Interaction diagram for columns with multi-spiral reinforcement: modeling and experimental evidence

P. Havlásek, Z. Bittnar, B. Li , J.V. Lau & Y.-C. Ou

FACULTY OF CIVIL ENGINEERING CTU IN PRAGUE

國立臺灣大學 National Taiwan University

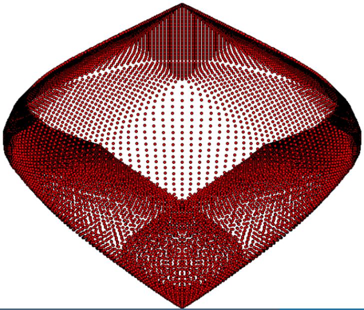
Contact: petr.havlasek@cvut.cz

Introduction

back then in 2008

Semestrální práce na téma:

Interakční diagram železobetonového prvku obdélníkového průřezu



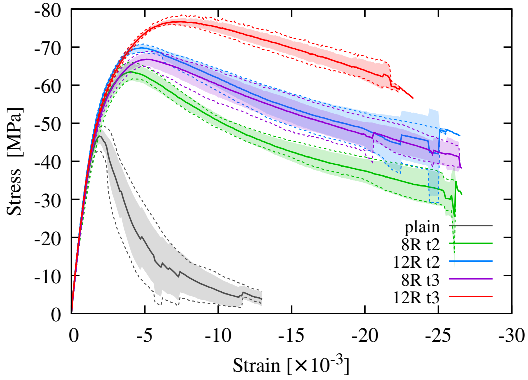
now in 2022

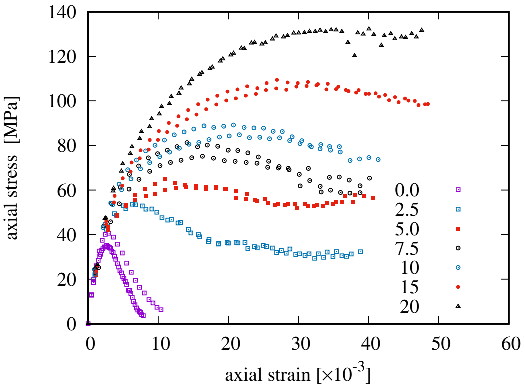
TAČR-MOST 2020-2022: Reducing material demands and enhancing structural capacity of multi-spiral reinforced concrete columns-advanced simulation and experimental validation

1. Software for the design and advanced FE modeling of reinforced concrete columns with the multi-spiral reinforcement (MSR)
2. Develop formulae for the robust yet efficient design of columns with MSR incorporating the effect of multiple-confined zones. Develop the interaction diagram for the design of columns with MSR

Introduction & Motivation

- Confined concrete → enhanced strength and ductility



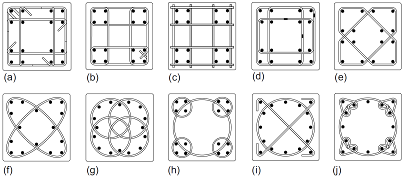


Havlásek et al. (2022): *Efficient Approach to Measuring Strength and Deformation of Passively Confined Concrete.*

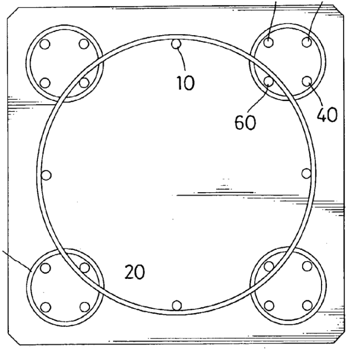
Li, Wu 2016: *Stress–strain behavior of actively and passively confined concrete under cyclic axial load.*

Introduction & Motivation

- Confined concrete → enhanced strength and ductility
- Spiral reinforcement:
  - ↳ circular CS, higher strength + ductility, material savings
  - ↳ uniaxial compression only
- Multispiral reinforcement:
  - ↳ arbitrary shape of CS + material savings (43%) + manufacture (33%)
  - ↳ M+N+V



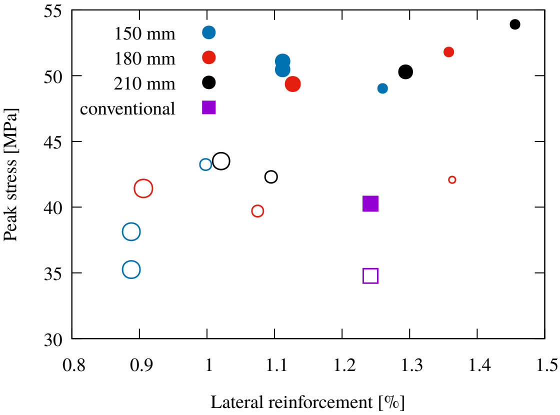
Yin et al. (2011): *Interlocking Spiral Confinement for Rectangular Columns*.



Samuel Yin: *Helical Rebar Structure* US 2004/0231278 A1 (Nov. 25, 2004).

Introduction & Motivation

- Confined concrete → enhanced strength and ductility
- Spiral reinforcement:
  - ↳ circular CS, higher strength + ductility, material savings
  - ↳ uniaxial compression only
- Multispiral reinforcement:
  - ↳ arbitrary shape of CS + material savings (43%) + manufacture (33%)
  - ↳ M+N+V



P. Havlásek et al. (2021): *Modeling of precast columns with innovative multispiral reinforcement*. Data from M. Kuo (2008): *Axial Compression Tests and Optimization Study of 5-Spiral Rectangular RC Columns*.

Introduction & Motivation

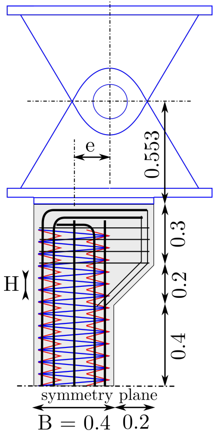
- Confined concrete → enhanced strength and ductility
- Spiral reinforcement:
  - ↳ circular CS, higher strength + ductility, material savings
  - ↳ uniaxial compression only
- Multispiral reinforcement:
  - ↳ arbitrary shape of CS + material savings (43%) + manufacture (33%)
  - ↳ M+N+V
- Design codes for conventional reinforcement
- No recommendations for MSR, absence of data

→ Conduct experiments: M+N, monotonous loading

→ Develop and validate computational model, compute interaction diagram

→ Use FEM results for formulation of formulae for engineers

OOFEM.ORG

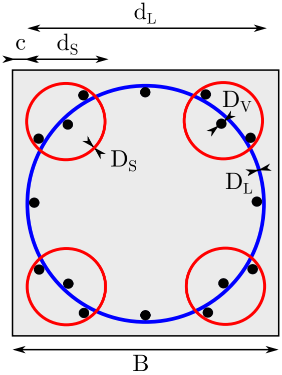


$e = 0, 50, 100, 150, 200$ mm

f_c = 43.0 MPa
$E_{S,40}$ = 26.9 GPa
f_y = 420 MPa

$\rho_V = 2.00\%$
$\rho_L = 2.51\%$

σ'_L = 5.65 MPa
σ'_S = 7.82 MPa

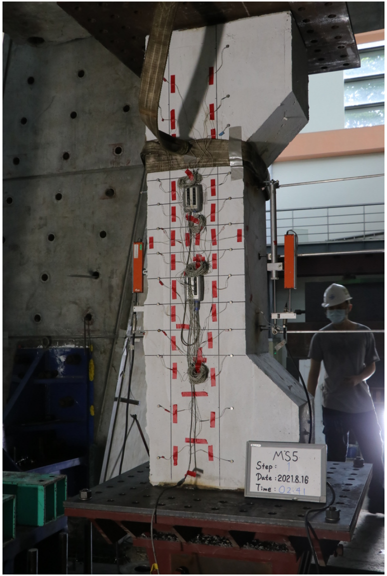


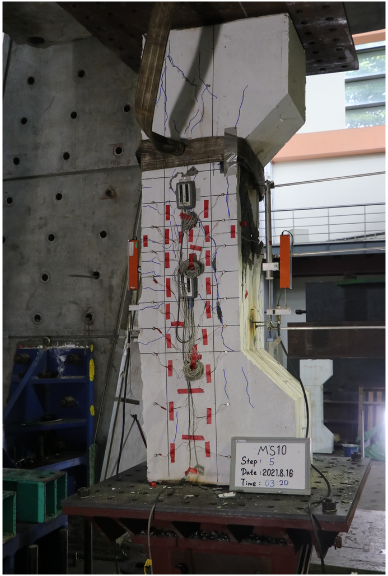
B = 400 mm, c = 20 mm, H = 60 mm
d_L = 360 mm, D_L = 13 mm, $k_{e,L}$ = 0.91
d_S = 120 mm, D_S = 10 mm, $k_{e,S}$ = 0.73
D_V = 16 mm

Experiment: Inova vs. MATS

Location: CTU, Czech Republic	NTU, Taiwan
Capacity: 2.5 MN	60 MN
Special feature: rapid unloading	6 independent DOFs

Experiment: e = 100 mm, $\hat{e}$ = 0.5

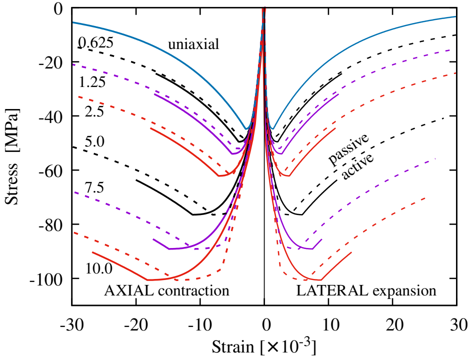


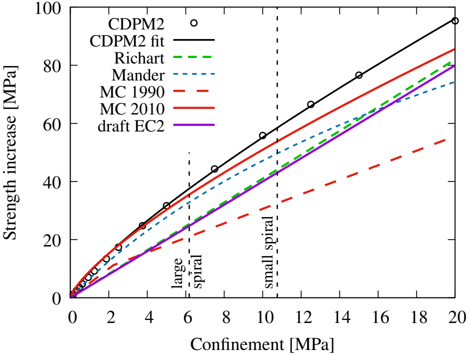


- **Concrete:** `Con2DPM`
  CDPM2: A damage-plasticity approach to modelling the failure of concrete (Grassl et al. 2013)

$$\bar{\boldsymbol{\sigma}} = \mathrm{D_e} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_\mathrm{p})$$

$$\boldsymbol{\sigma} = (1 - \omega_\mathrm{t})\,\bar{\boldsymbol{\sigma}}_\mathrm{t} + (1 - \omega_\mathrm{c})\,\bar{\boldsymbol{\sigma}}_\mathrm{c}$$





Material models

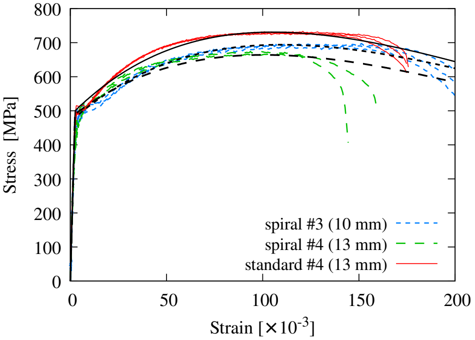
- **Concrete:** `Con2DPM`
  CDPM2: A damage-plasticity approach to modelling the failure of concrete (Grassl et al. 2013)
- **Reinforcement:** `MisesMat`
  Mises plasticity + isotropic damage + linear isotropic hardening)

$$\sigma = (1-\omega)\bar{\sigma} = (1-\omega)\mathrm{D}(\varepsilon - \varepsilon_{\mathrm{p}})$$

$$f(\bar{\sigma}, \kappa) = \sqrt{3J_2(\bar{\sigma})} - \sigma_Y(\kappa)$$

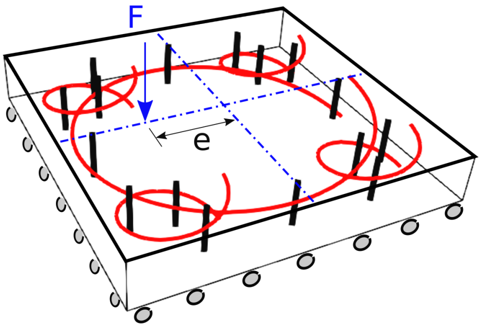
$$\sigma_Y(\kappa) = \sigma_0 + H\kappa$$

$$\omega(\kappa) = \omega_c(1 - \mathrm{e}^{-a\kappa})$$



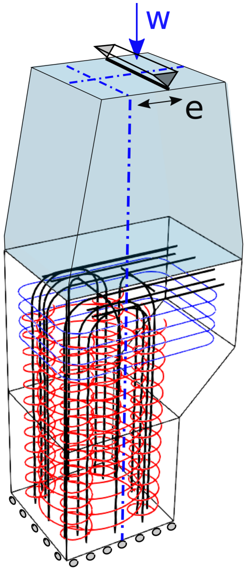
Computational models

- Representative section
  - indirect displacement control
  - top surface: weighted master-slave condition
  - reinforcement: linear truss elements
  - concrete-reinforcement interaction: hanging nodes



Computational models

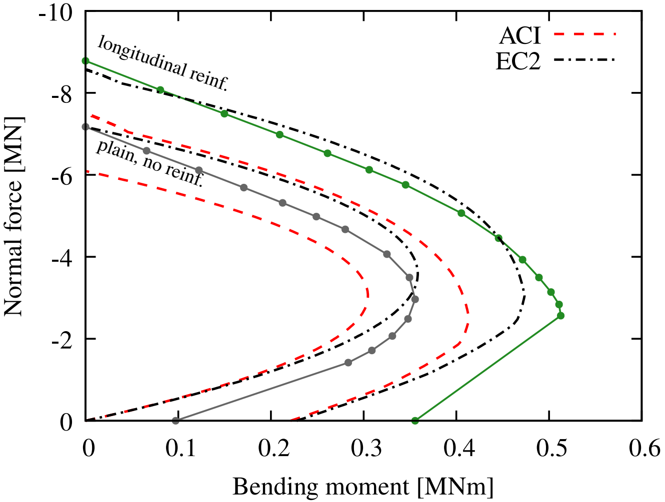
- Representative section
- Symmetric half
  - complex reinforcement geometry
  - direct displacement control
  - geometrically nonlinear using `nlgeo 1`
  - reinforcement `Truss3dNL ...nlgeo 1`



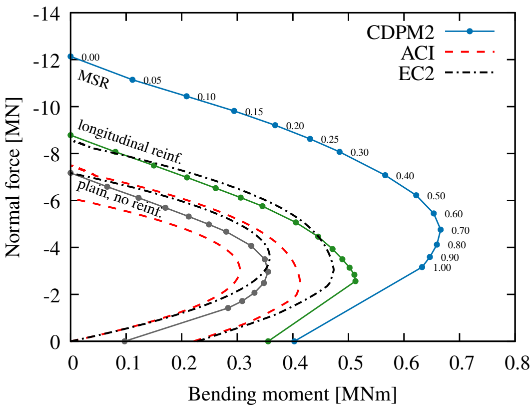
Computational models

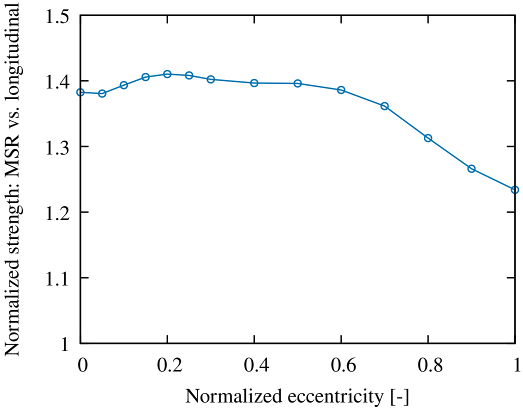
- Representative section
- Symmetric half
- Engineering model
  - `NonLinearStatic`
  - elastic stiffness matrix, initial guess
  - DSS solver, OpenMP

Results: representative section, CDPM2 vs. design codes

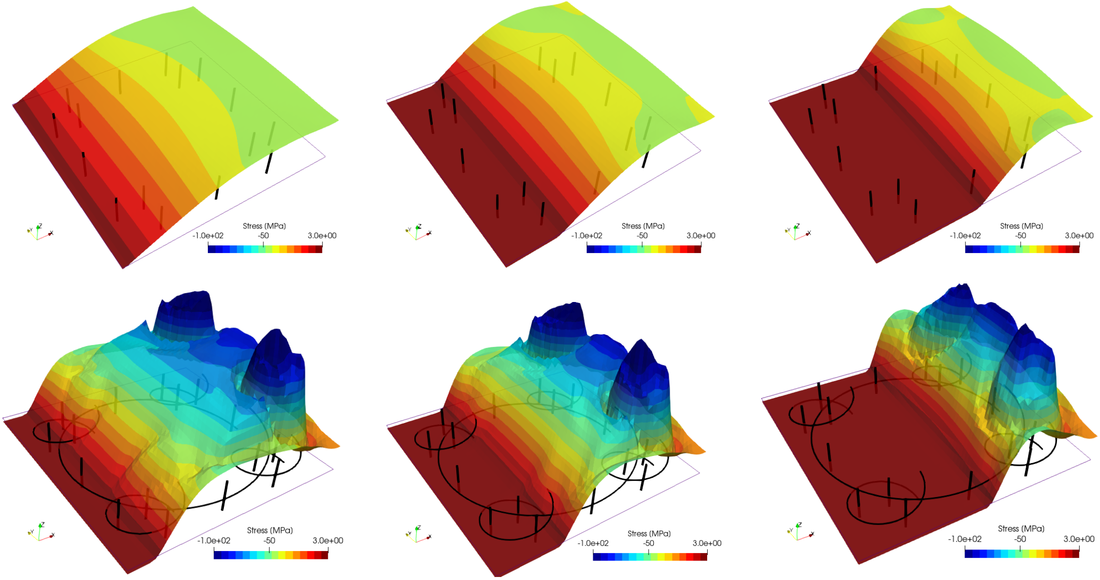


Results: MSR vs. longitudinal reinforcement

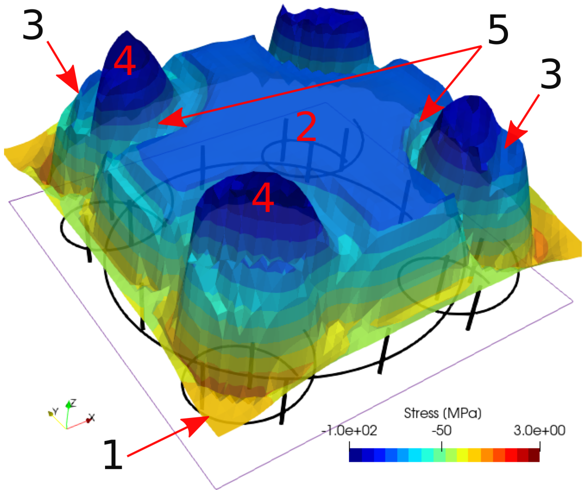




$e = 0.25$ $e = 0.5$ $e = 1.0$

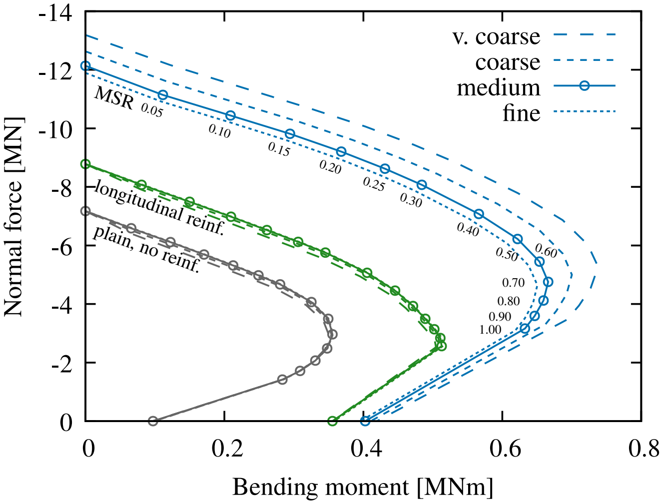

Stress (MPa)
-1.0e+02
-50
3.0e+00
Stress (MPa)
-1.0e+02
-50
3.0e+00
Stress (MPa)
-1.0e+02
-50
3.0e+00
Stress (MPa)
-1.0e+02
-50
3.0e+00
Stress (MPa)
-1.0e+02
-50
3.0e+00
Stress (MPa)
-1.0e+02
-50
3.0e+00

Results: MSR, axial compression

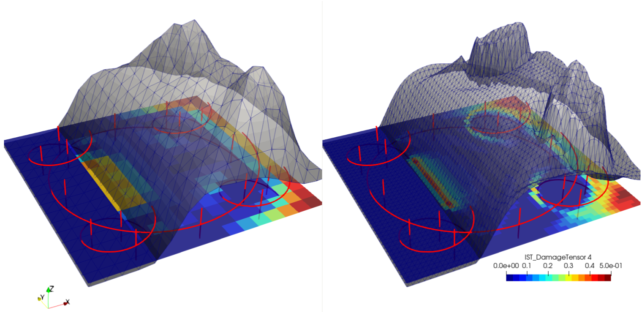


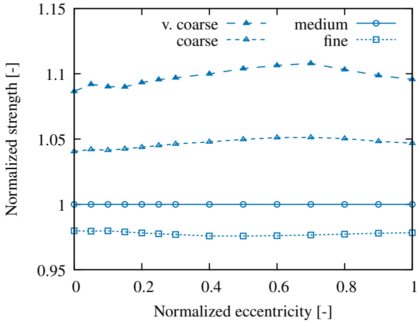
1 Unconfined concrete
2 Single-confined concrete, large spiral
3 Single-confined concrete, small spiral
4 Double-confined concrete
5 Reduced confinement

Results: mesh sensitivity



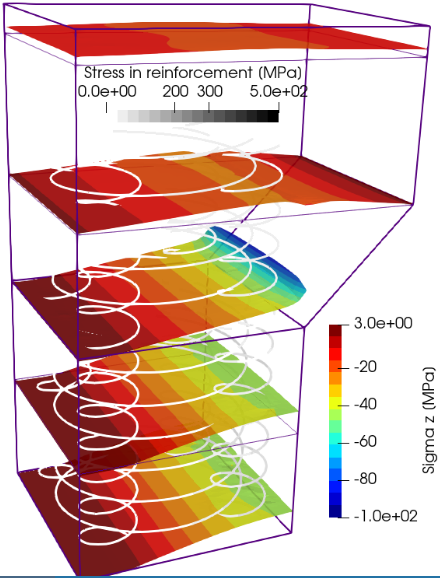
Results: mesh sensitivity



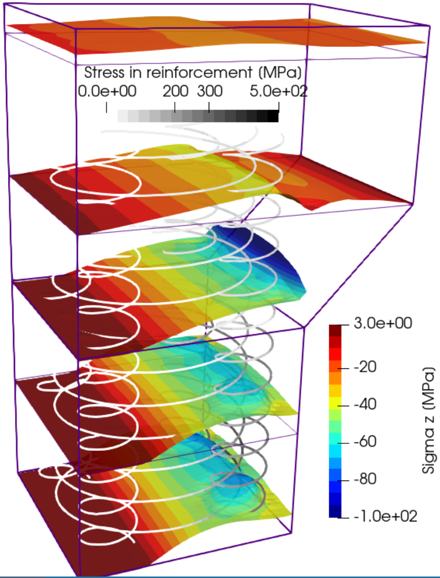


Mesh	Computational time [s]
v. coarse, $8 \times 8 \times 2$	21
coarse, $16 \times 16 \times 4$	168
medium, $32 \times 32 \times 8$	1 518
fine, $46 \times 46 \times 12$	5 284

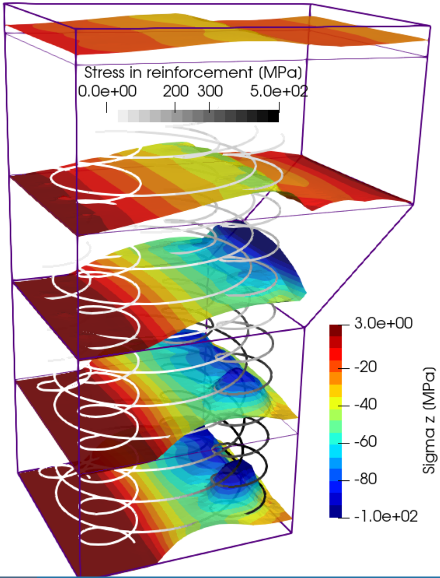
Results: symmetric half



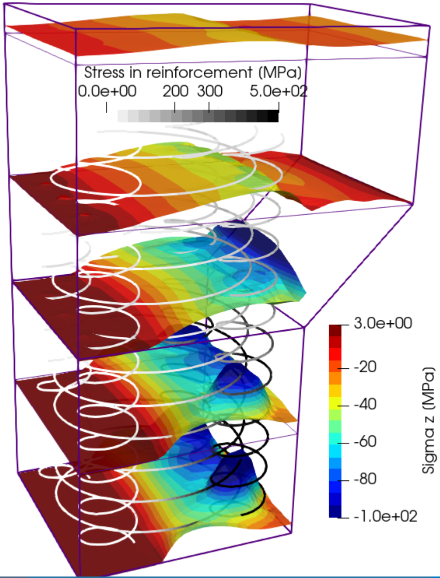
Results: symmetric half



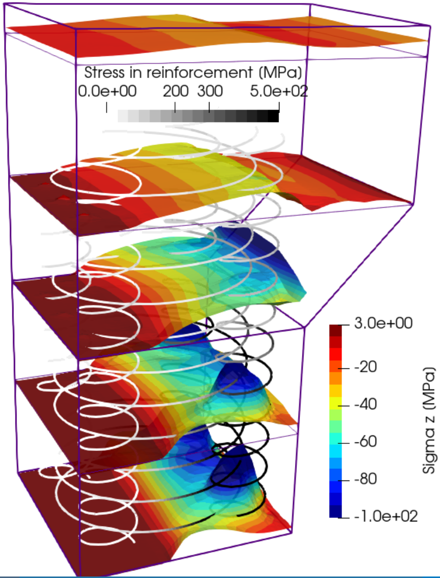
Results: symmetric half



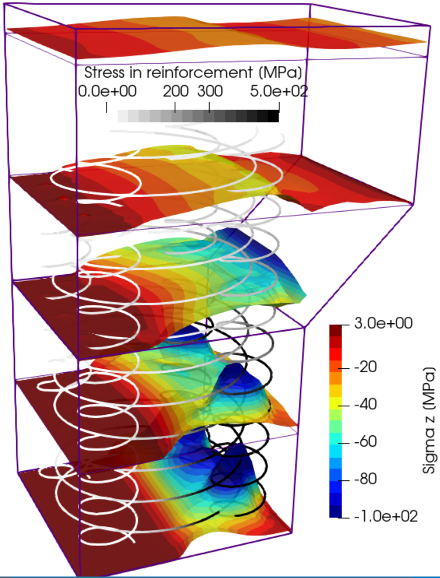
Results: symmetric half



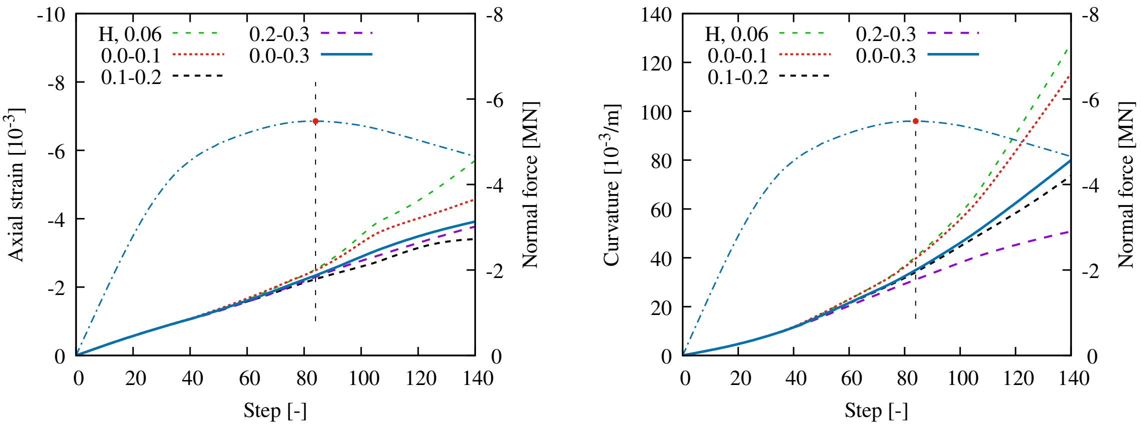
Results: symmetric half



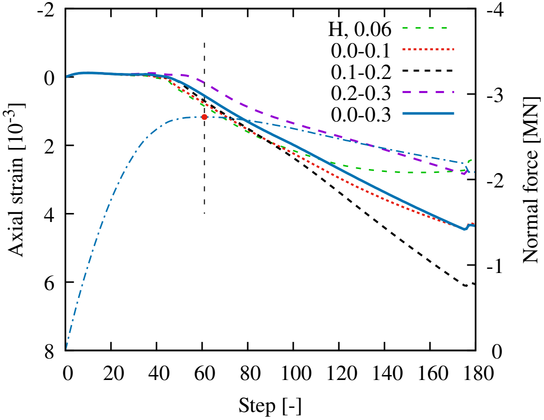
Results: symmetric half

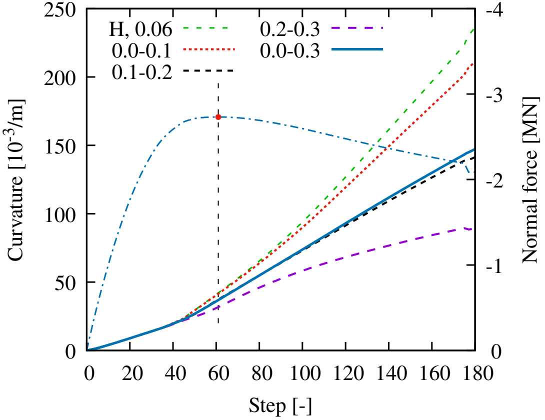


Results: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)

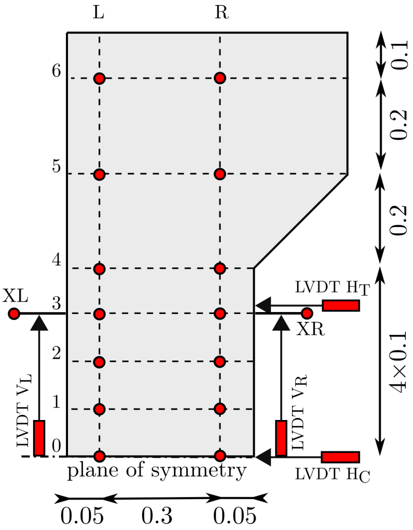


Results: axial strain and curvature, $\hat{e} = 1.0$ ($e = 200$ mm)

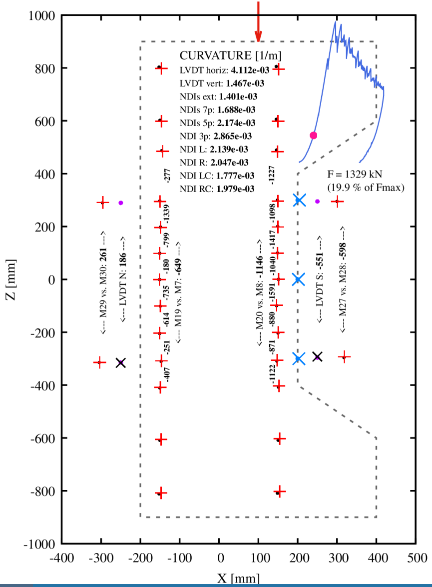




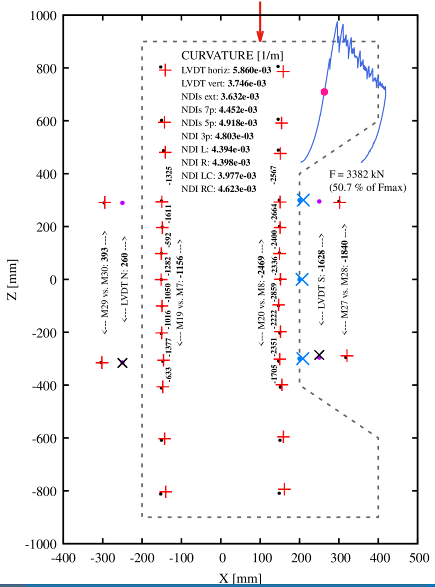
Experiment: layout of displacement sensors



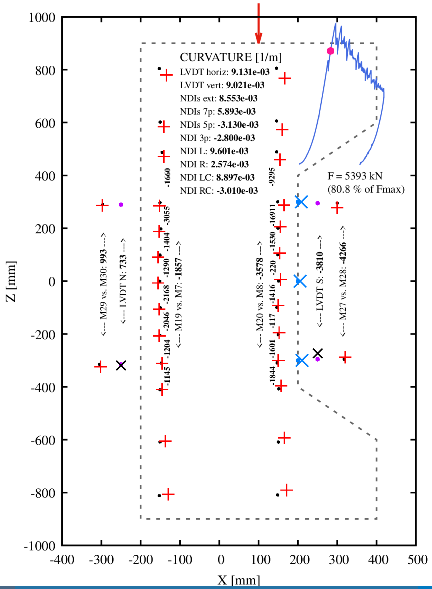
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)



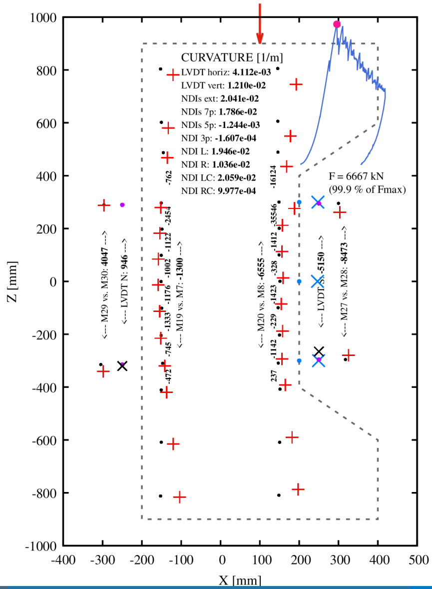
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)



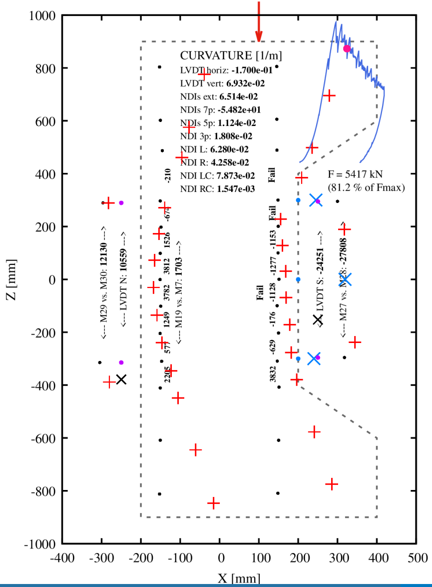
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)



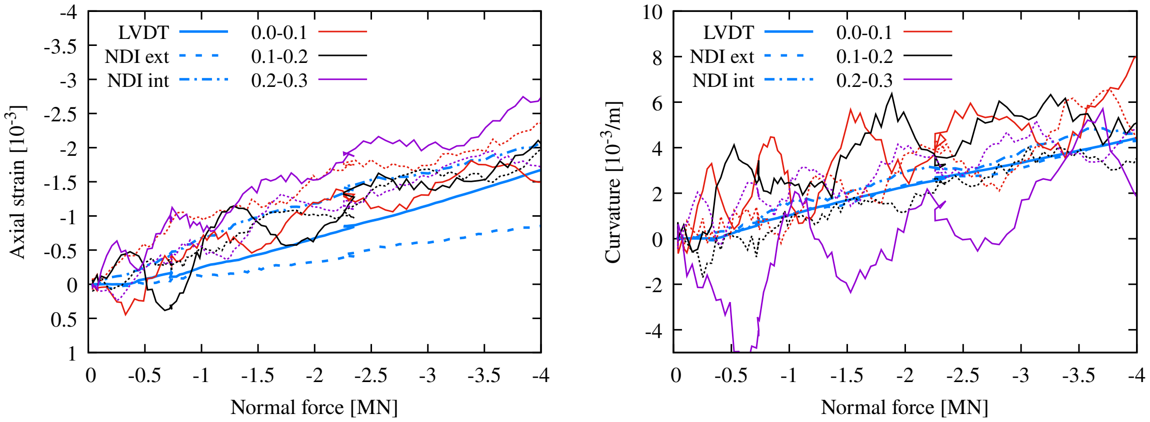
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)



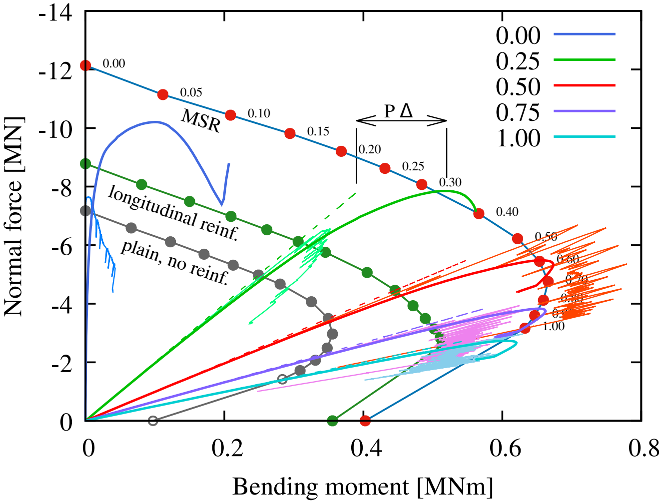
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)



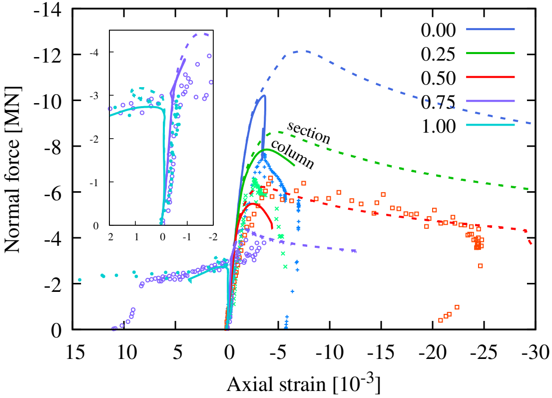
Experiment: axial strain and curvature, $\hat{e} = 0.5$ ($e = 100$ mm)

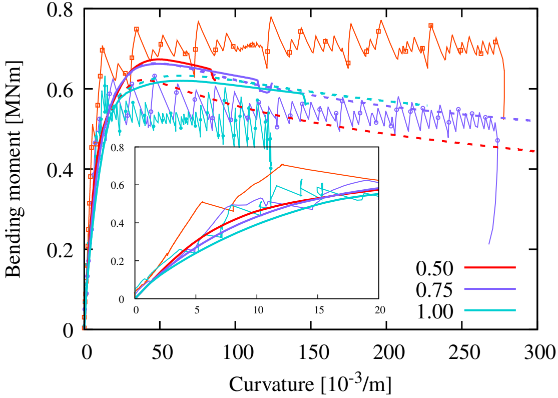


Results: ID, representative section vs. symmetric half vs. experiment



Results: FEM vs. experiment





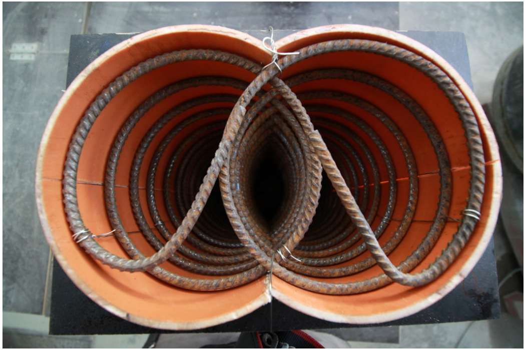
Conclusions

- In the case of longitudinal reinforcement only, the numerical results obtained with the *representative section approach* and CDPM2 material model comply with the design codes. The MSR reinforcement enhances strength from $\approx 25\%$ (high eccentricity) to 40% (low eccentricity).
- The peak load is reached at the onset of spiral yielding, which corresponds to the maximum confinement.
- A considerable mesh dependence of the MSR simulations has been detected. The explanation was found in the behavior of the zone with *reduced confinement*, just outside the small spirals. Coarser meshes lead to strength overestimation because this effect is not considered properly.
- Second-order moments are important in both experiments and modeling. An exceptional agreement between the experiments and numerical results was obtained, which proves the superior performance of MSR layout stemming from laterally confined concrete.

Future goals

- 2 outputs for CeSTaR 2 project

1. Formulae for the design of columns with MSR
    - Mechanical response of compressed concrete columns with two interlocking circular spirals (bachelor thesis of Marketa Venclova) + experiments



Future goals

- 2 outputs for CeSTaR 2 project

1. Formulae for the design of columns with MSR
    - Mechanical response of compressed concrete columns with two interlocking circular spirals (bachelor thesis of Marketa Venclova) + experiments
2. MaLCoLM 2.0 (Multi-spiral column simulation module, OOFEM extension module)
    - PySide (LGPL) = Python Qt bindings
    - OOFEM python bindings (full or partial?)
    - primary purpose: quick design + interaction diagram

Thank you for your attention.

petr.havlasek@cvut.cz

Financial support for this work was provided by the Technology Agency of the Czech Republic (TA ČR), project number TM01000059 (Reducing material demands and enhancing structural capacity of multi-spiral reinforced concrete columns - advanced simulation and experimental validation).