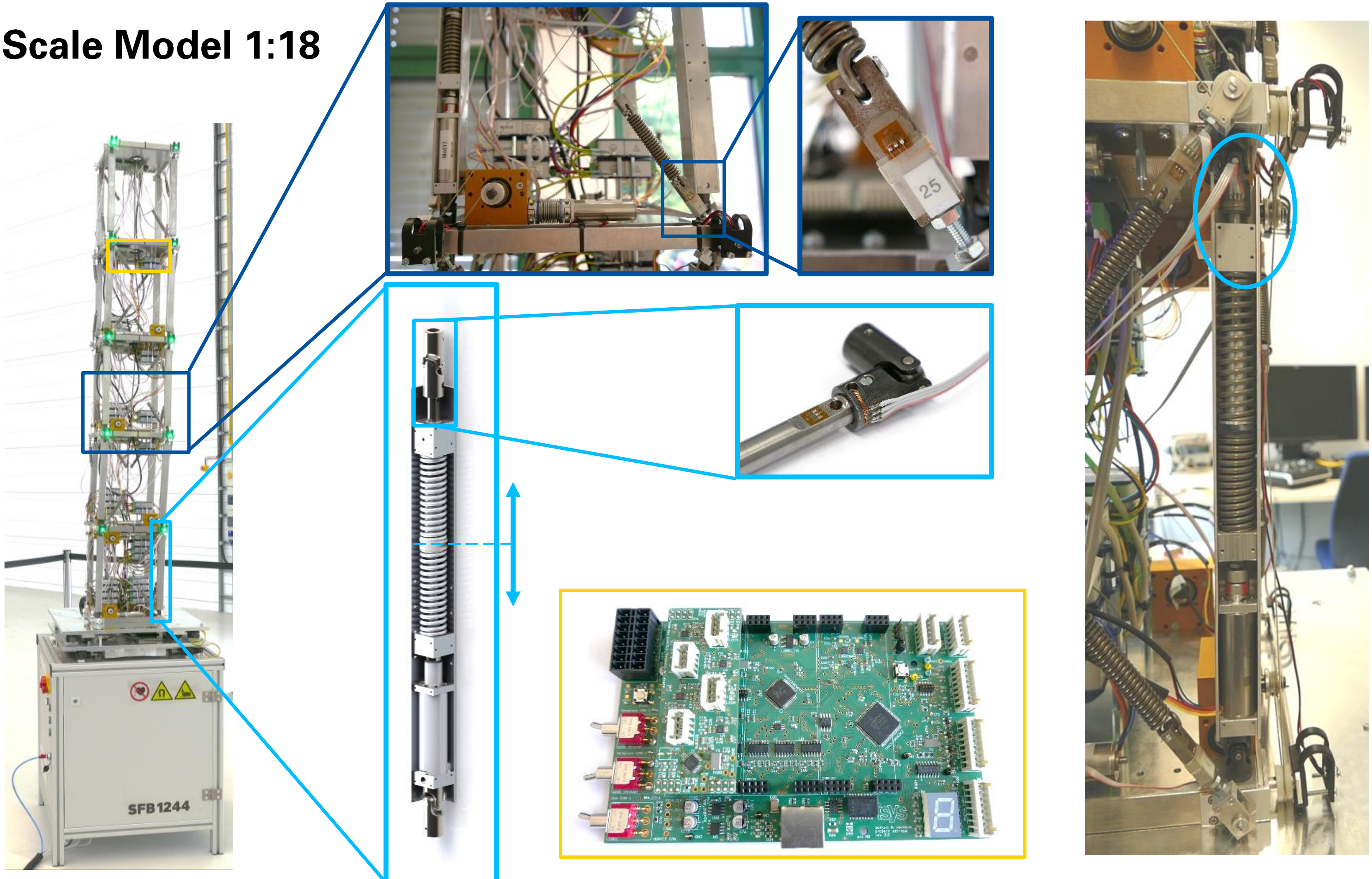
Plans



CRC 1244 – First adaptive high rise building of the world
Status

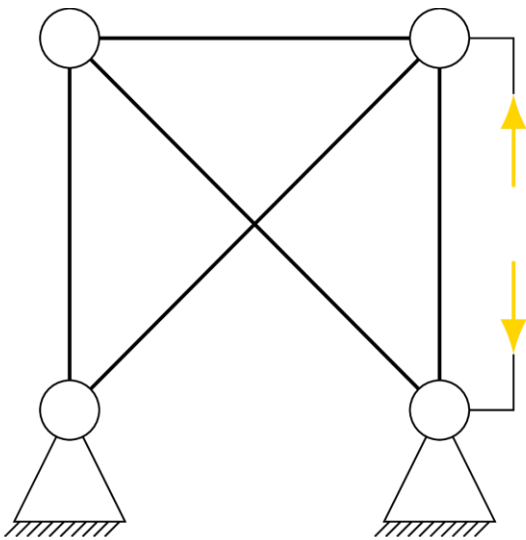
Source: ILEK

Scale Model 1:18



Prototype

Actuation Strategies – parallel actuation



- Force from structural element and actuator are added:

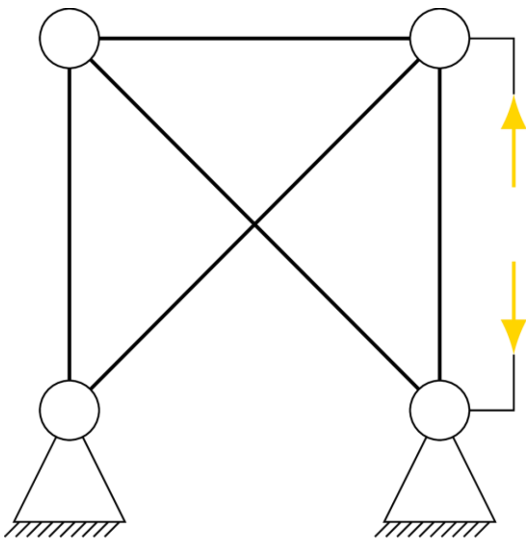
$$F_a + F_p = F_e$$

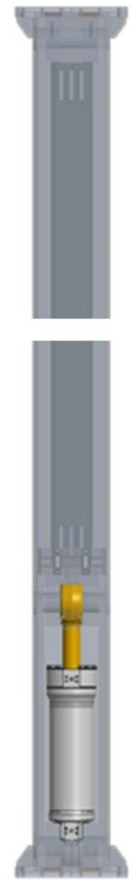
- Displacements are equal:

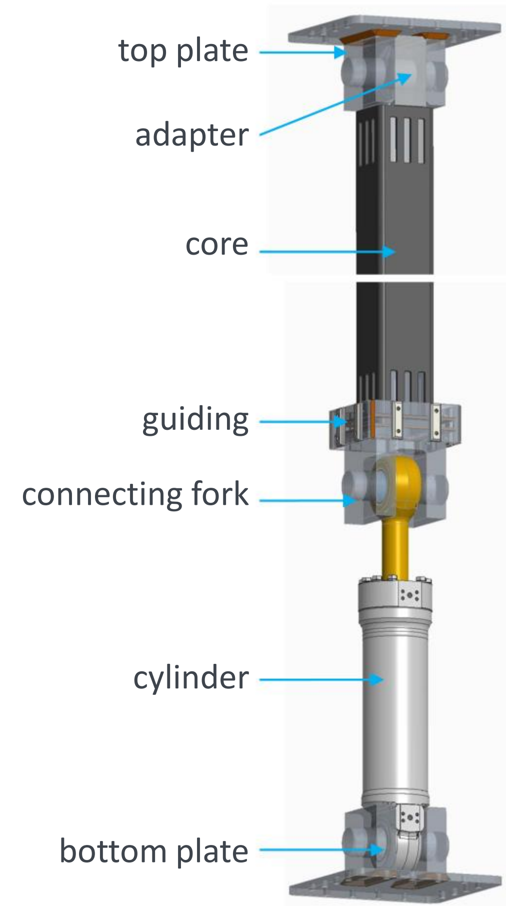
$$\Delta l_a = \Delta l_p = \Delta l_e$$

- Used for elements with high loads due to dead load
  - Columns
- Actuator with zero force at parking position
- Mechanical integration more complicated

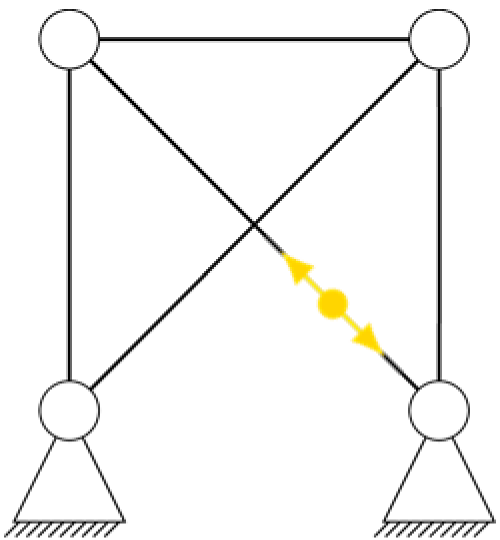
Actuation Strategies – parallel actuation







Actuation Strategies – serial actuation



- Element force equals actuator force

$$F_a = F_p = F_e$$

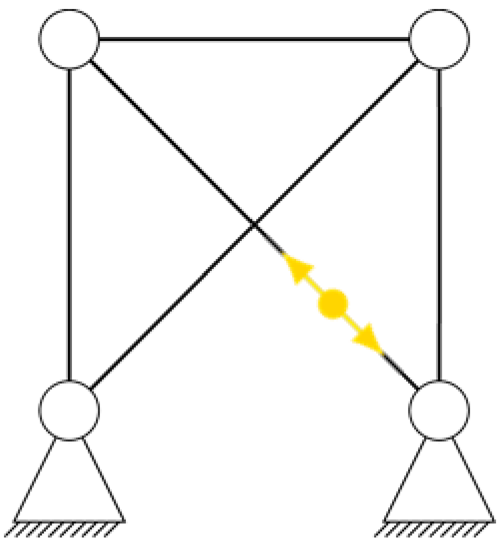
- Displacements are added:

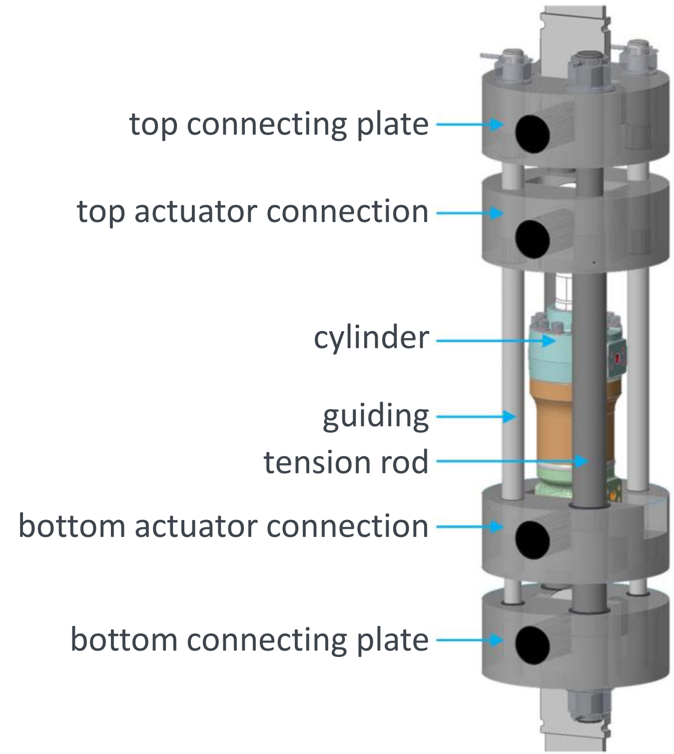
$$\Delta l_a + \Delta l_p = \Delta l_e$$

- Suitable especially for structures with initially small loads
  - Diagonal bracings

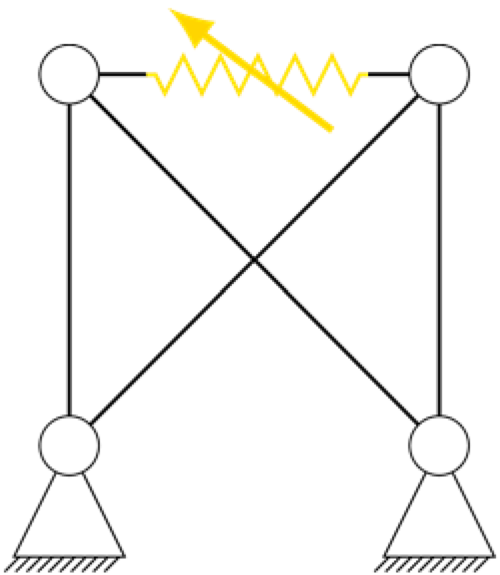
- Mechanical integration much simpler

Actuation Strategies – serial actuation



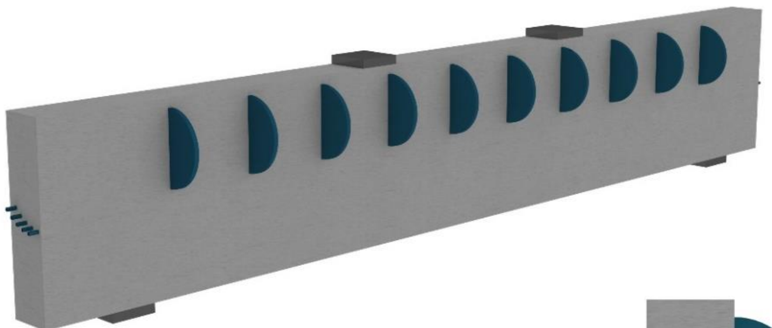


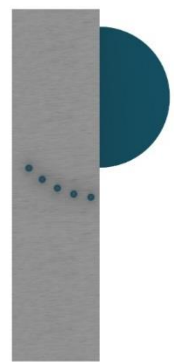
Actuation Strategies – integrated actuation



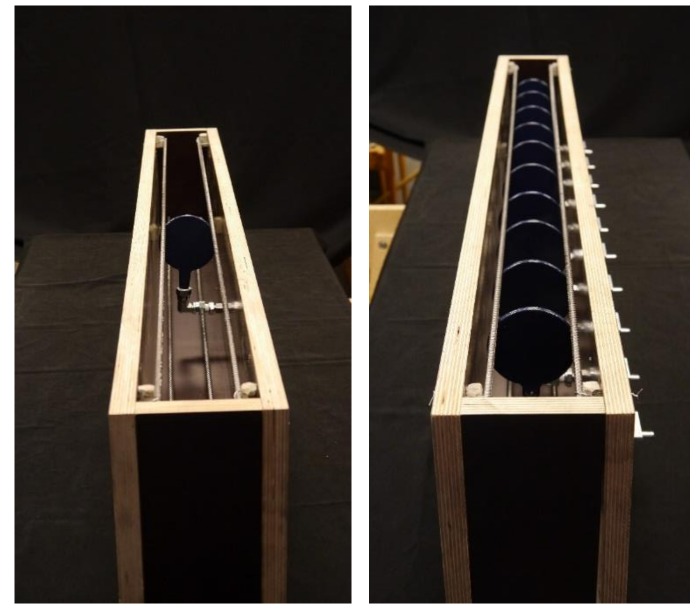
- Manipulation of the element stiffness
  - Nonlinear Input characteristic
- Suitable for normally prestressed elements
  - Cables, horizontal bars and plates
- Mechanical integration much simpler

Fluidic Actuator – Video Prototype





Rendering of the experimental model
Source: ILEK



Beam with 1 actuator (left) and 10 actuators (right)
Source: ILEK

Fluidic actuator – Video Prototype

Source: ILEK, University of Stuttgart

Fluidic actuator – Modeling and placement of pressure chambers

- Euler-Bernoulli beam equation

Input profile $\tilde{\theta}(x, \xi_i)$ Pressure p_i

Stationary System Equation

$$EI \frac{\mathrm{d}^4 w(x)}{\mathrm{d}x^4} = \sum_{i=1}^{m} \tilde{\theta}(x, \xi_i) p_i + q(x) \qquad 0 < x < L$$

Deflection curve $w(x)$ Spatial variable x Load $q(x)$

Boundary Conditions

$$w(0) = 0, \quad w(L) = 0, \quad \left.\frac{\mathrm{d}^2 w(x)}{\mathrm{d}x^2}\right|_{x=0} = 0, \quad \left.\frac{\mathrm{d}^2 w(x)}{\mathrm{d}x^2}\right|_{x=L} = 0$$

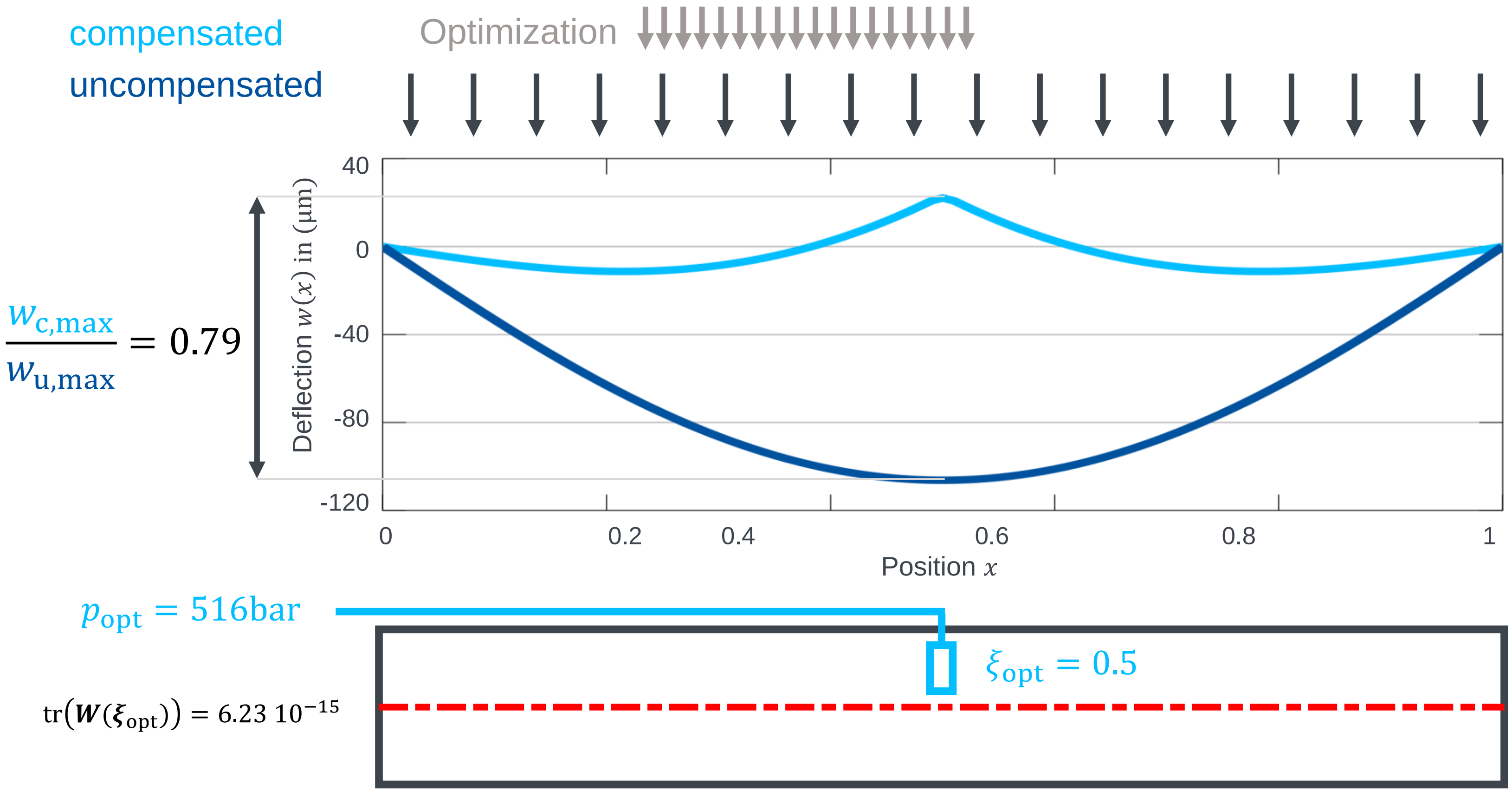
Analytical solution

Optimal input

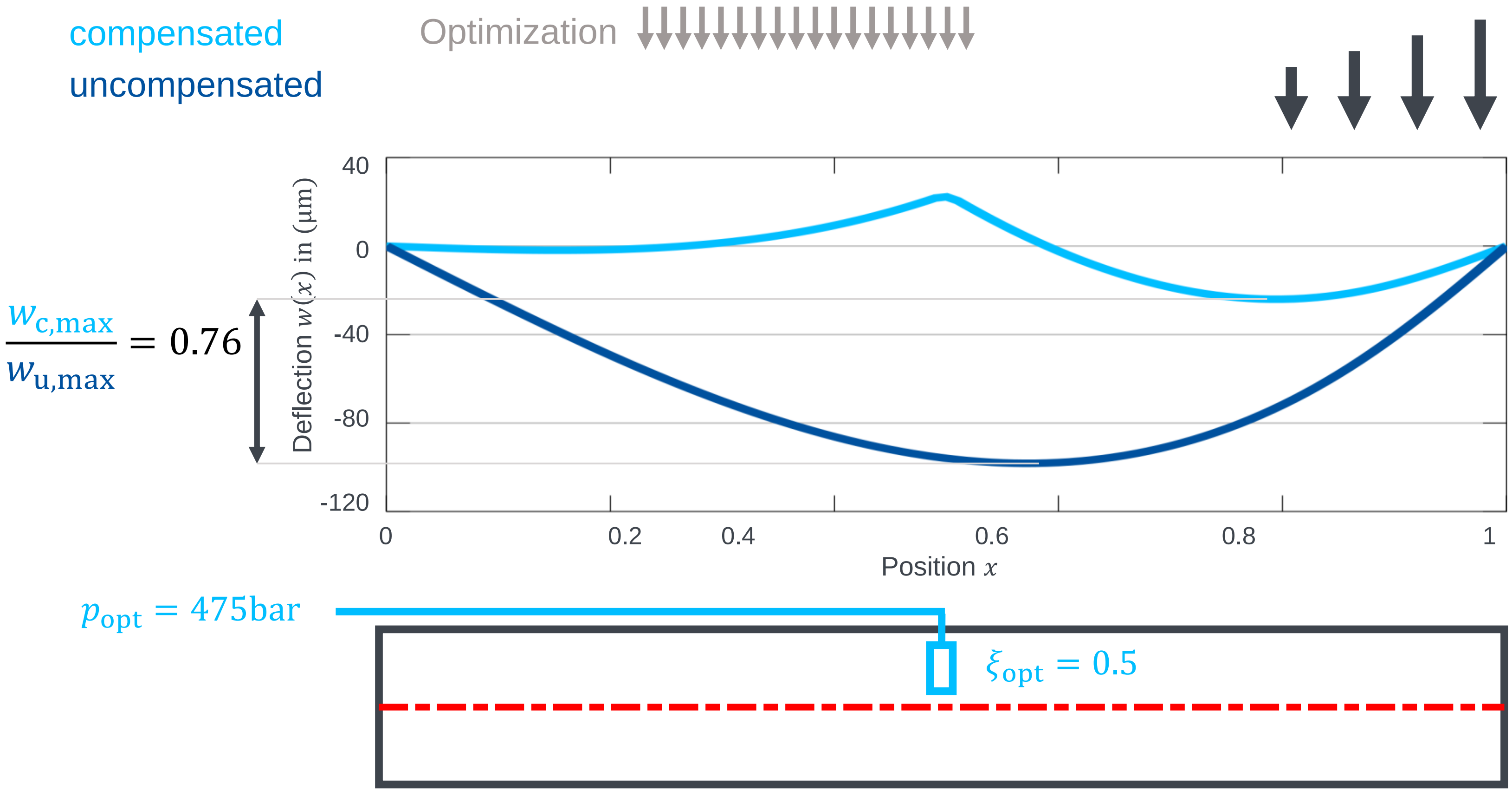
Optimal Deflection curve

Optimization

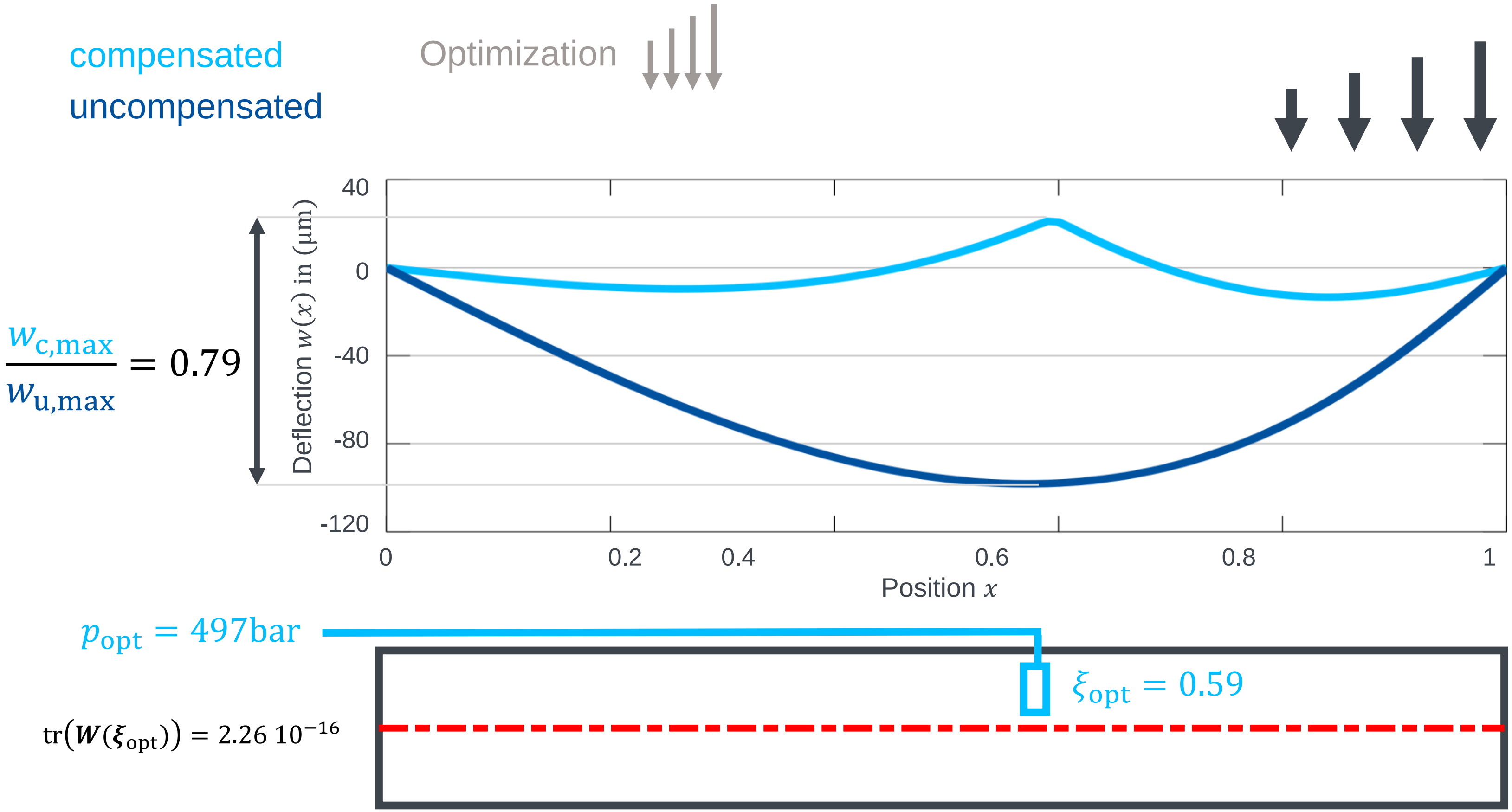
Results – Optimal Deflection Curve



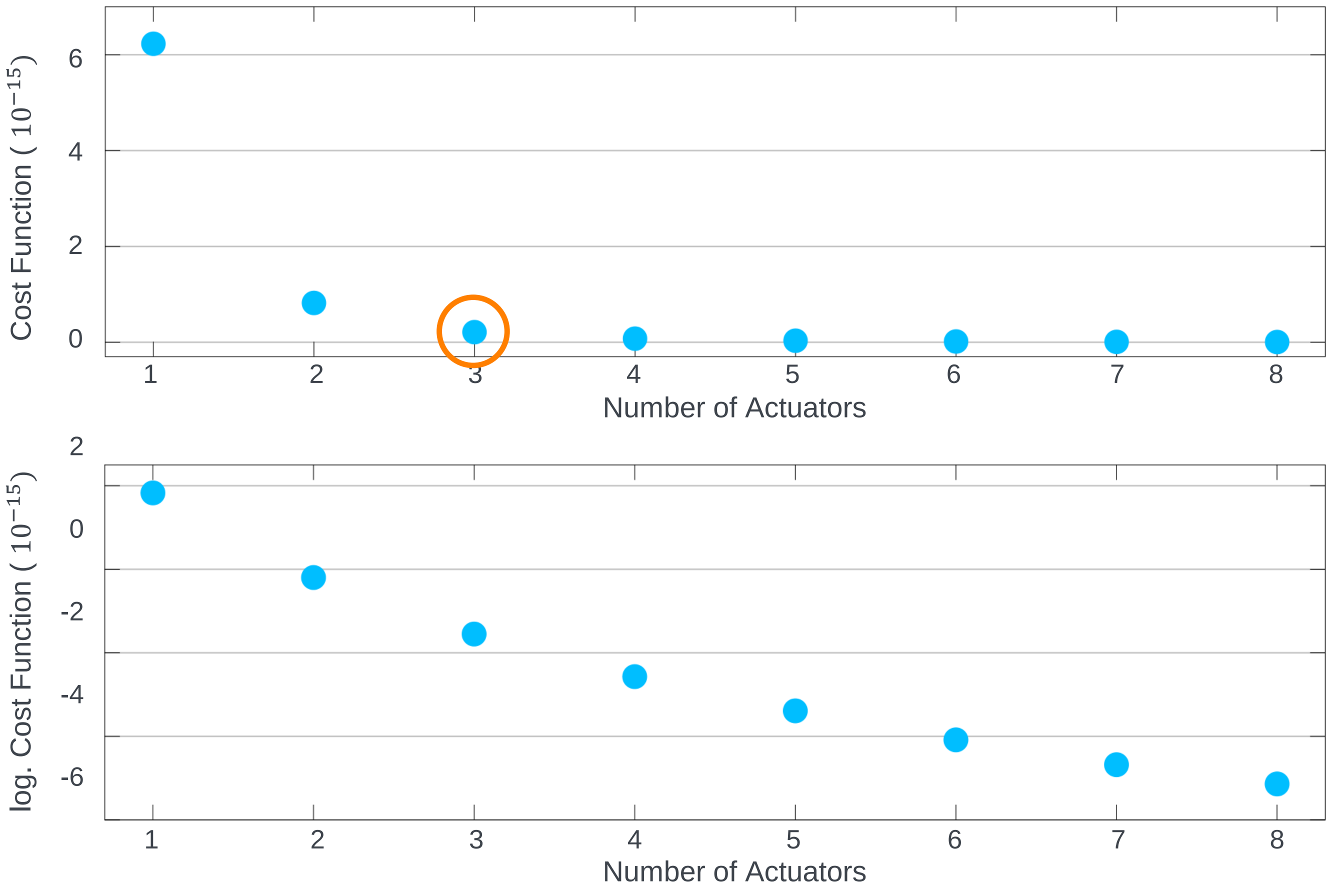
Results – Optimal Deflection Curve



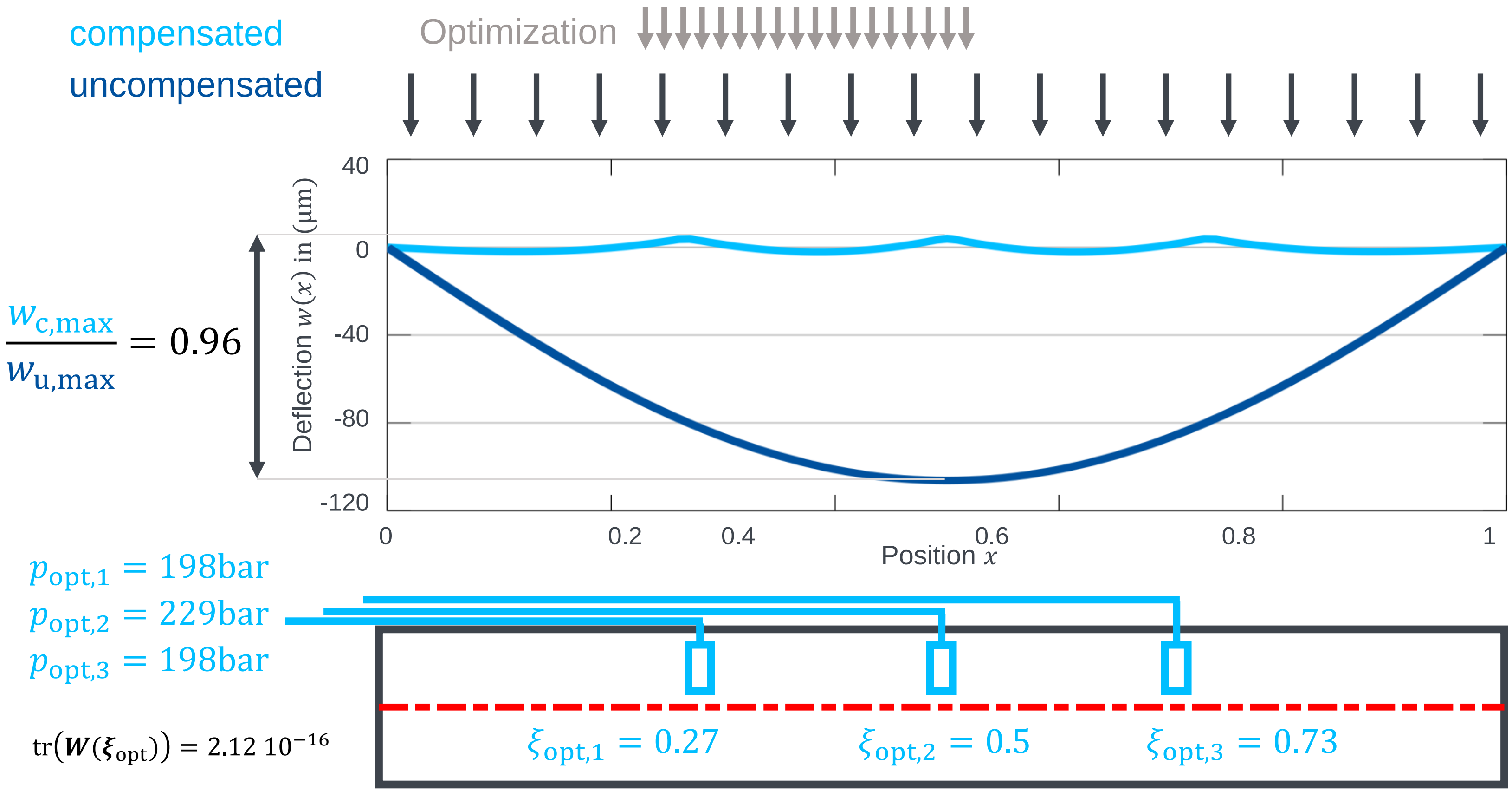
Results – Optimal Deflection Curve



Results – Number of Actuators



Results – Optimal Deflection Curve



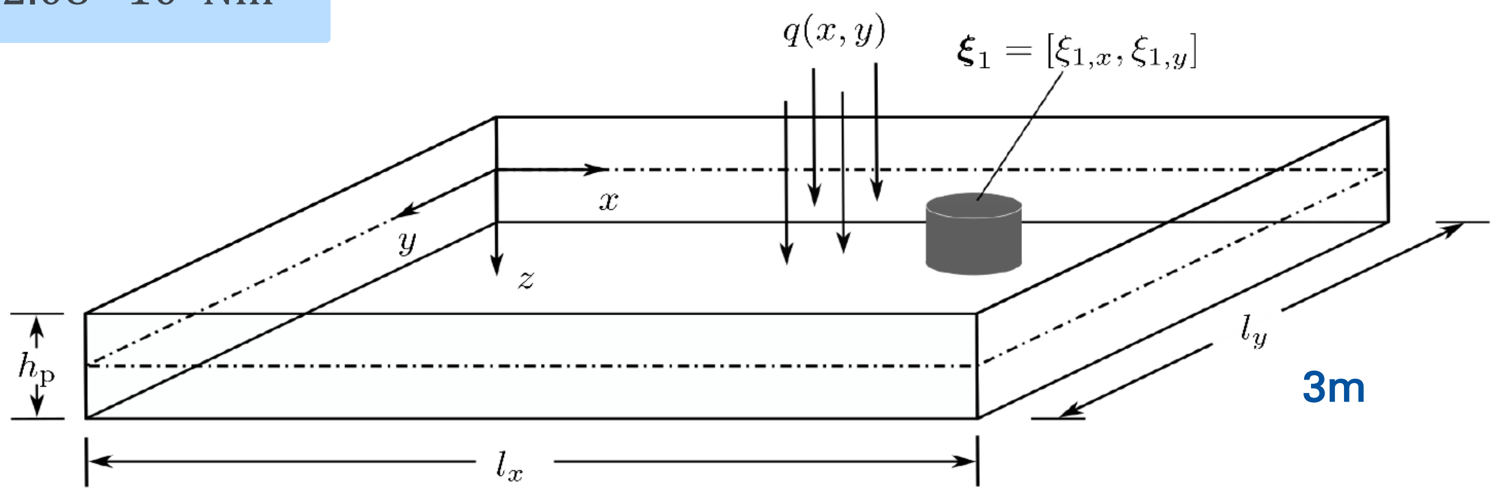
More Actutator Placement Results for Integrated Fluidic Actuators

Concrete

$$E = 30 \cdot 10^9 \frac{\mathrm{N}}{\mathrm{m}^2}$$
$$\nu = 0.2$$
$$K = 2.08 \cdot 10^7 \mathrm{Nm}$$

Actuator

$$r_a = 0.03\mathrm{m}$$
$$h_a = 0.08\mathrm{m}$$
$$d_a = 0.05\mathrm{m}$$
$$d_m = 0.06\mathrm{m}$$

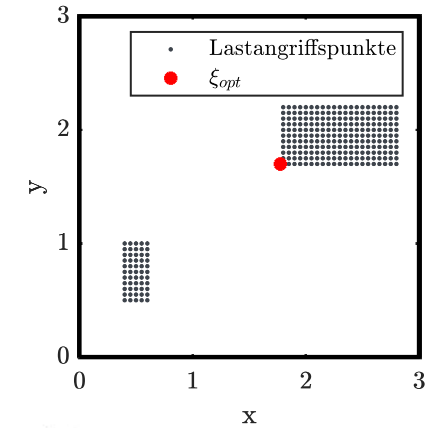


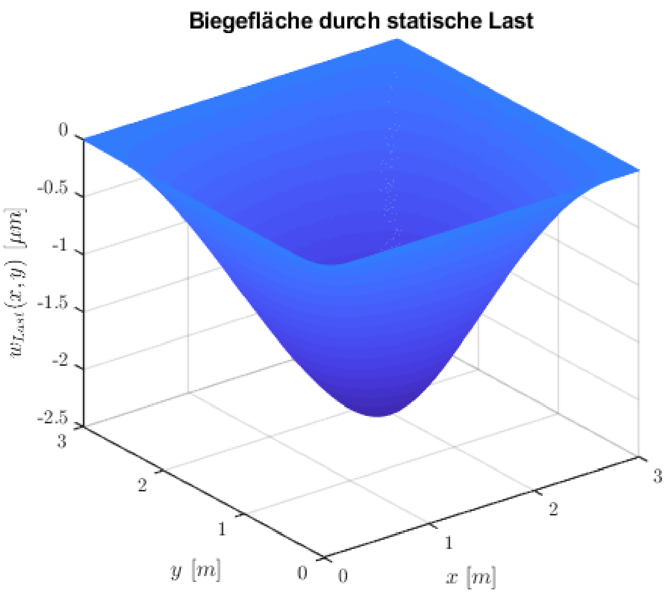
0.2m

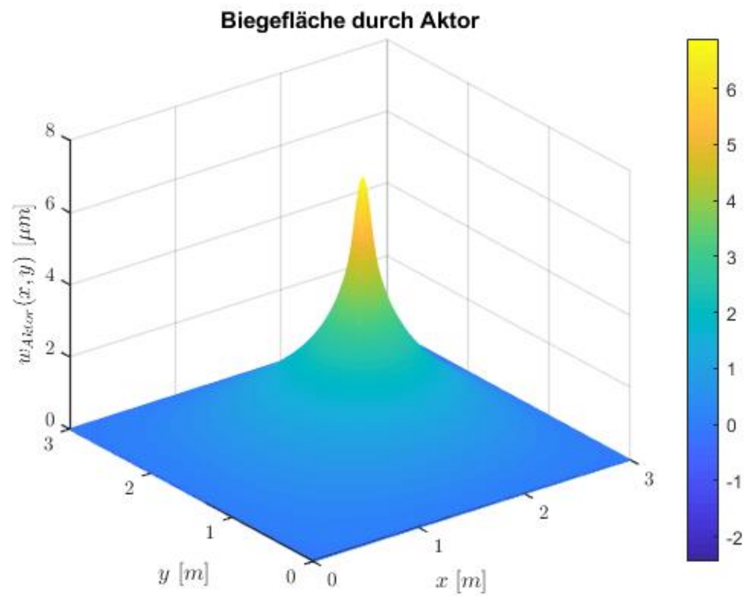
3m

3m

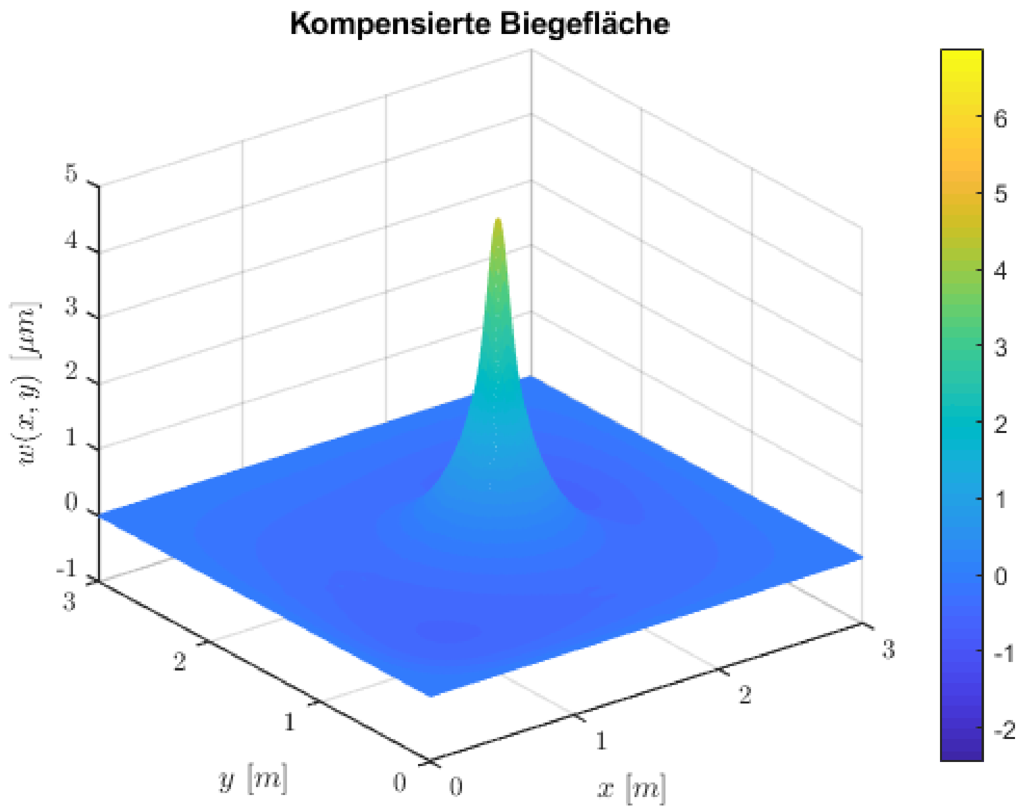
Example: Two different loads

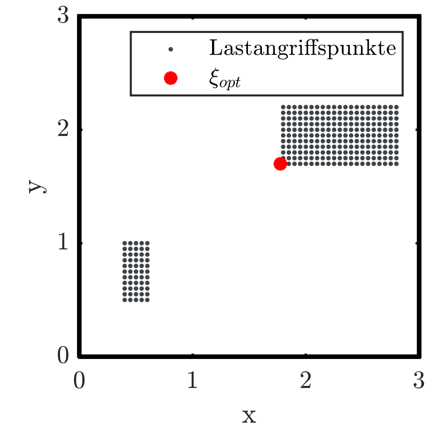






Example: Two different loads

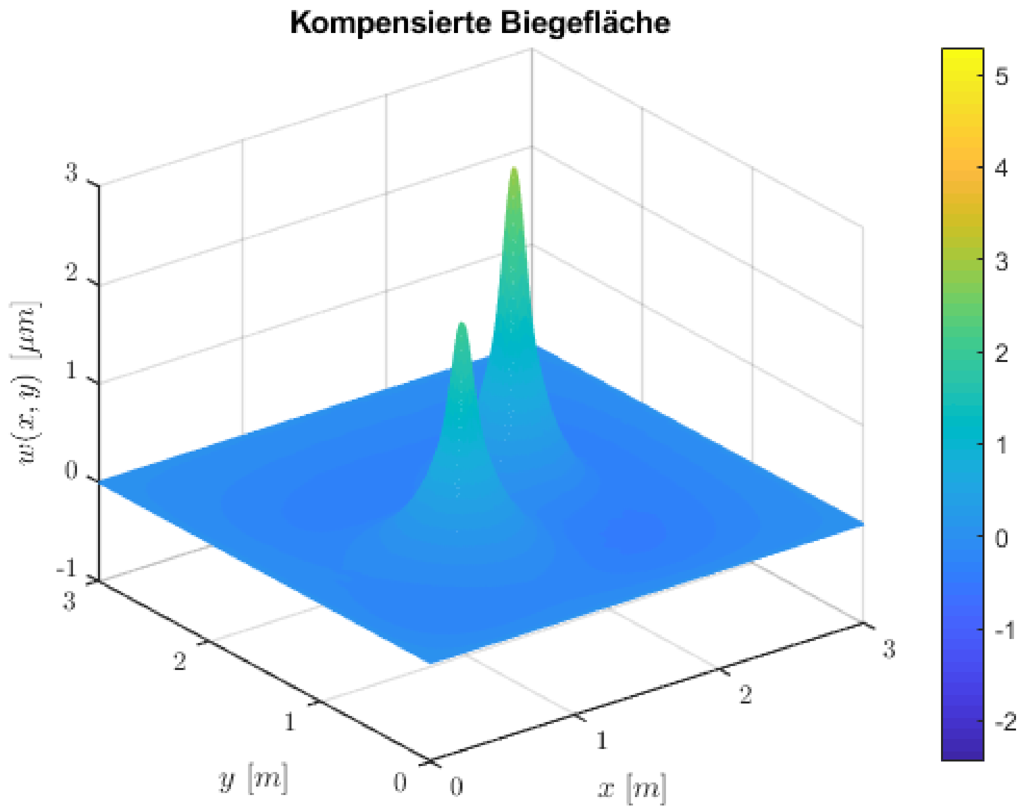


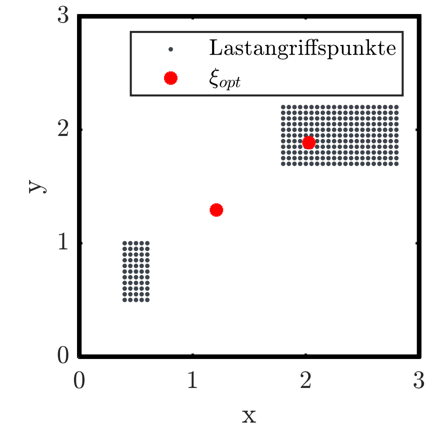


Statische Lastkompensation
88,4%

Optimaler Druck
188,9 bar

Example: Two different loads and two actuators

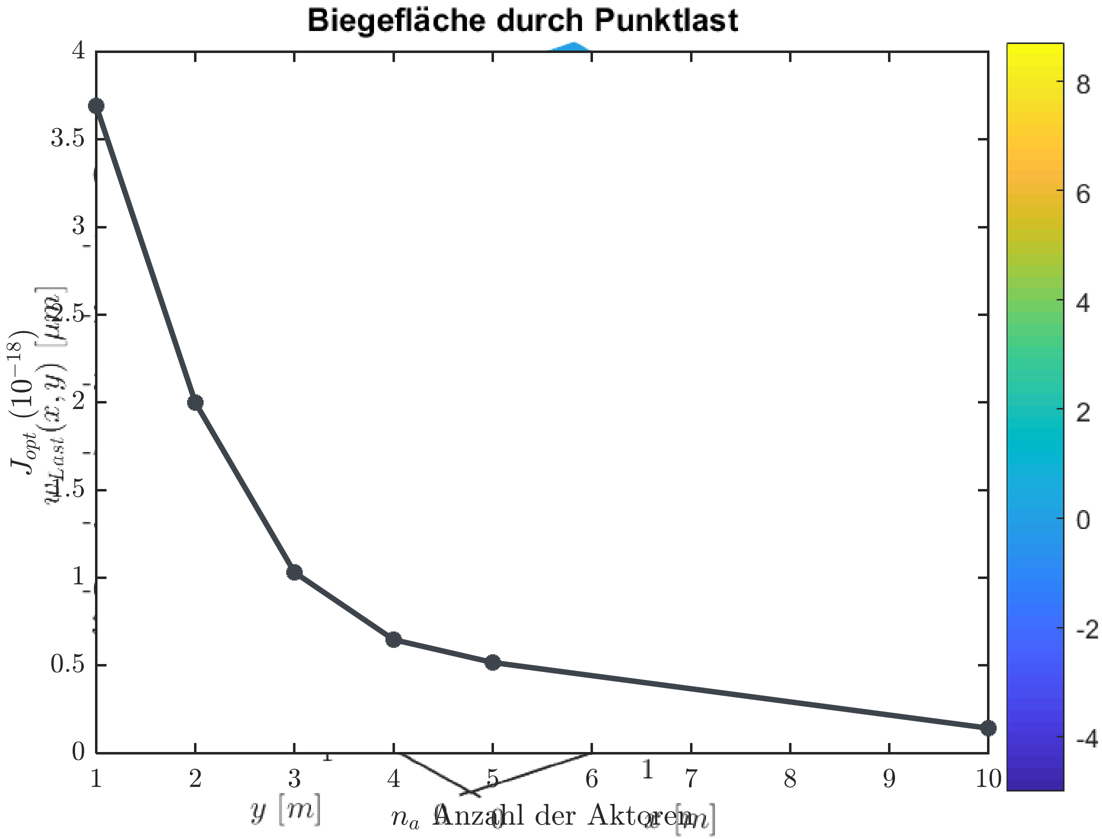


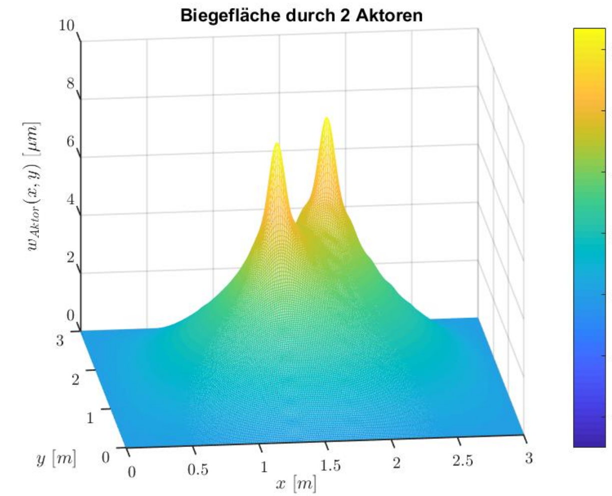


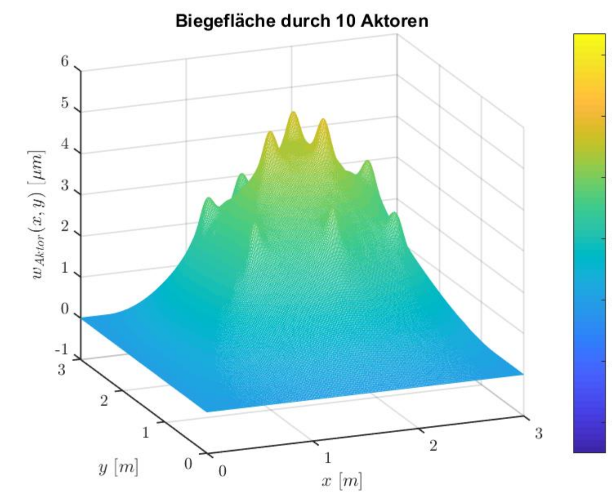
Statische Lastkompensation
94,6%

Optimaler Druck
138,0 bar
90,2 bar

Example: Impact of number of actuators







Modeling of Mechanical Structures

- finite element modelling
  - ceiling
  - vertical beam
  - diagonal bracing
- all connections modeled as ideal joints

linear, time-invariant mechanical system

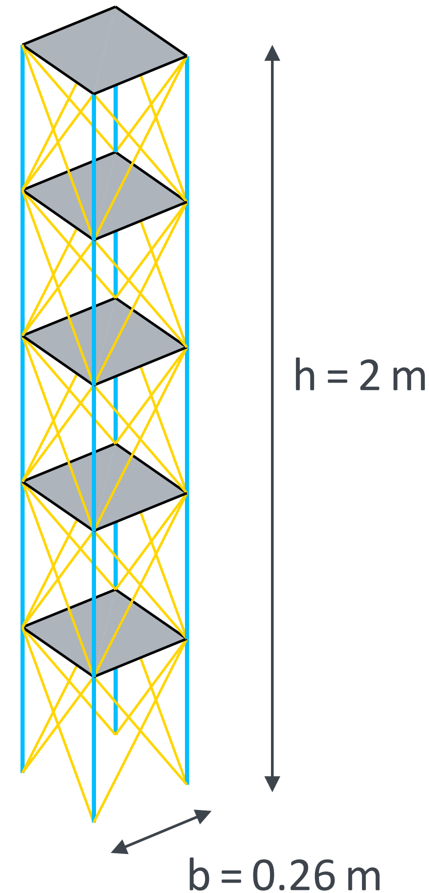
$$\boldsymbol{M}\ddot{\boldsymbol{q}}(t) + \boldsymbol{D}\dot{\boldsymbol{q}}(t) + \boldsymbol{K}\boldsymbol{q}(t) = \boldsymbol{f}(t), \qquad t > 0$$

$$\boldsymbol{q}(0) = \boldsymbol{q}_0, \qquad \dot{\boldsymbol{q}}(0) = \boldsymbol{q}_1$$

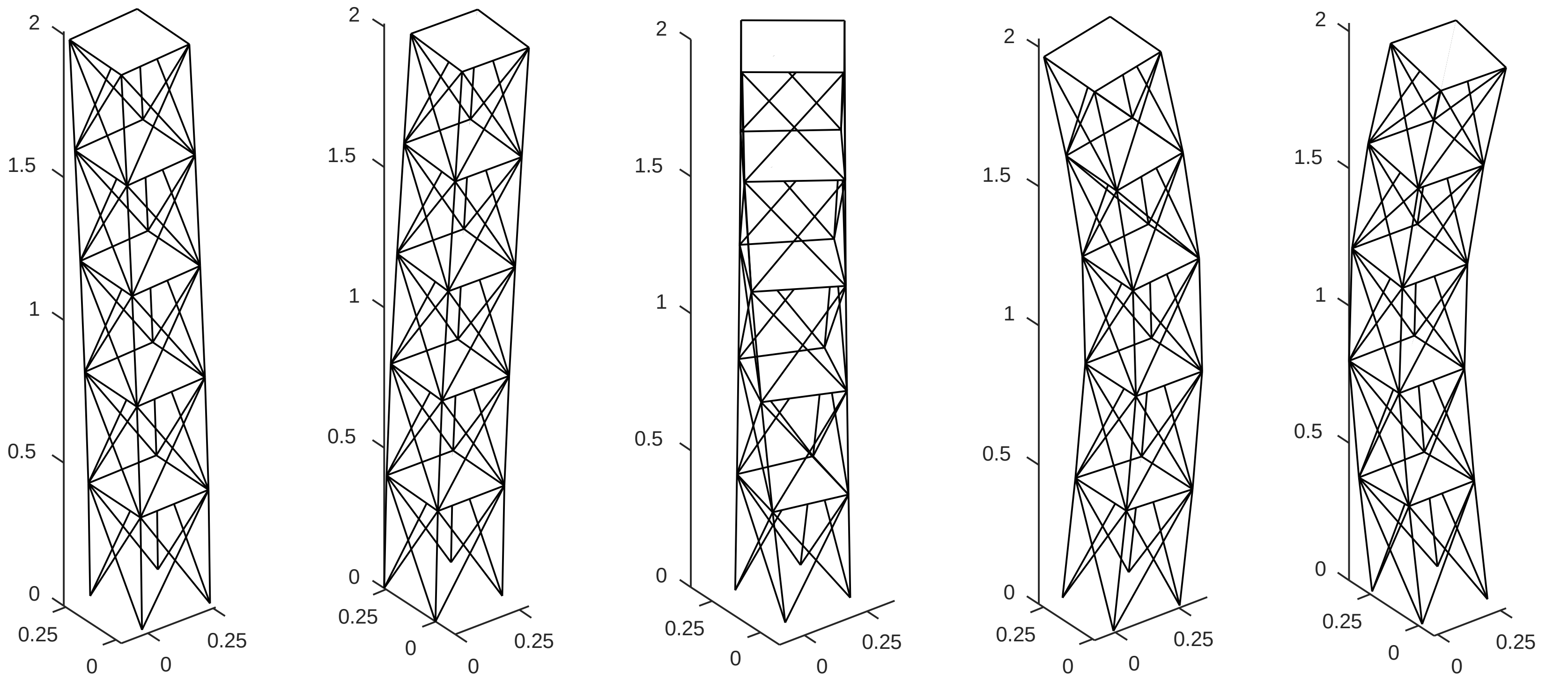
modal equations of motion

$$\ddot{\boldsymbol{\eta}}(t) + 2\mathbf{Z}\boldsymbol{\Omega}\dot{\boldsymbol{\eta}}(t) + \boldsymbol{\Omega}^2\boldsymbol{\eta}(t) = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{f}(t)$$

$$\boldsymbol{\eta}(0) = \boldsymbol{\Phi}^{-1}\boldsymbol{q}_0, \qquad \dot{\boldsymbol{\eta}}(t) = \boldsymbol{\Phi}^{-1}\boldsymbol{q}_1$$



Eigenmodes and Eigenfrequencies

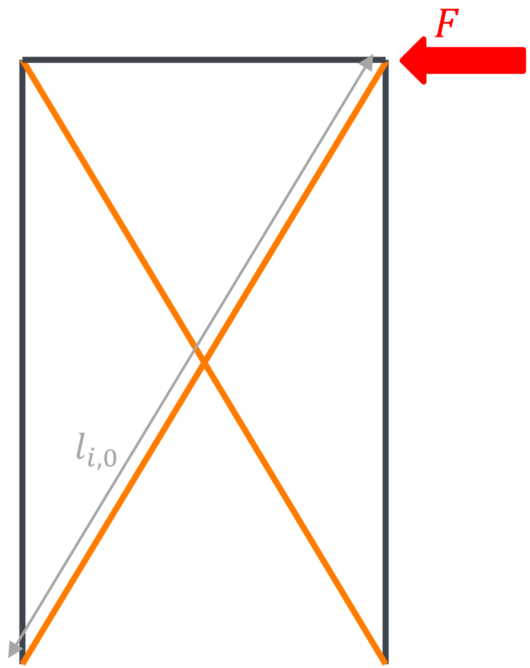


$\omega_{1,2}$ = 0.7 Hz
$\boldsymbol{\varphi}_{1,2}$ 1st order bending mode

ω_3 = 3.2 Hz
$\boldsymbol{\varphi}_3$ torsion mode

$\omega_{4,5}$ = 3.4 Hz
$\boldsymbol{\varphi}_{4,5}$ 2nd order bending mode

System Modeling – Nonlinear Equations of Motion



State dependent stiffness

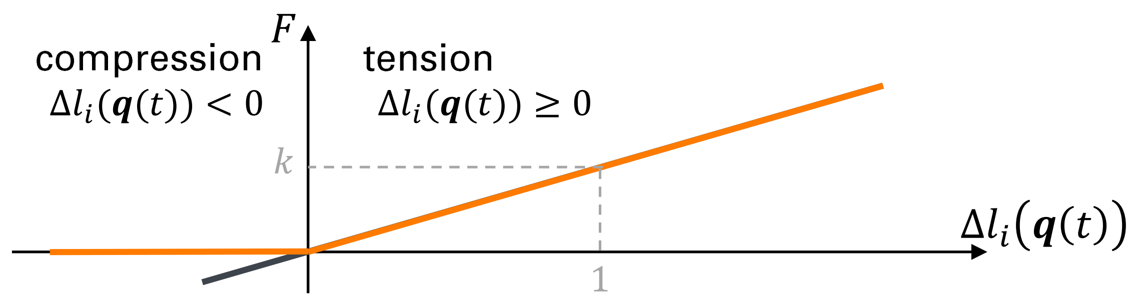
$$k_i(\boldsymbol{q}(t)) = \begin{cases} k_i, & \Delta l_i(\boldsymbol{q}(t)) \geq 0 \\ 0, & \Delta l_i(\boldsymbol{q}(t)) < 0 \end{cases} \qquad i = 1, \dots, n_t$$

Criterium

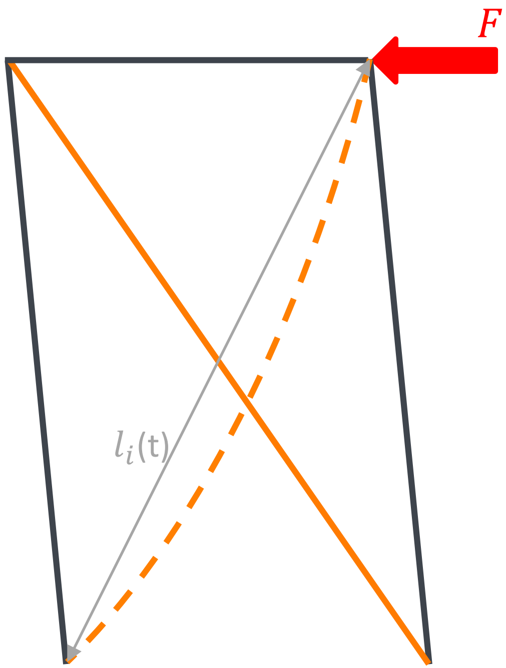
$$\Delta l_i\big(\boldsymbol{q}(t)\big) = l_i(t) - l_{i,0}$$

reference length

virtual current length



System Modeling – Nonlinear Equations of Motion



State dependent stiffness

$$k_i(\boldsymbol{q}(t)) = \begin{cases} k_i, & \Delta l_i(\boldsymbol{q}(t)) \geq 0 \\ 0, & \Delta l_i(\boldsymbol{q}(t)) < 0 \end{cases} \qquad i = 1, \dots, n_t$$

Criterium

$$\Delta l_i(\boldsymbol{q}(t)) = l_i(t) - l_{i,0}$$

reference length

virtual current length

Assembling: $\boldsymbol{K}(\boldsymbol{q}(t))$

Rayleigh damping

$$\boldsymbol{D}(\boldsymbol{q}(t)) = \alpha_1 \boldsymbol{M} + \alpha_2 \boldsymbol{K}(\boldsymbol{q}(t))$$

Nonlinear mechanical system

$$\boldsymbol{M}\ddot{\boldsymbol{q}}(t) + \boldsymbol{D}(\boldsymbol{q}(t))\dot{\boldsymbol{q}}(t) + \boldsymbol{K}(\boldsymbol{q}(t))\boldsymbol{q}(t) = \boldsymbol{F}\boldsymbol{u}(t), \quad t > 0, \quad \boldsymbol{q}(0) = \boldsymbol{q}_0, \quad \dot{\boldsymbol{q}}(0) = \boldsymbol{q}_1$$

Proper Orthogonal Decomposition (POD)

Proper orthogonal decomposition

$$A = V\Sigma W^*$$

A: data

V: left eigenvectors of A, POD basis

Σ: singular values matrix of A

W: right eigenvectors of A

Nonlinear mechanical system

$$M\ddot{q}(t) + D(q(t))\dot{q}(t) + K(q(t))q(t) = Fu(t), \quad t > 0, \quad q(0) = q_0, \quad \dot{q}(0) = q_1$$

POD transformation

$$q(t) = V_c\,\zeta(t), \quad V_c \in \mathbb{R}^{n \times n_c}$$

transformed state

reduced POD basis $V_c^T M_c V_c \approx I$

V_c columns of V

Nonlinear reduced mechanical system

$$M_c\ddot{\zeta}(t) + V_c^T D\big(V_c\zeta(t)\big)V_c\dot{\zeta}(t) + V_c^T K\big(V_c\zeta(t)\big)V_c\zeta(t) = F_c u(t), \qquad t > 0,$$

$$\zeta(0) = V_c^{-1}q_0, \quad \dot{\zeta}(0) = V_c^{-1}q_1$$

Nonlinear Model Order Reduction by Proper Orthogonal Decomposition

Nonlinear reduced mechanical system

$$\boldsymbol{M}_{\mathrm{c}}\ddot{\boldsymbol{\zeta}}(t) + \boldsymbol{V}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{D}\big(\boldsymbol{V}_{\mathrm{c}}\boldsymbol{\zeta}(t)\big)\boldsymbol{V}_{\mathrm{c}}\dot{\boldsymbol{\zeta}}(t) + \boldsymbol{V}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{K}\big(\boldsymbol{V}_{\mathrm{c}}\boldsymbol{\zeta}(t)\big)\boldsymbol{V}_{\mathrm{c}}\boldsymbol{\zeta}(t) = \boldsymbol{F}_{\mathrm{c}}\boldsymbol{u}(t), \qquad t > 0,$$

$$\boldsymbol{\zeta}(0) = \boldsymbol{V}_{\mathrm{c}}^{-1}\boldsymbol{q}_0, \quad \dot{\boldsymbol{\zeta}}(0) = \boldsymbol{V}_{\mathrm{c}}^{-1}\boldsymbol{q}_1$$

State

$$\boldsymbol{x}(t) = \begin{bmatrix} \boldsymbol{\zeta}(t) \\ \dot{\boldsymbol{\zeta}}(t) \end{bmatrix}$$

POD transformation

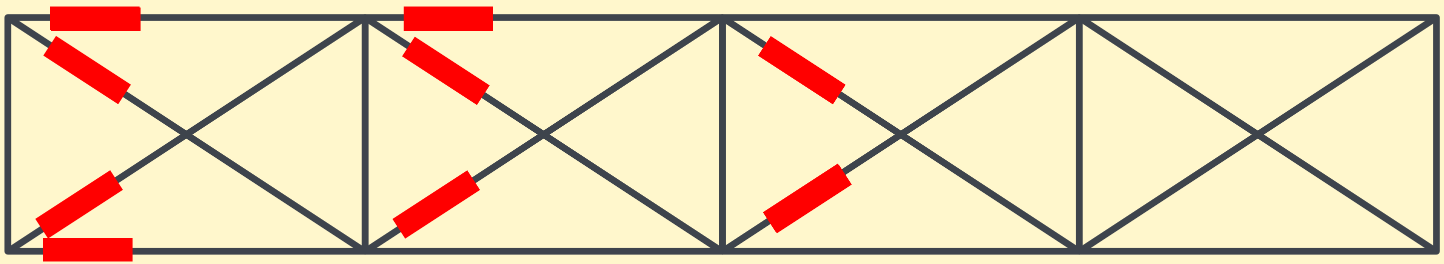
$$\boldsymbol{q}(t) = \boldsymbol{V}_{\mathrm{c}}\,\boldsymbol{\zeta}(t), \qquad \boldsymbol{V}_{\mathrm{c}} \in \mathbb{R}^{n \times n_{\mathrm{c}}}$$

State space

$$\dot{\boldsymbol{x}}(t) = \underbrace{\begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} \\ -\boldsymbol{V}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{K}\big(\boldsymbol{V}_{\mathrm{c}}\boldsymbol{\zeta}(t)\big)\boldsymbol{V}_{\mathrm{c}} & -\boldsymbol{V}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{D}\big(\boldsymbol{V}_{\mathrm{c}}\boldsymbol{\zeta}(t)\big)\boldsymbol{V}_{\mathrm{c}} \end{bmatrix}\boldsymbol{x}(t)}_{\boldsymbol{f}(\boldsymbol{x}(t))} + \underbrace{\begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{F}_{\mathrm{c}} \end{bmatrix}}_{\boldsymbol{g}}\boldsymbol{u}(t), \quad t > 0, \quad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

Actuator Placement

How do we find the optimal actuator position?



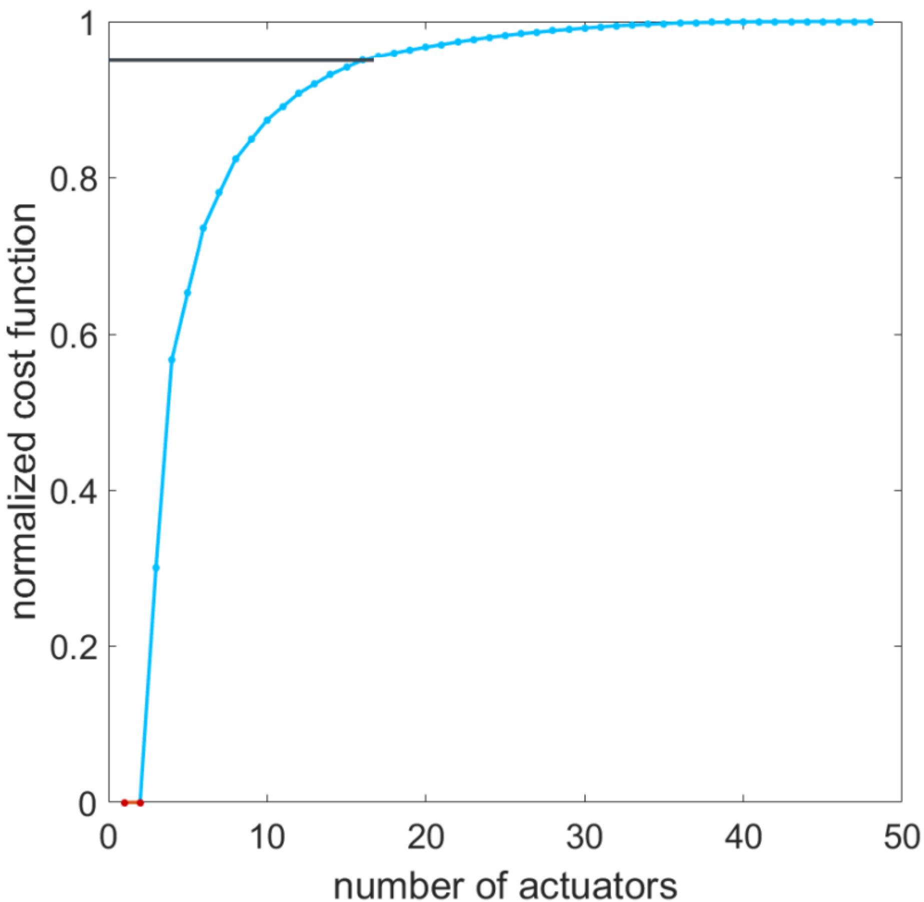
Can the ability to compensate the effects of disturbances be a general property of a structure, and thus be quantified independent of a specific load?

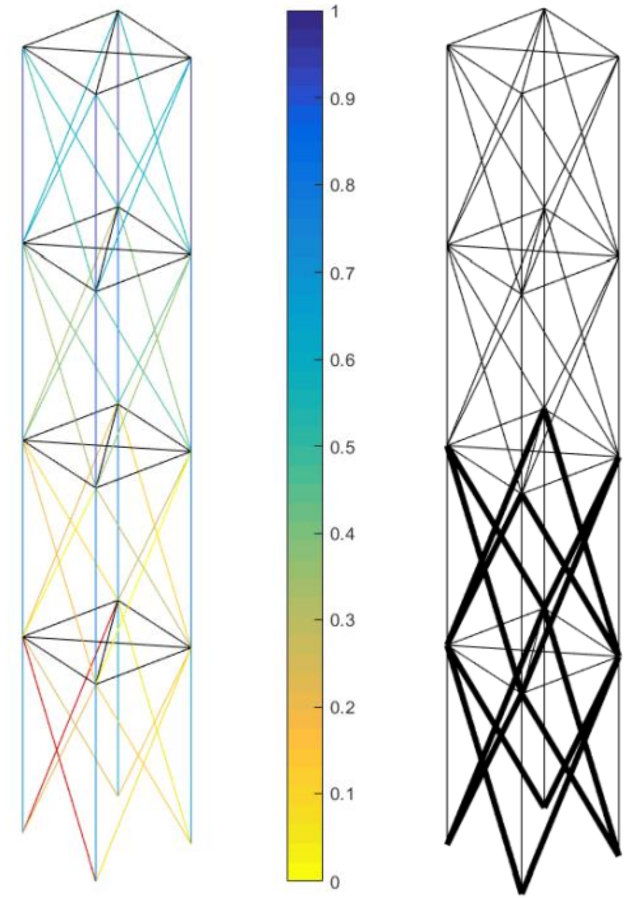
Controllability Gramian $$W = \int_0^\infty e^{A\tau} B B^T e^{A^T\tau}\,\mathrm{d}\tau$$

Homogenizability Gramian $$W = H^\top H, \qquad H = \left((C_{\mathrm{hom}} K^{-1} B)(C_{\mathrm{hom}} K^{-1} B)^+ - I \right) C_{\mathrm{hom}} K^{-1} E$$

Deformability Gramian $$W = H^\top H, \qquad H = \left((C_{\mathrm{def}} K^{-1} B)(C_{\mathrm{def}} K^{-1} B)^+ - I \right) C_{\mathrm{def}} K^{-1} E$$

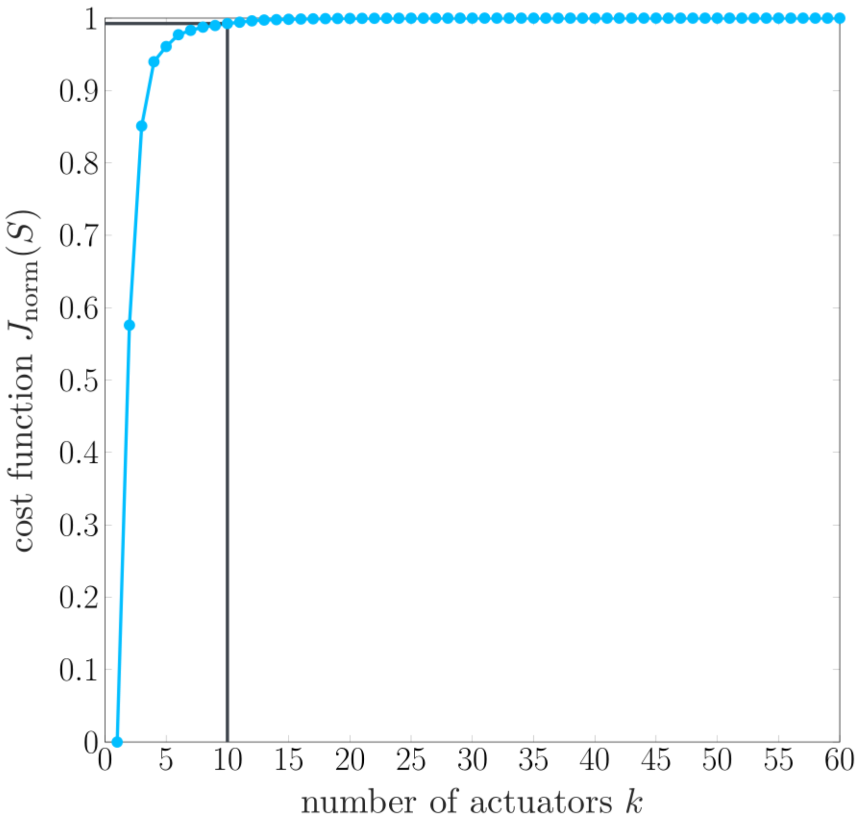
Actuator Placement – Results for optimal Controllability

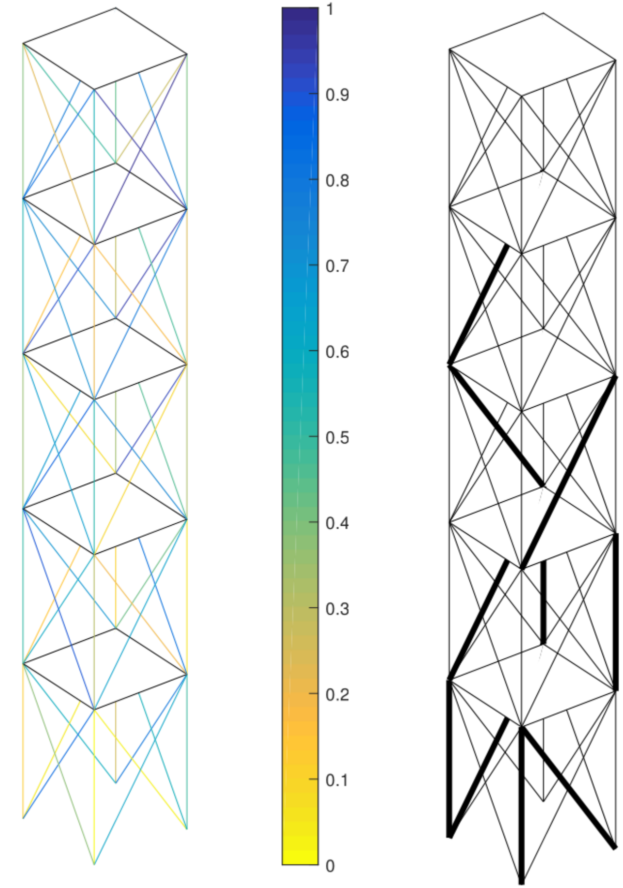




Actuator Placement – Results for optimal static compensability

- normalized average nodal displacement error





Claims to a Structure - Aims of Control

Stability

Property of a structure to widthstand all possible loads without loss of functionality

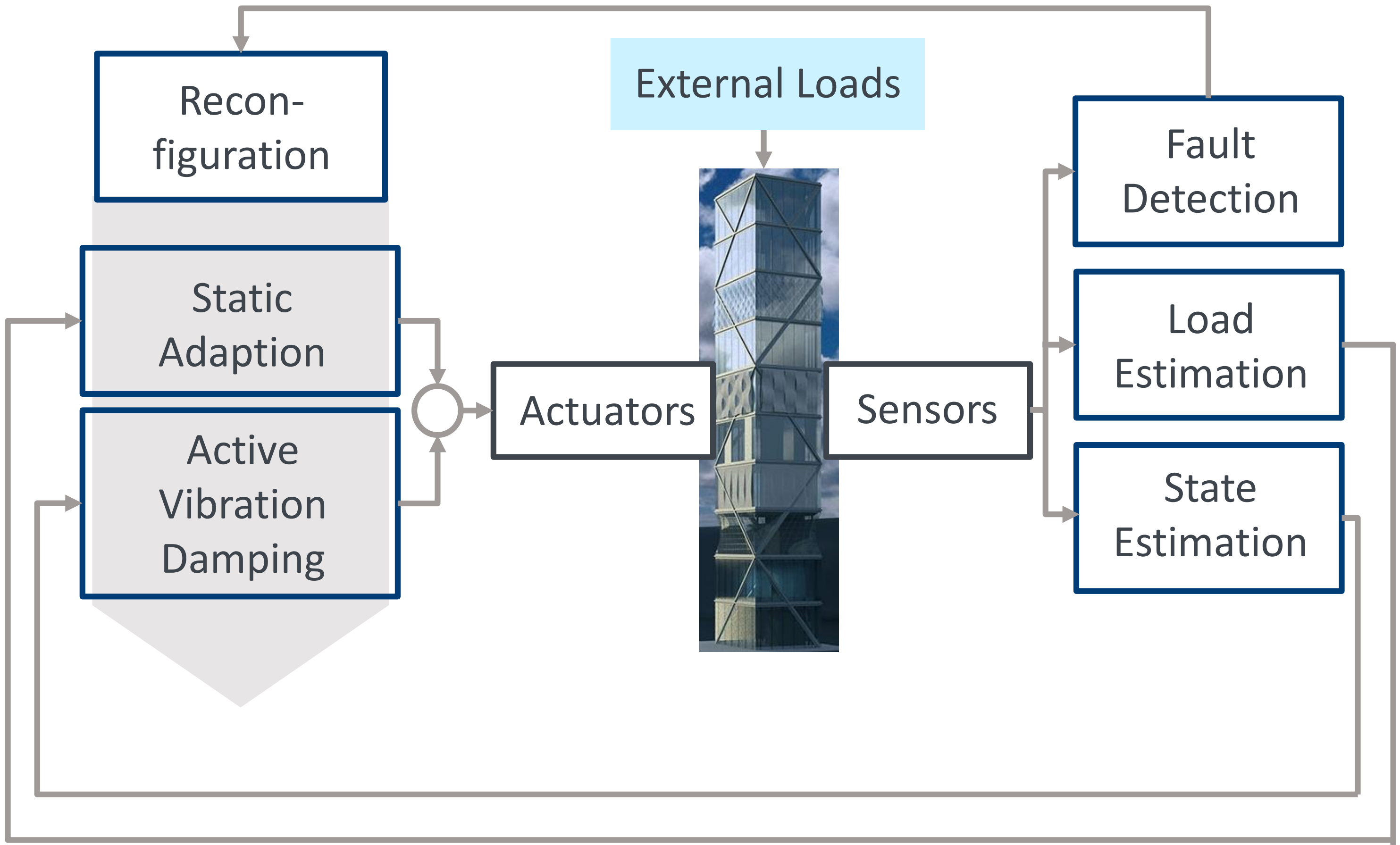
https://www.antenne.de/nachrichten/welt/turnhalle-in-st-gallen-stuerzt-unter-schneelast-ein

Usability

Property of a structure to provide unrestricted use for the designated purpose

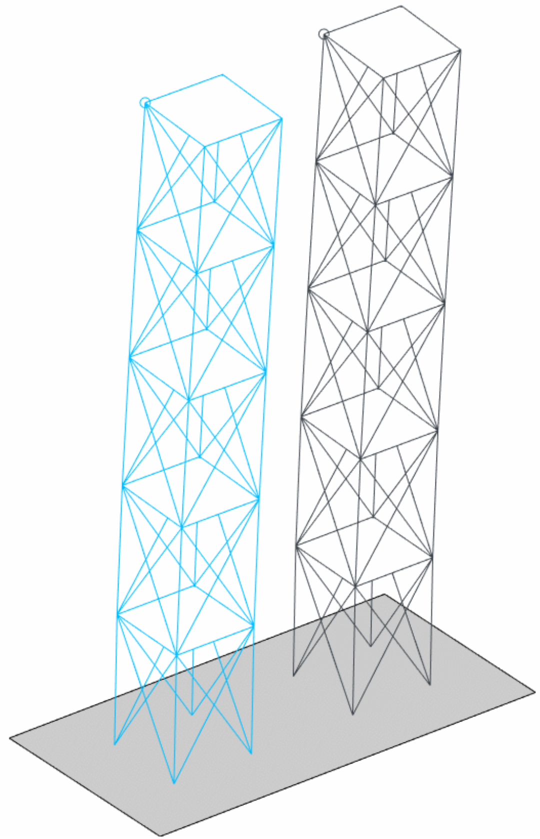
http://german.people.com.cn/n3/2017/1128/c209053-9297975.html

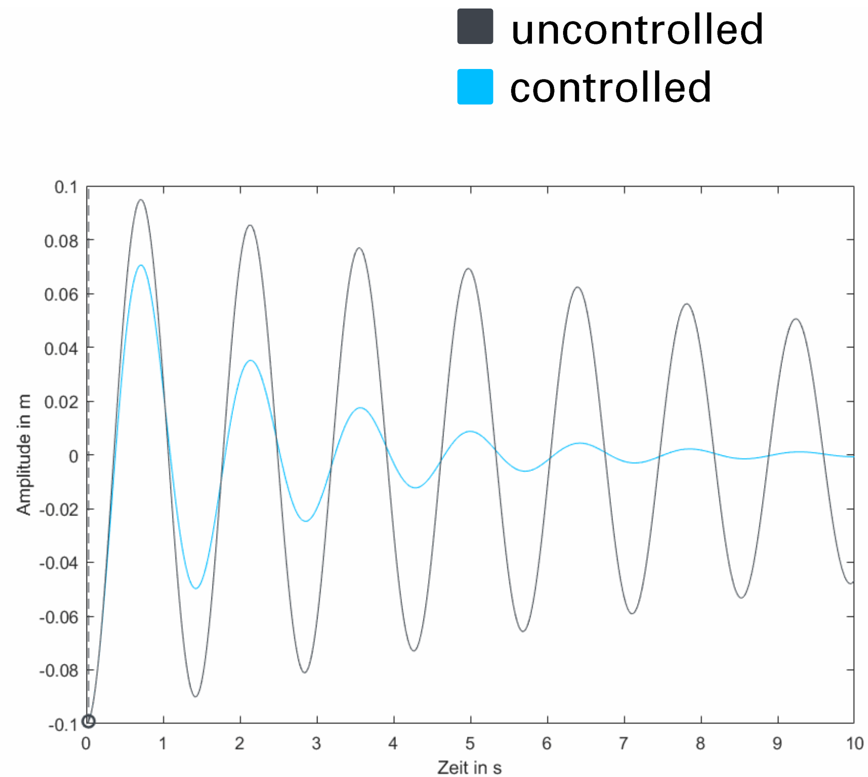
Feedforward and Feedback Control



Centralized control strategy – linear quadratic regulator (LQR)

- Initial condition first bending mode



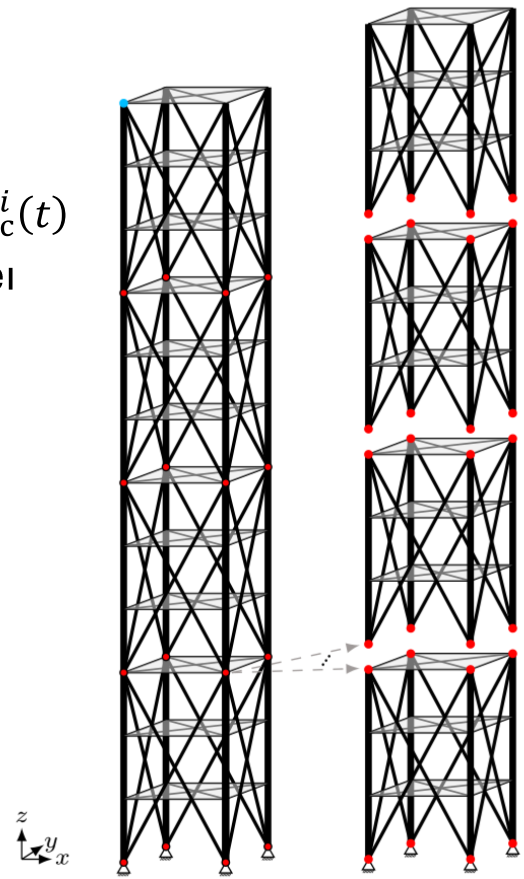


Decentralized control strategy – substructuring and local LQR

- Craig-Bampton Reduktion auf Randknoten
  - Randknoten
  - Rigid-body Moden

$$\begin{bmatrix} \boldsymbol{q}_\mathrm{b}^i(t) \\ \boldsymbol{q}_\mathrm{i}^i(t) \end{bmatrix} = \boldsymbol{T}^i \boldsymbol{q}_c^i(t)$$

- Elimination von abhängigen Randknoten $\boldsymbol{q}_\mathrm{l}^i(t) = \boldsymbol{\Phi}_\mathrm{l}^i \boldsymbol{q}_\mathrm{c}^i(t)$
- Regelerentwurf am lokalen Modell mit lokalen Aktoren

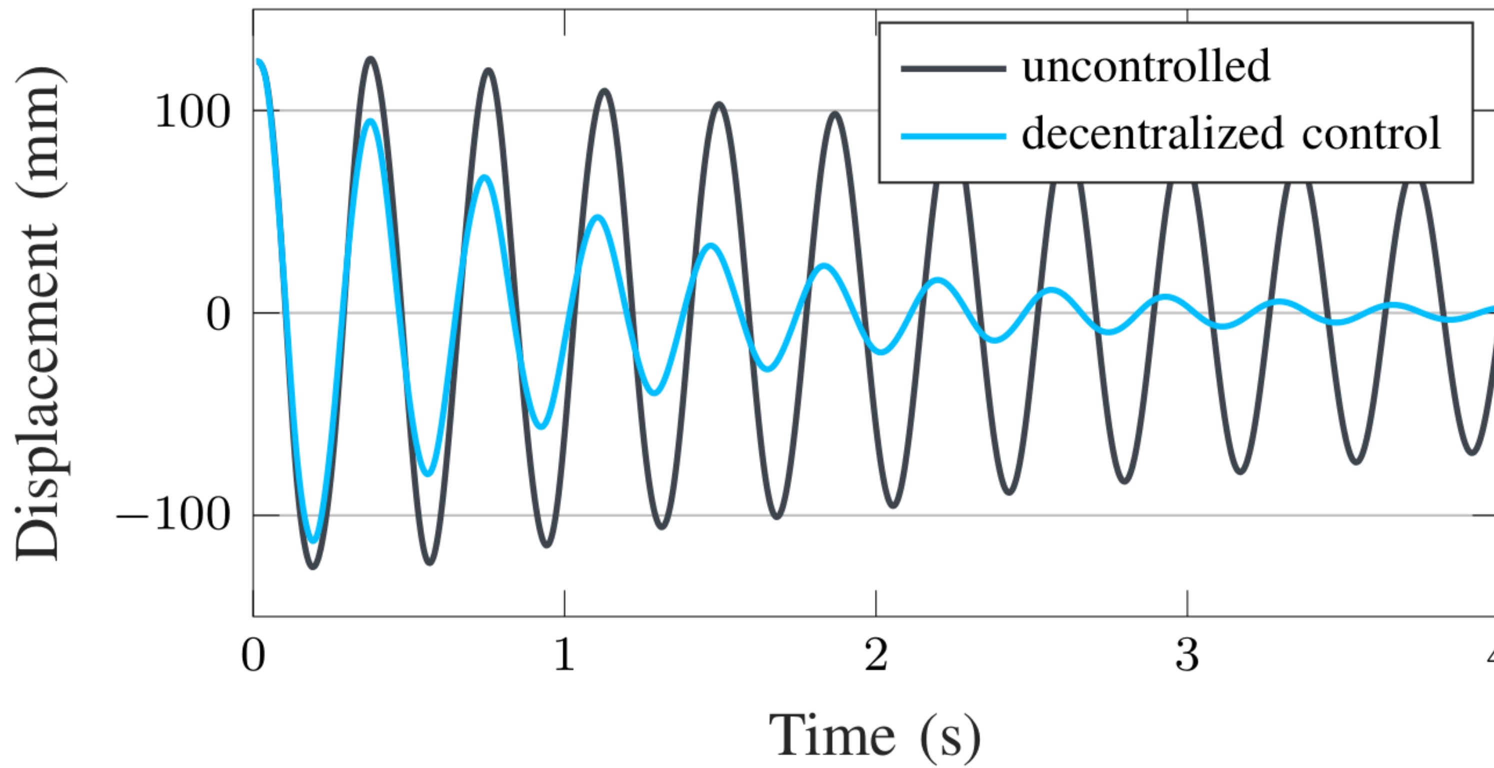


Linear mechanical system

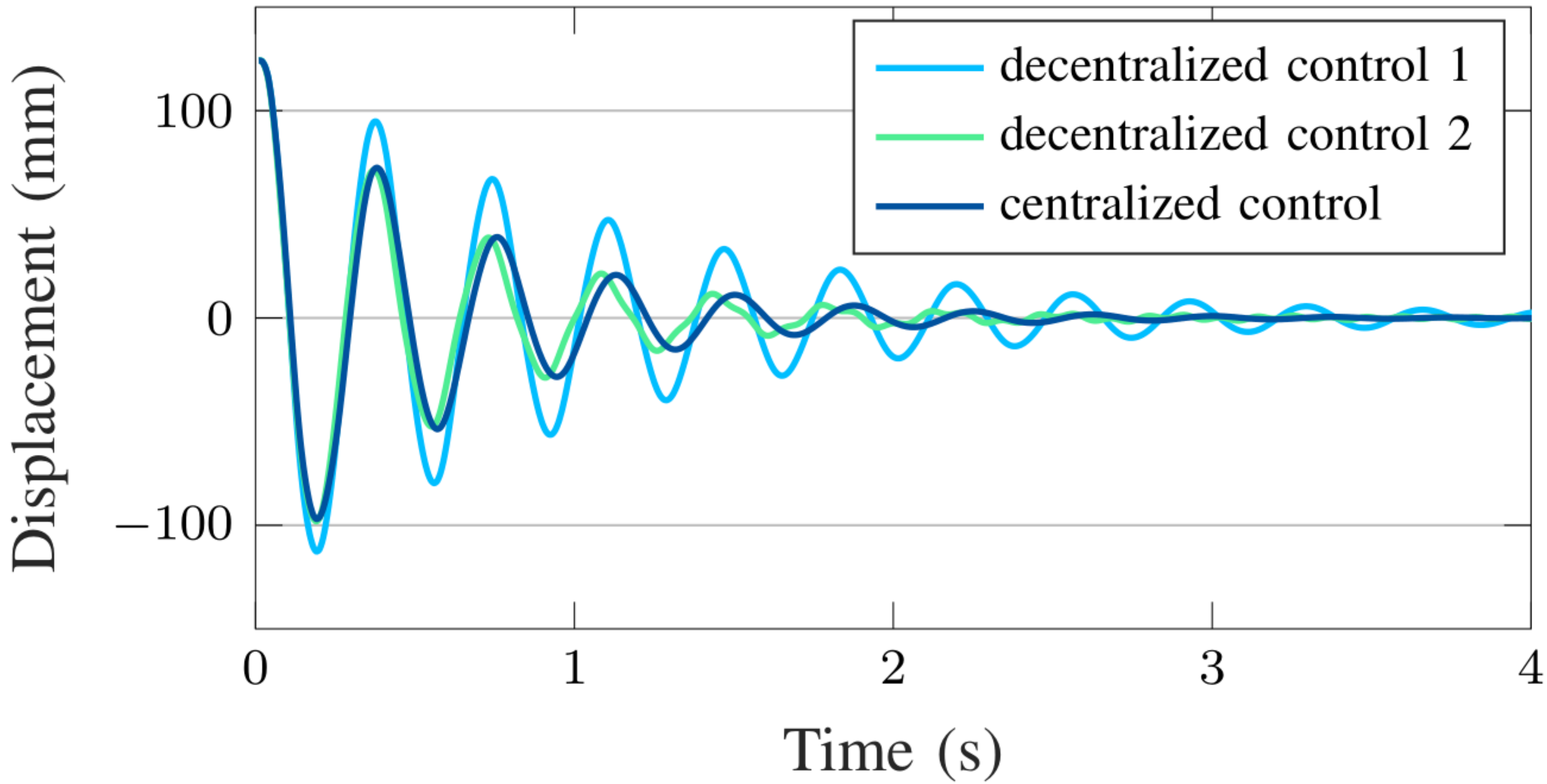
$$\boldsymbol{M}^i \ddot{\boldsymbol{q}}(t) + \boldsymbol{D}^i \dot{\boldsymbol{q}}(t) + \boldsymbol{K}^i \boldsymbol{q}(t) = \boldsymbol{F}^i \boldsymbol{u}^i(t) \quad t > 0,$$

$$\boldsymbol{q}^i(0) = \boldsymbol{q}_0^i, \qquad \dot{\boldsymbol{q}}^i(0) = \boldsymbol{q}_1^i$$

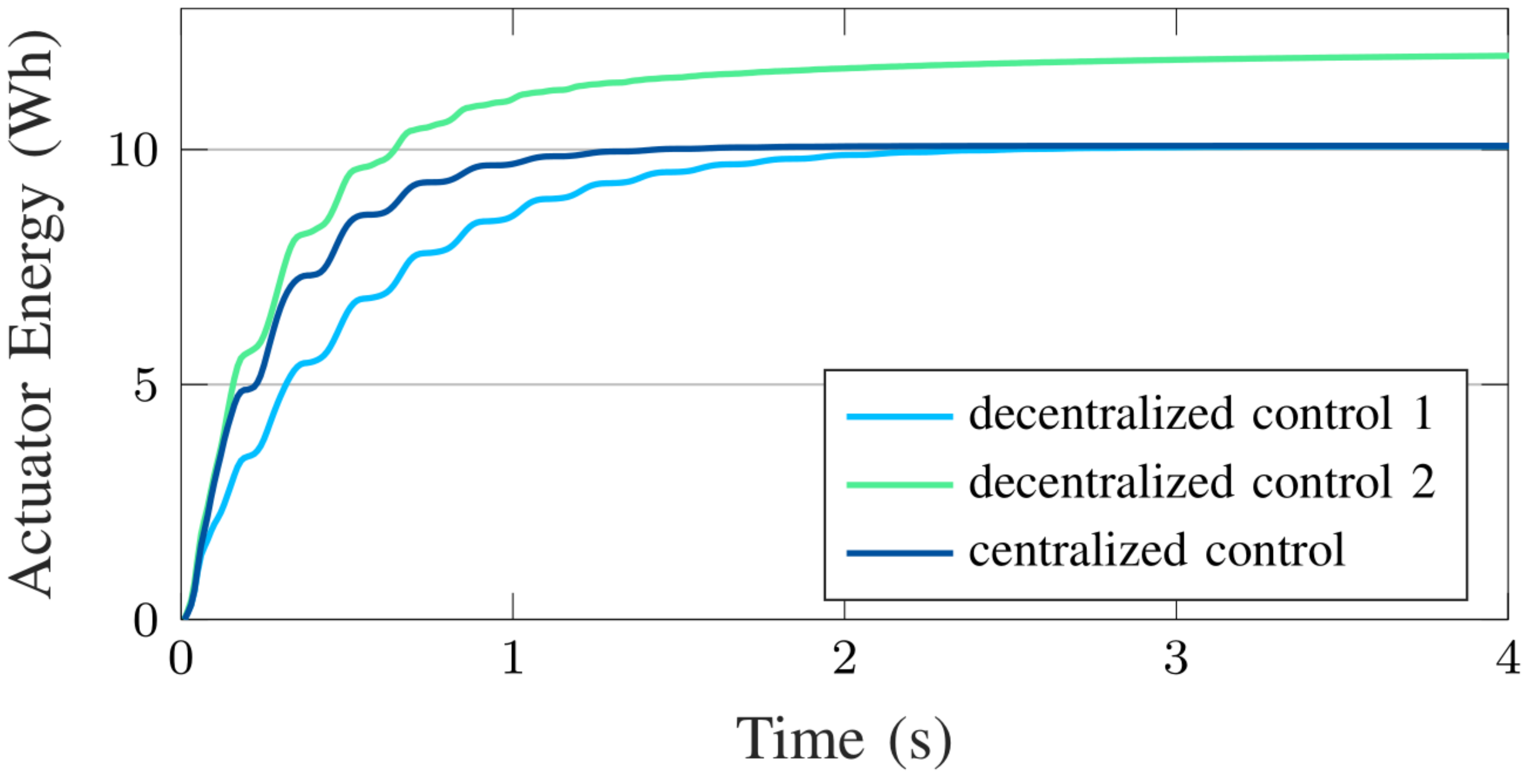
Decentralized control strategy – results



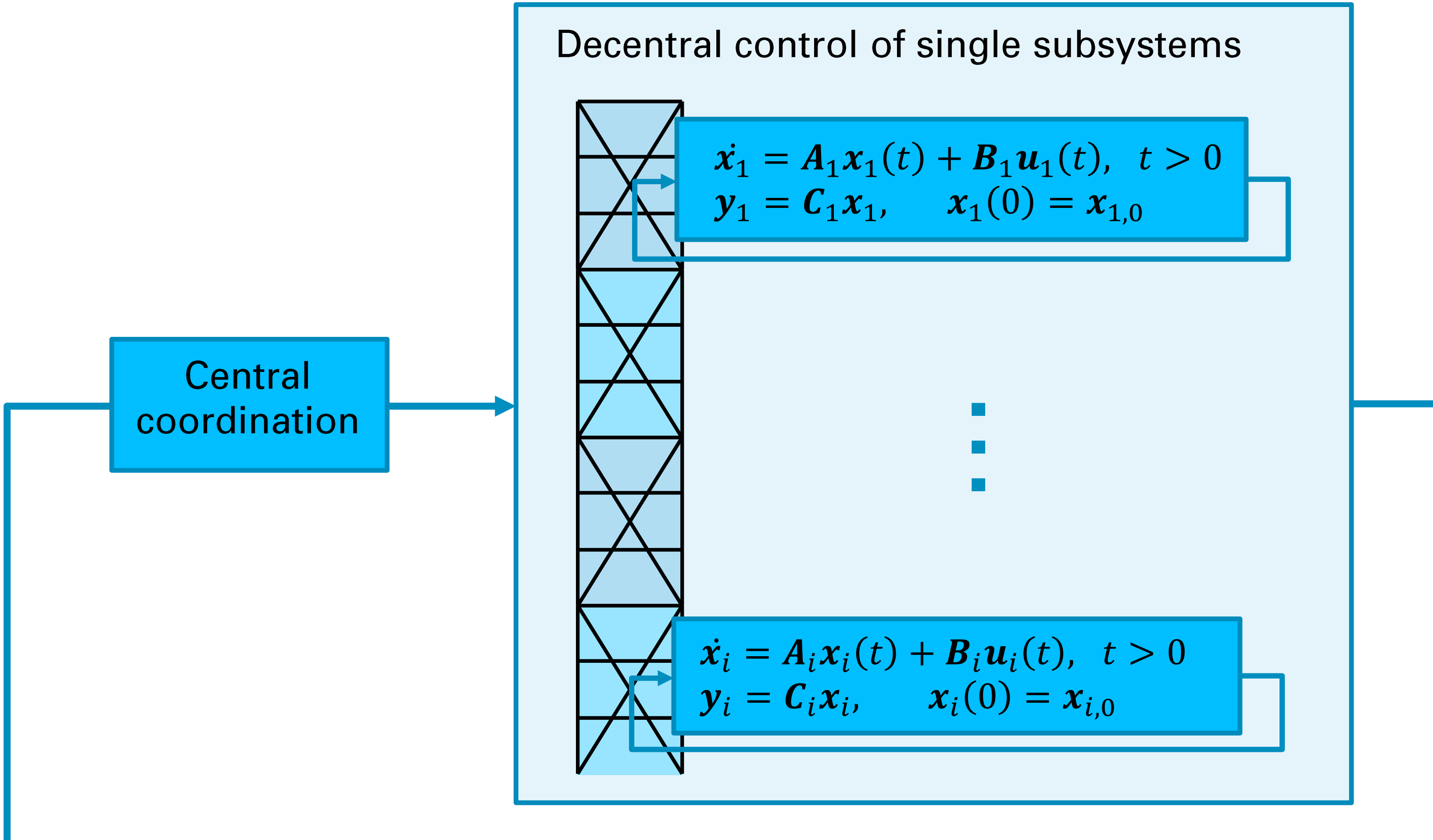
Decentralized control strategy – results



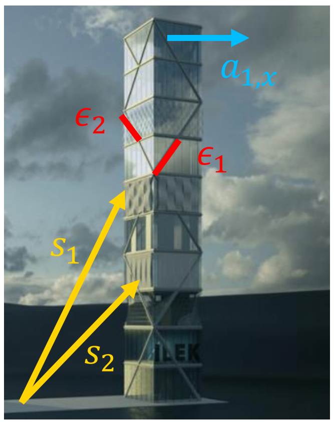
Decentralized control strategy – results



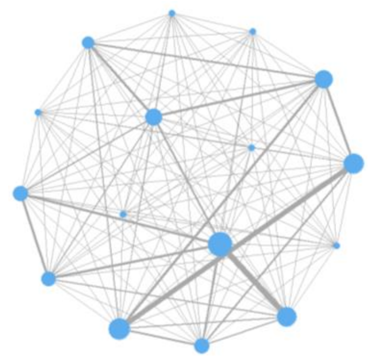
Distributed Control Approach



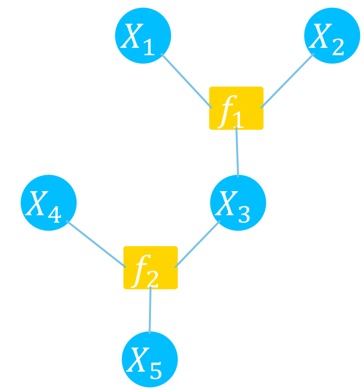
Data driven model for fault detection and diagnosis



High number of Sensors generate loads of data



Quantify the correlation between measurements



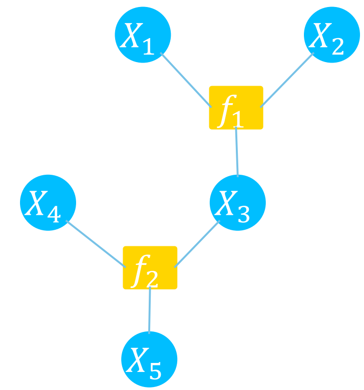
Model featuring structural and quantitative dependencies

Data driven model for fault detection and diagnosis

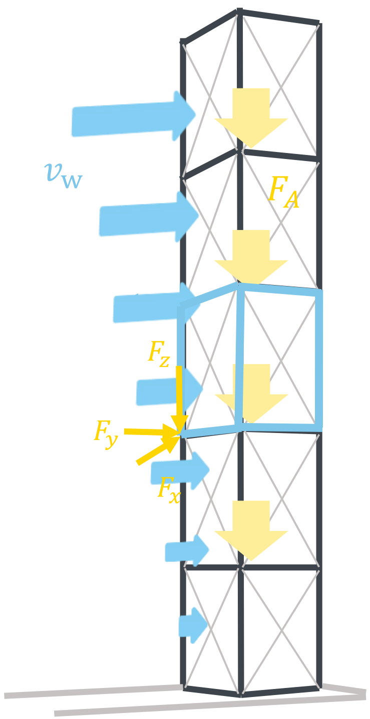
Approach:

1. Generate measurement data from simulation model
2. Determination of significant correlation between measurements using covariance and partial mutual information matrix
3. Quantitative modeling of dependencies using probability graphs (Gaussian processes)
4. Analysis w.r.t. fault detectability (Structural Analysis)

$$I(x,y) = \frac{1}{n}\sum_{i=1}^{n} \log\left[\frac{p(x_i, y_i)}{p(x_i)p(y_i)}\right]$$



Model based decentralized fault diagnosis



Decentralized fault diagnosis

- State space system for individual module
- Unknown coupling between modules

Discrete-time state space model

$$x_{k+1} = Ax_k + B_u u_k + B_f f_k + b_v(v_k), \qquad x_0 = \bar{x}_0$$
$$y_k = Cx_k + D_u u_k + D_f f_k + d_v(v_k) + D_\epsilon \epsilon_k$$

$y_k \in \mathbb{R}^{l_y}$: Systemausgänge
$u_k \in \mathbb{R}^{l_u}$: Systemeingänge
$f_k \in \mathbb{R}^{l_f}$: Fehler
$v_k \in \mathbb{R}^{l_\epsilon}$: Störungen
$\epsilon_k \in \mathbb{R}^{l_\epsilon}$: Messrauschen

Disturbances due to physical coupling for distributed modeling

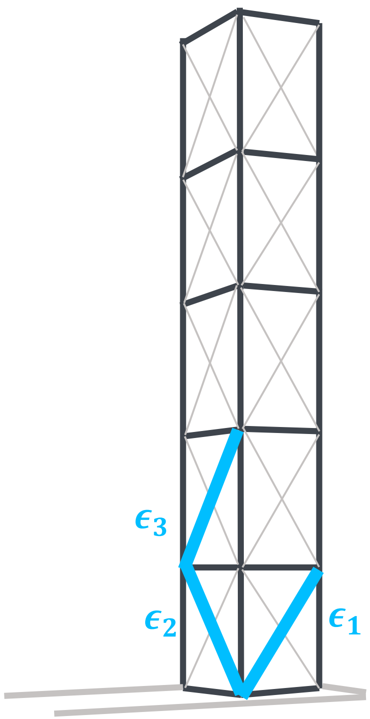
$$x_k = \begin{bmatrix} x_{1,k} \\ x_{2,k} \end{bmatrix},\ u_k = \begin{bmatrix} u_{1,k} \\ u_{2,k} \end{bmatrix},\ y_k = \begin{bmatrix} y_{1,k} \\ y_{2,k} \end{bmatrix},\ f_k = \begin{bmatrix} f_{1,k} \\ f_{2,k} \end{bmatrix}$$
$$b_{1,v}(v_k) = b_{1,v}(x_{2,k}, u_{2,k}, v_k)$$

Goal

- Identification and elimination of disturbance impact by data based methods (PCA)

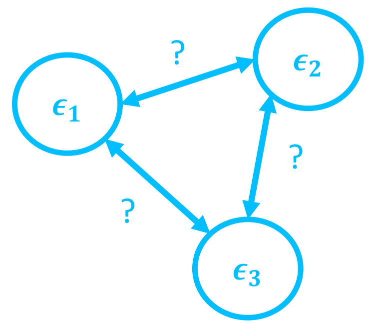
*) Andreas Gienger, Oliver Sawodny, Cristina Tarín. “Kombination von modell- und datenbasierten Methoden für die Fehlerdetektion und Diagnose in adaptiven Strukturen”. Fachtagung GMA 1.30, Anif, Österreich

Model based decentralized fault diagnosis



Problem

What sensors are necessary to detect defined fault?



Approach

Identify a set of dependent sensors and actuators using data → Redundancy:

- Optimization-based methods (LASSO-regression)
- Statistical correlation

Implications for Telescopes

- Same stiffness level with 70% mass reduction
  - Larger telescopes possible at less mass
- New building materials
- Decoupling of alignment and telescope pose