COMPUTATIONAL ENGINEERING RESEARCH

FOR A SUSTAINABLE WORLD

UdG

AMADE

AMADE Days

July 11th 2024

CIMNE

EXCELENCIA SEVERO OCHOA

CENTRE INTERNACIONAL DE MÈTODES NUMÈRICS A L'ENGINYERIA

UN CONSORCI DE

Generalitat de Catalunya

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

EN COL·LABORACIÓ AMB

unesco Chair

CERCA Centres de Recerca de Catalunya

INTERNATIONAL CENTRE
FOR NUMERICAL METHODS
IN ENGINEERING

CAMMS Group

Composites and Advanced Materials for Multifunctional Structures

La institució

UPC centre R+D+i **creat el 1987** enfocat a la **recerca**, **transferència tecnològica** i **disseminació** de l'**enginyeria computacional** i els **mètodes numèrics** a l'enginyeria.

Consorci

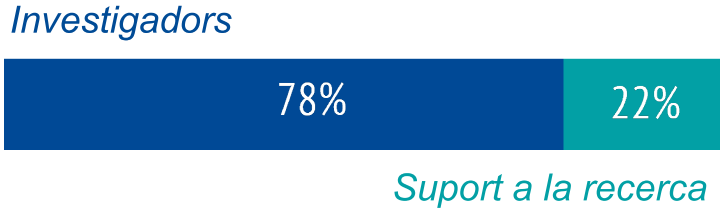
En col·laboració amb

Centre

La institució

En xifres

286 persones



72 projectes competitius

72 contractes amb empreses

8 empreses derivades

32 aules internacionals

Dades de personal: juny 2024. Resta: desembre de 2023

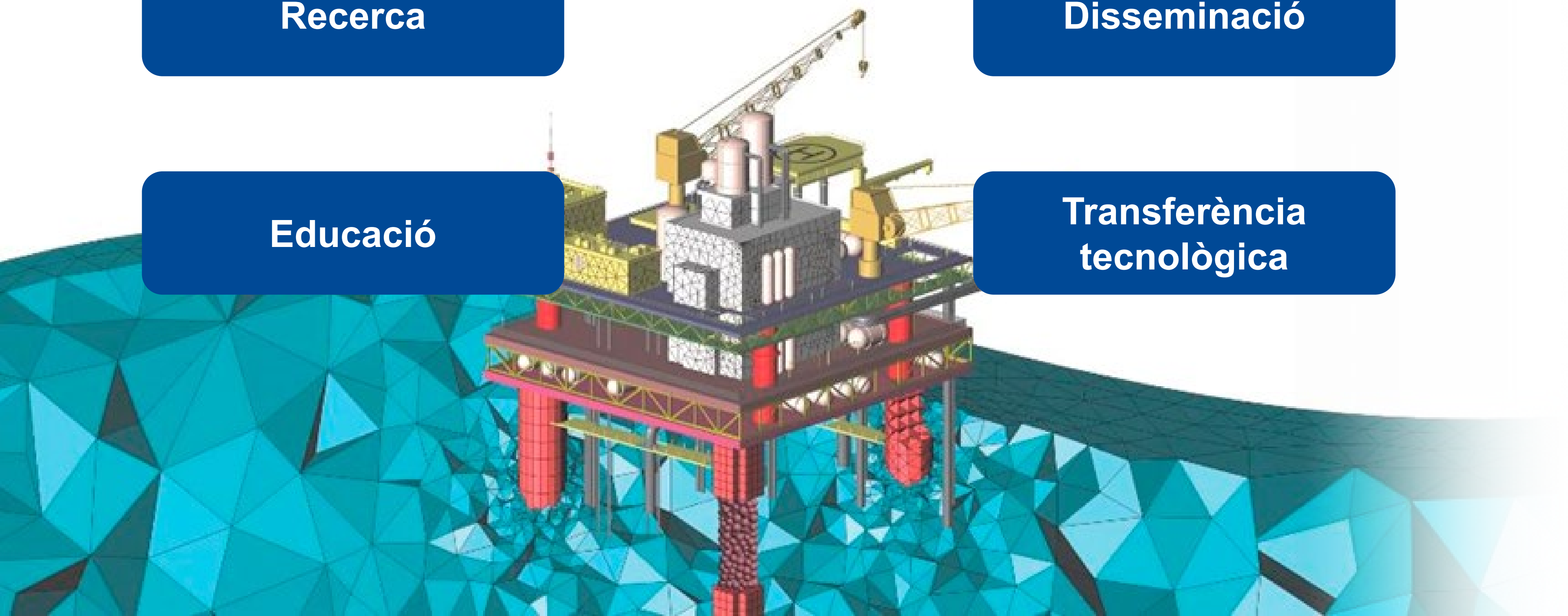
Els nostres pilars

Recerca

Disseminació

Educació

Transferència tecnològica



L'estructura de recerca

"Convertir les idees de recerca en productes, processos o serveis innovadors al servei de la societat"

Pla estratègic CIMNE

CLÚSTERS DE RECERCA	
1) Geomecànica i hidrogeologia	**6)** Mecànica estructural i de partícules
2) ML i models en enginyeria hidroambiental	**7)** Mecànica de materials avançats i metamaterials
3) Enginyeria aeronàutica, marina, d'automoció i energia	**8)** Models d'alta fidelitat basats en dades
4) Simulació de sòlids i fluids per processos industrials	**9)** Multifísica computacional a gran escala
5) Mecànica computacional en enginyeria mèdica i de material viva	

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CIMNE EXCELENCIA SEVERO OCHOA

CAMMS

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CAMMS

Objective

The **CAMMS'** objective is developed numerical methods and procedures for the prediction and characterization of the performance of composites and advanced materials, and to use these methods in the analysis of large multifunctional structures that are found in all engineering fields: naval, energy, aeronautical, civil, automotive, etc.

About us

UPC Professors (6)

Lucia Barbu
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Alex Ferrer
Xavier Martinez
Fermin Otero

Post-Doc. (2)

Sergio Jimenez
Francesc Turon

Res. Engineers (2)

Sergi Ocón
Shakib Ayoubzadeh

Visiting Prof. (1)

Sergio Oller

PHD Students (11)

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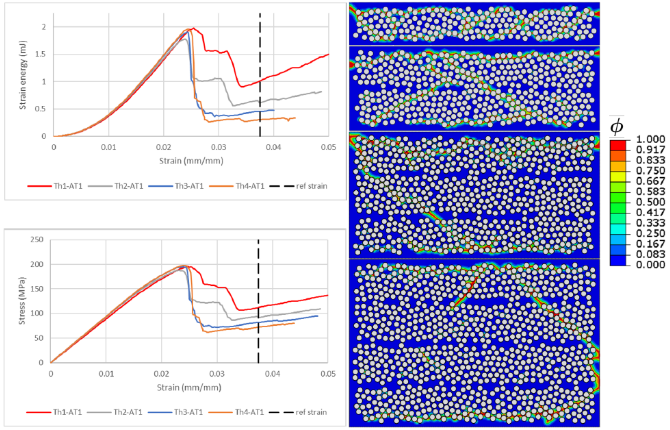
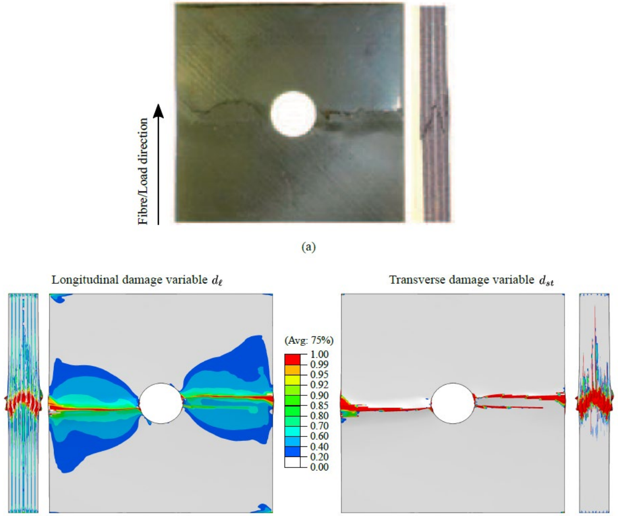
Nima Zahedan
José Torres
Polytimi Zisimopoulou
Lluís Martorell
Montserrat Dolz
Gerard Villalta
Andrea Gorgi
Luis Antonio Gonçalves
Raul Rubio
Ton Creus

Research lines

Advanced constitutive modelling for composite materials

Novel and advanced constitutive models have been developed and applied for the simulation of failure process in unidirectional fibre reinforced polymers. The failure of a multidirectional laminate has been studied using **a coupled plastic and damage constitutive model**.



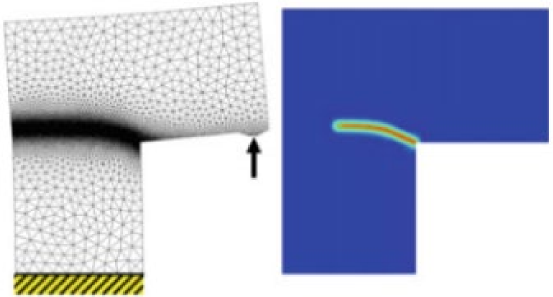


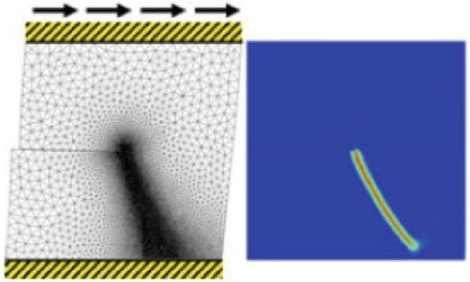
Stress and Strain energy (vs Strain) during matrix cracking at the microstructural level (left side). Full numerical simulation of Open Hole under compression load and its comparison with experimental results

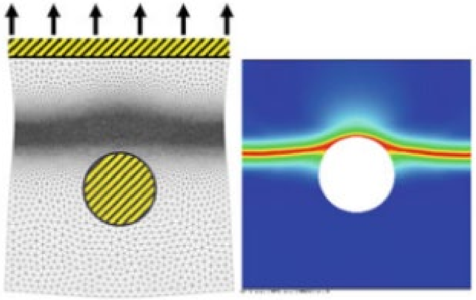
Research lines

Advanced constitutive modelling for composite materials

Novel and advanced constitutive models have been developed and applied for the simulation of failure process in unidirectional fibre reinforced polymers. Matrix cracking at the microstructural level has been simulated using **Phase Field techniques**.



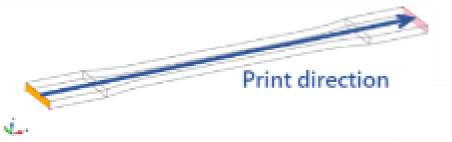


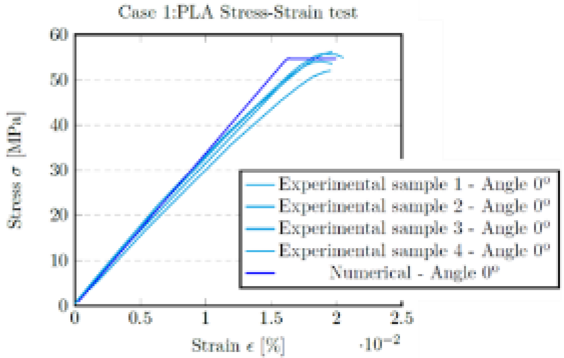


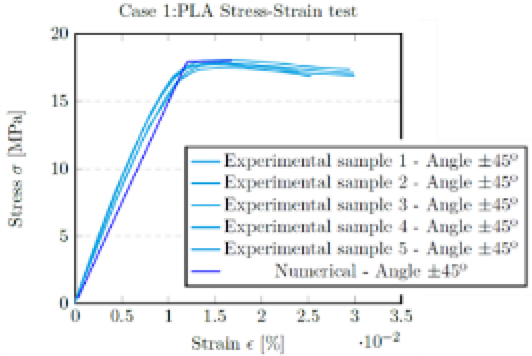
Research lines

Numerical models to predict the performance of additive manufactured materials

The group is working on the characterization of the mechanical performance of additive manufactured composite materials by means of anisotropy models coupled with composite formulations such as the serial-parallel mixing theory





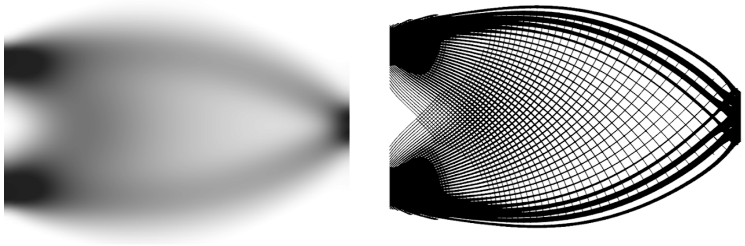


Characterization of an additive manufactured dog bone specimen made of PLA material with different printing orientations (0º and 45º)

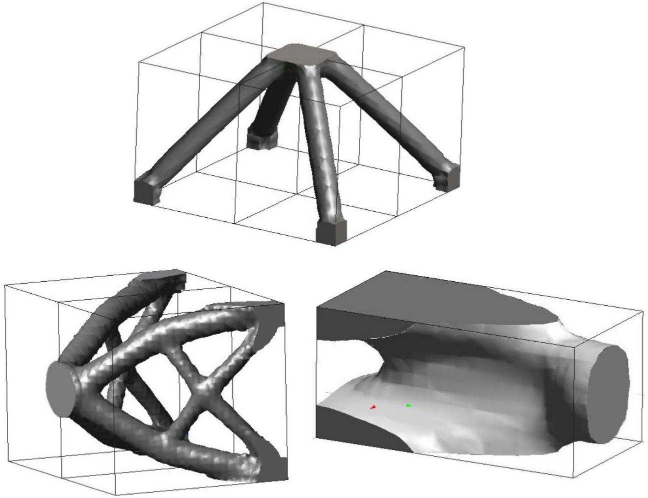
Research lines

Design of architectured materials and lattice structures

New fast algorithms have been defined and implemented in the group to obtain lightweight structures. Through a new dehomogenization technique, the team has developed new algorithms for the design of lattice structures



New algorithms developed to rapidly design optimal lattice structures

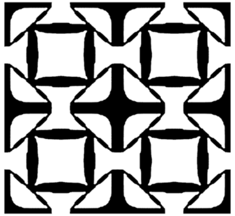


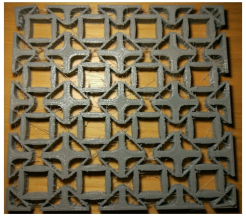
Shape and topology algorithms implemented for generative design of materials and structures

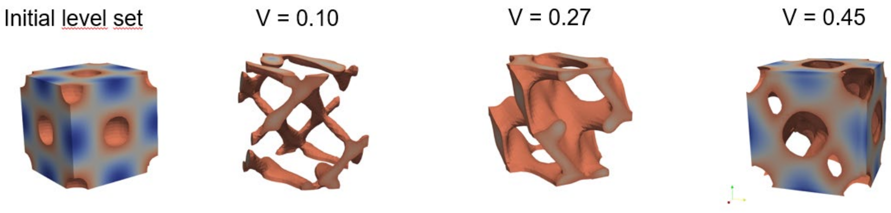
Research lines

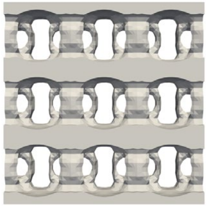
Design of 3D lightweight structures

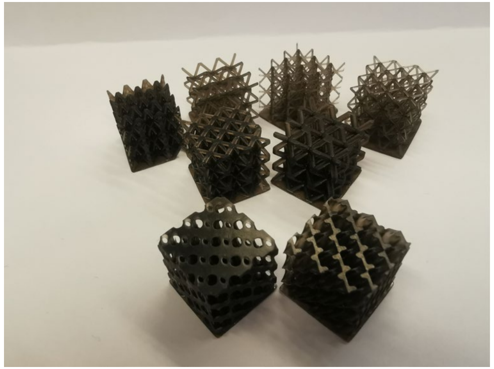
New algorithms have been developed for the design of materials including metamaterials, and architectured materials.









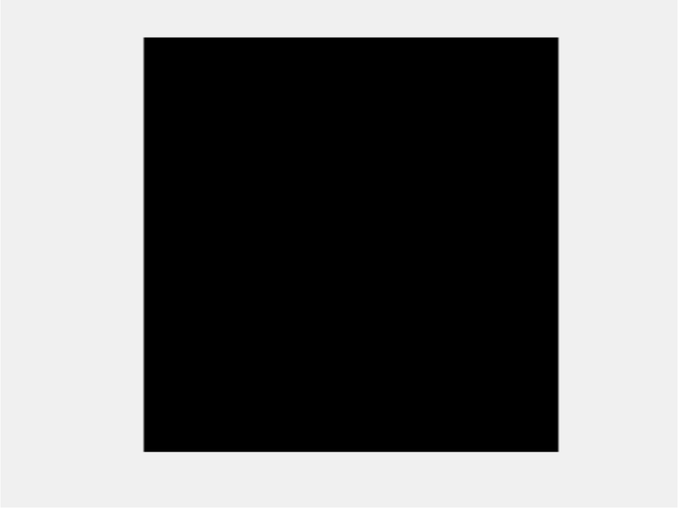


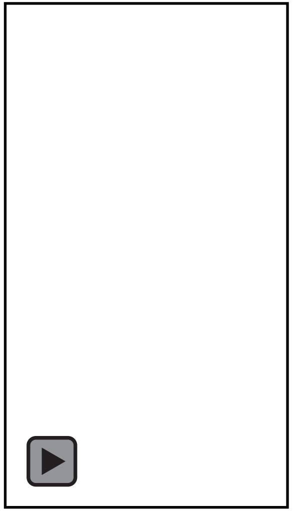
Design of metamaterials considering additive manufacturing constraints

Research lines

Generative design for additive manufacturing

New designs have to fulfil the manufacturing requirements. New algorithms have been developed to consider additive manufacturing constraints in the design process including overhang constraints



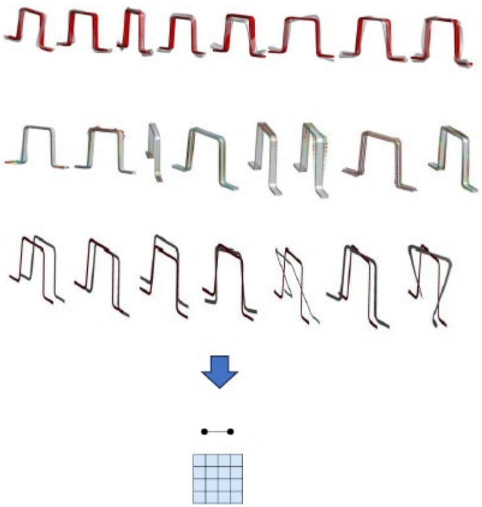


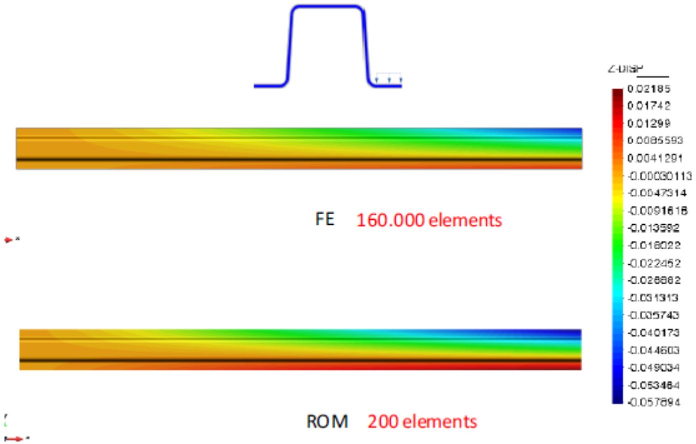
Overhang constraints implemented in topology optimization algorithms.
Now structures may be built using 3D printers

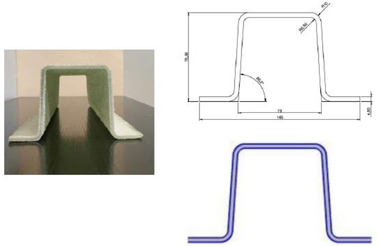
Research lines

Reduced order models to characterize composite beams

The existing anisotropy of composite pultruded beams can be captured by a reduced order model that is obtained from a full 3D characterization of the beam configuration. The results obtained from the reduced order model are then condensed to a standard beam formulation in order to facilitate their use by standard finite element codes.





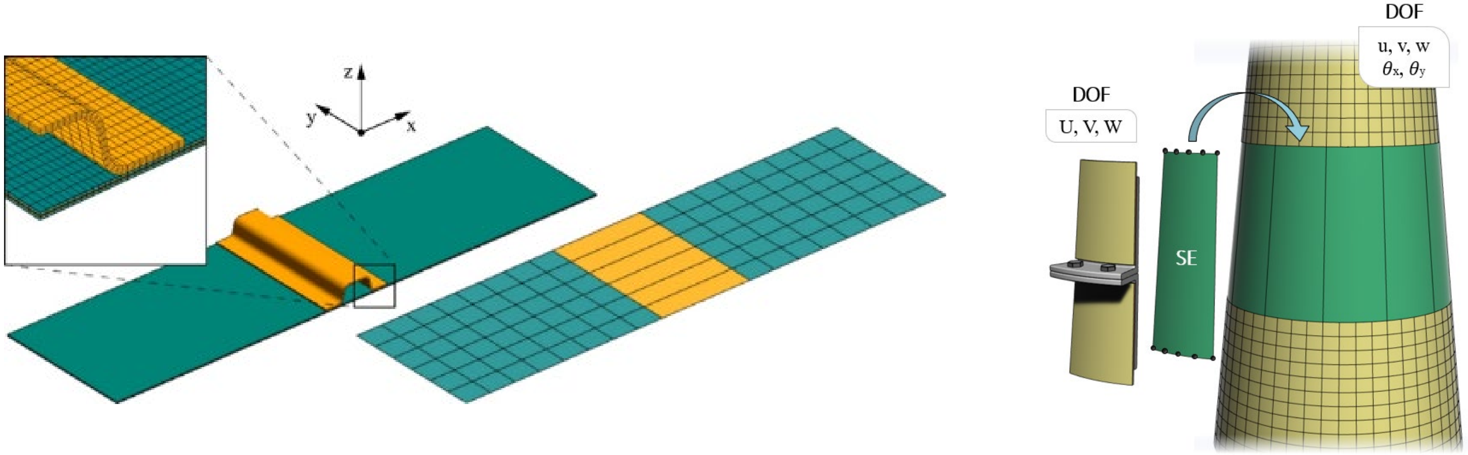


Subdomain deformation modes of an omega pultruded beam obtained with the reduced order model

Research lines

Analysis of structural connections and shell discontinuities by means of reduced order models

The analysis of large composite structures is usually conducted with shell elements that cannot capture irregularities such as connections, stiffeners and other discontinuities. The group is working on the definition of new shell elements that obtain their stiffness matrix from the analysis of a detailed 3D solid model.

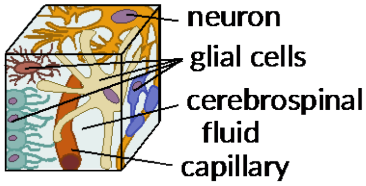


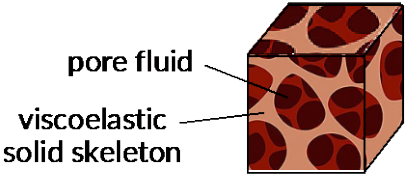
Analysis of a stiffened shell element with the reduced order model developed

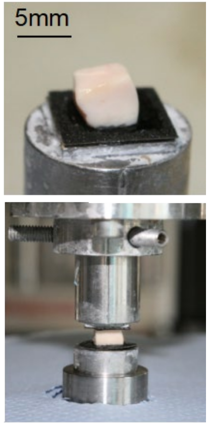
Research lines

Advanced constitutive modelling for biological materials

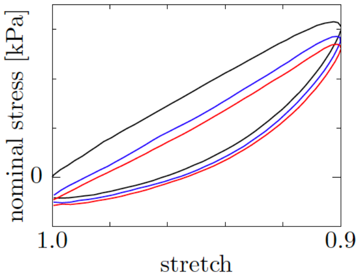
Constitutive models have been developed and combined to capture a wide range of biological tissue behaviour, including passive mechanical behaviour like **hyperelasticity, anisotropy, and poro-viscoelasticity** as well as active responses like **growth and healing**. Computational simulations using these models are used to test biological hypothesis.

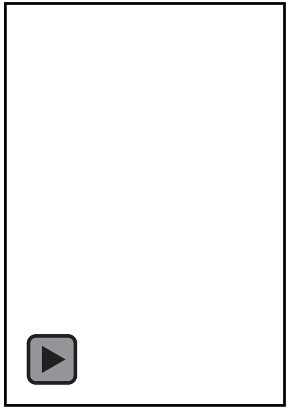




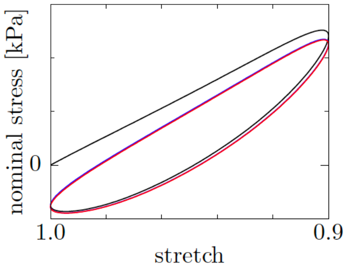


experiments





simulations



Understanding the porous and viscous effects of brain tissue (collaboration with FAU in Erlangen, Germany).

Research lines

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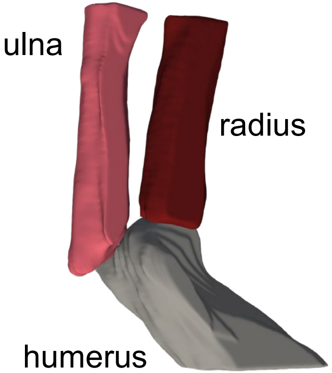
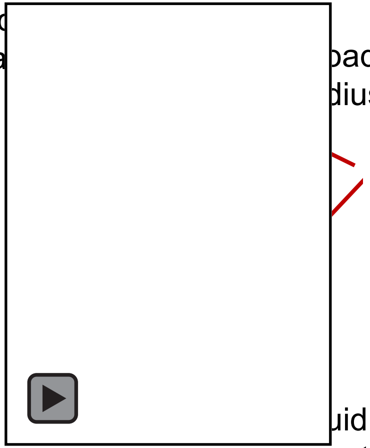
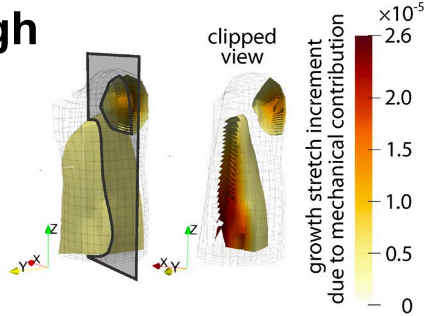




regions of high mechanical growth



Influence of mechanics on bone growth and joint formation (collaboration with Northeastern University in Boston US).

Research lines

Advanced constitutive modelling for biological materials

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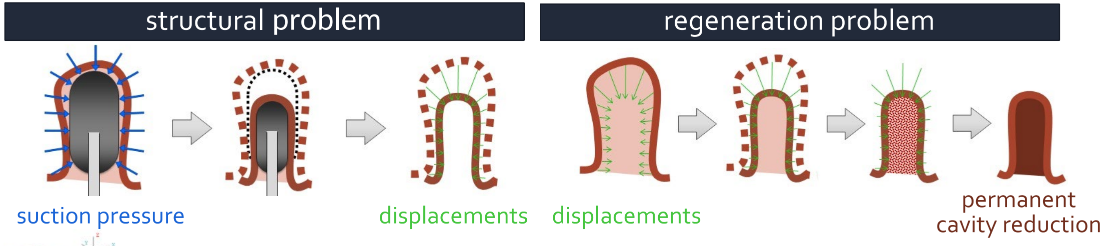
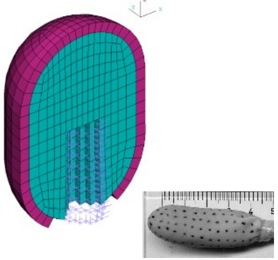
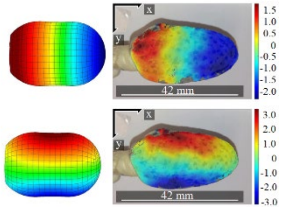
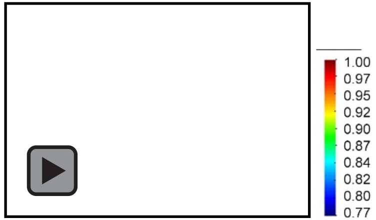
B BRAUN









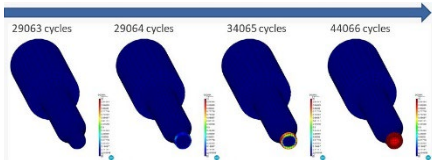
Mechanobiological mechanisms in the vacuum-assisted closure of an oesophagal anastomotic leakage (collaboration with B. Braun Barcelona).

Research lines

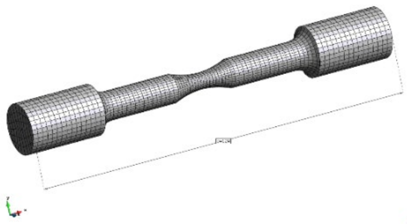
High cycle fatigue formulation

Numerical capabilities in the HCF study.

- **Close link with experiment**. The model is calibrated through standard information: 2 SN curves + strength/stiffness evolution information.
- **Continuous description of the phenomenon**. After the model calibration any S_{max} – R pair can be addressed and constant/variable amplitude loading.
- **Crack path detection**. The analysis allows to detect the initiation and describe the evolution of the associated degradation.
- **Multi-material application**. The model has been used on AHSS, PHS, aluminum, GFRP and CFRP materials.
- **Geometry independent material parameters.** Calibration of S-N curves is done at coupon level followed by processing into geometry independent curves, ensuring transferability to component scale.



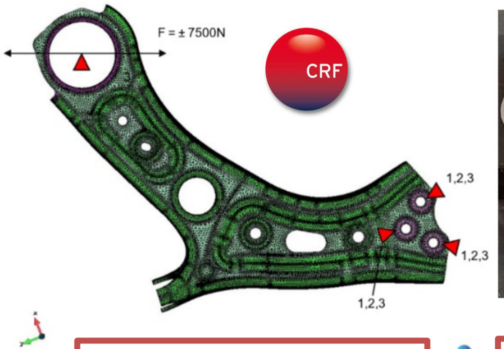
Resulting in a tool **easy to implement**, **versatile** allowing for an **advanced study of the phenomenon**, useful for **optimization** and **design purposes**

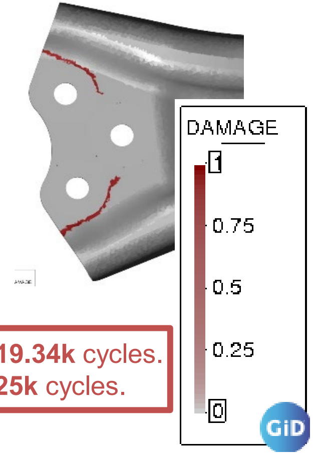


Research lines

High cycle fatigue formulation

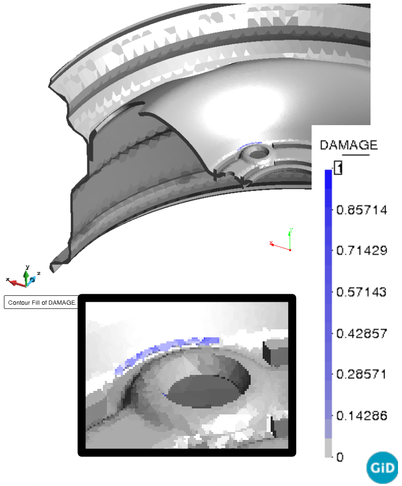
Lower control arm – AHSS / CFRP / GFRP solutions

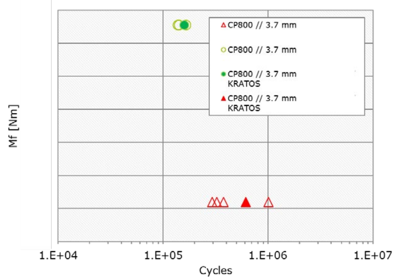




First crack → **13.35k** cycles.
Final state → **24.80k** cycles.

First crack → **19.34k** cycles.
Final state → **25k** cycles.

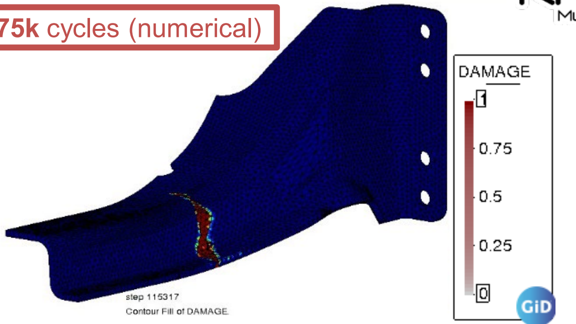


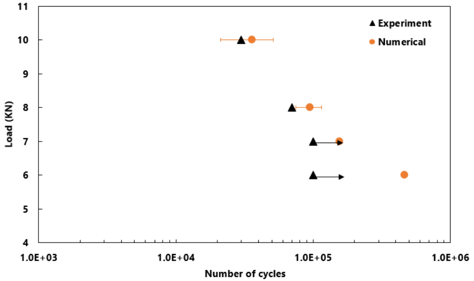


Cross member beam – PHS solution

70k cycles (experiment)

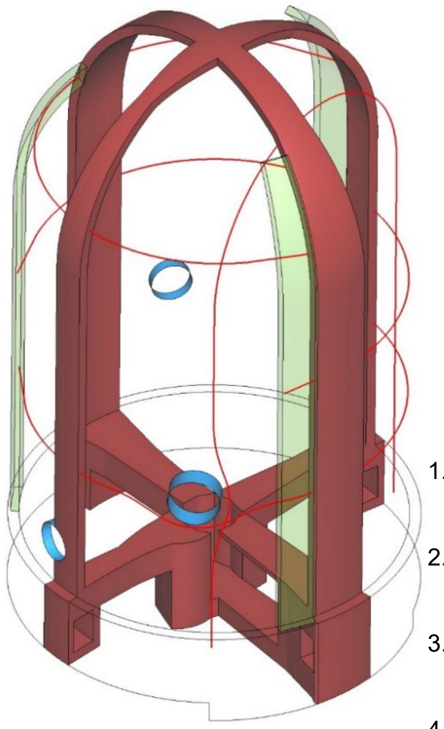
75k cycles (numerical)

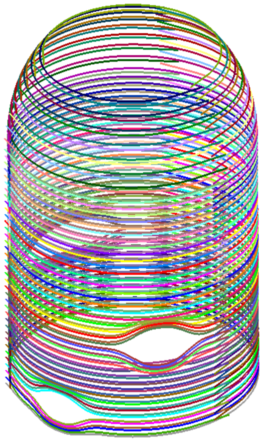


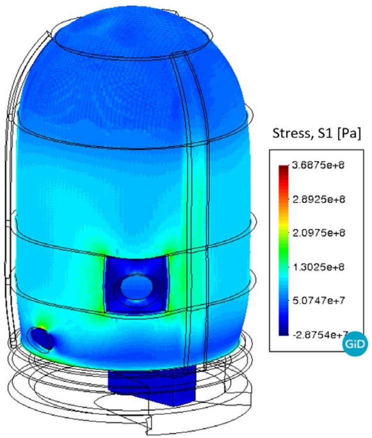


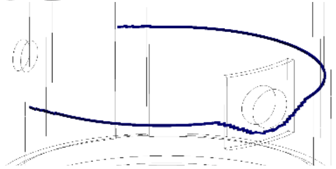
Research lines

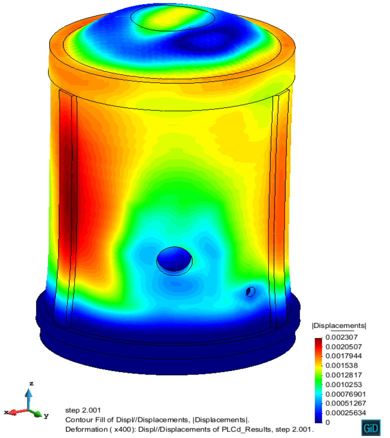
Reinforced concrete as composite material – application to prestressed structures







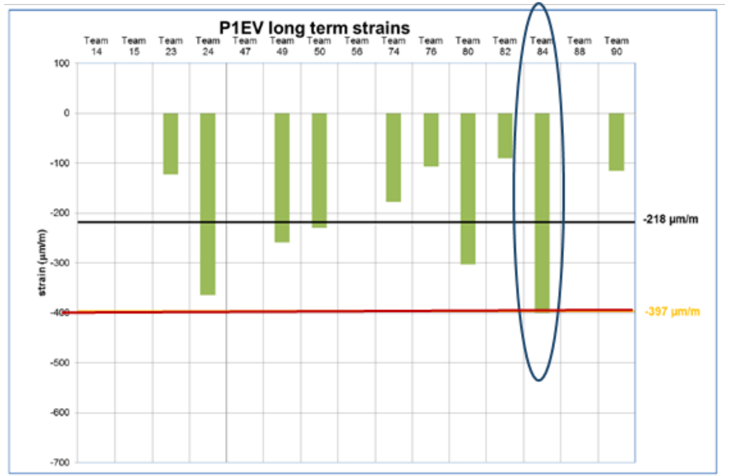


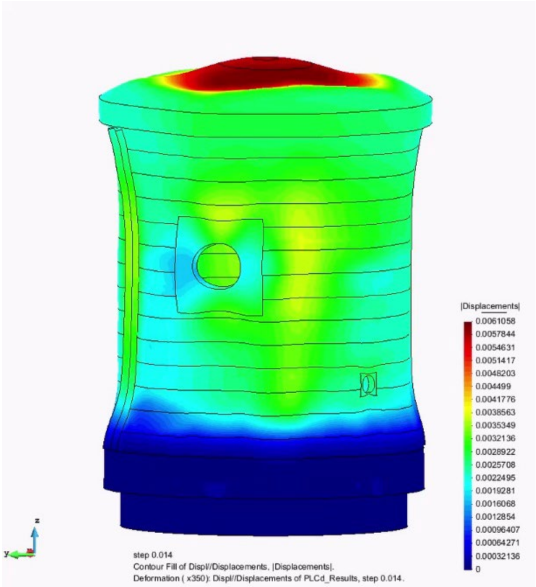


1. Jiménez S., Cornejo A., Barbu L.G., Barbat AH. and Oller S., Failure pressure analysis of a nuclear reactor prestressed concrete containment building. Engineering Structures, 2021. Vol: 236. Pg.: 112052:12.
2. Jimenez, S.; Cornejo, A.; Barbu, L.; Oller, S.; Barbat, A. H. Analysis of the mock-up of a reactor containment building: comparison with experimental results. Nuclear engineering and design. 2020. Vol: 359. Pg.: 110454:1 ~ 110454:13.
3. Barbu, L.; Cornejo, A.; Martinez, X.; Oller, S.; Barbat, A. H. Methodology for the analysis of post-tensioned structures using a constitutive serial-parallel rule of mixtures: large scale non-linear analysis. Composite structures. 2019. Vol: 216. Pg.: 315-330.
4. Cornejo, A.; Barbu, L.; Escudero-Torres, C.; Martinez, X.; Oller, S.; Barbat, A. H. Methodology for the analysis of post-tensioned structures using a constitutive serial-parallel rule of mixtures. Composite structures. 2018. Vol: 200. Pg.: 480-497.

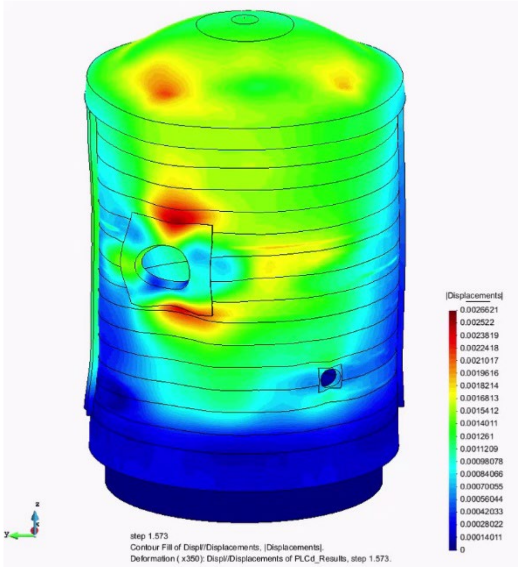
Research lines

Reinforced concrete as composite material – application to prestressed structures





Pre-stressing



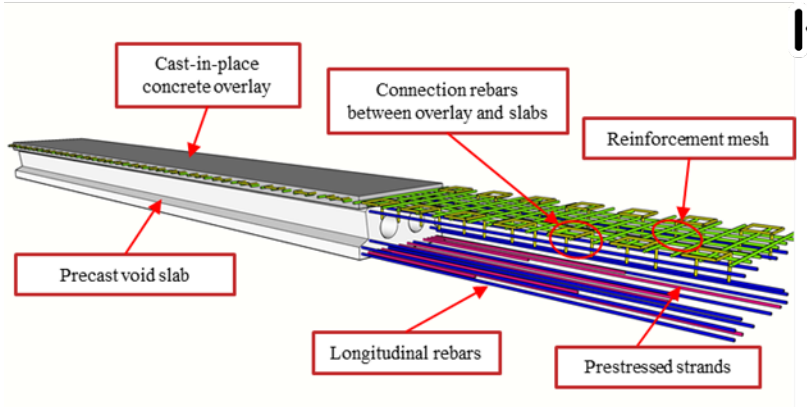
Internal pressure x350

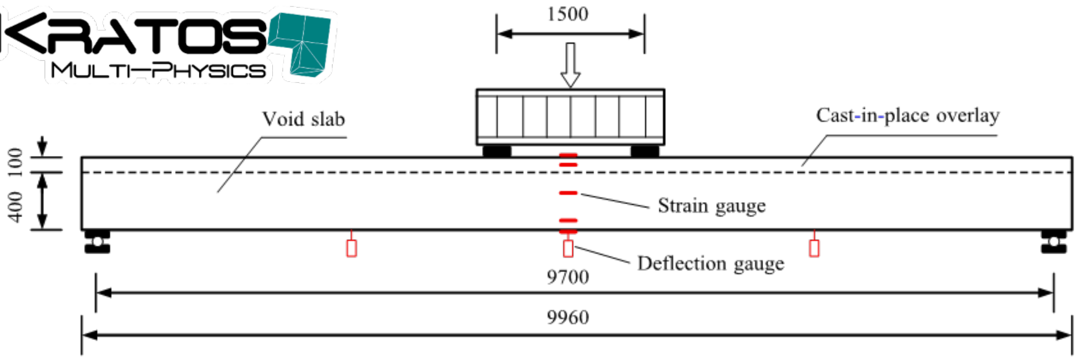
Benchmark **VeRCoRs** 2018. Invited by **EDF** S.A (Paris)

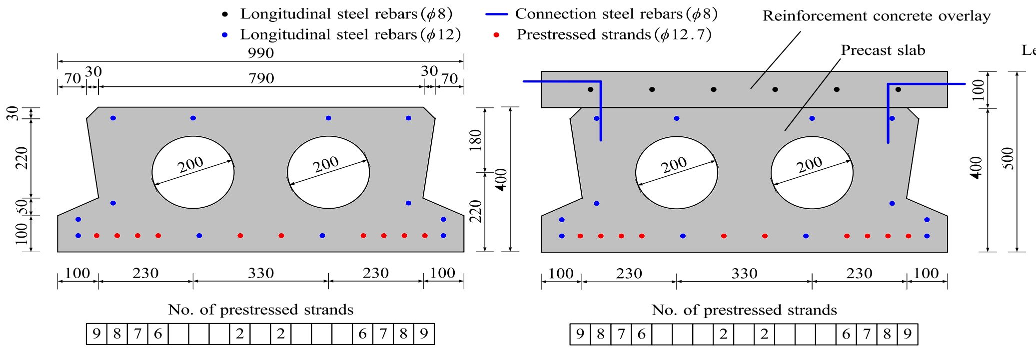
Appreciation of the quality of predictions	Teams
Good predictions in both direction and on numerous sensors	24, 47, 84 and 88
Good predictions in only one direction or only in some sensors	15, 50, 56 and 80
Predictions distant from experimental values in both direction in almost all sensors	14, 49, 76 and 82
Predictions very distant from experimental in all sensors and very much below average values	23, 74 and 90

Research lines

Reinforced concrete as composite material – application to prestressed structures

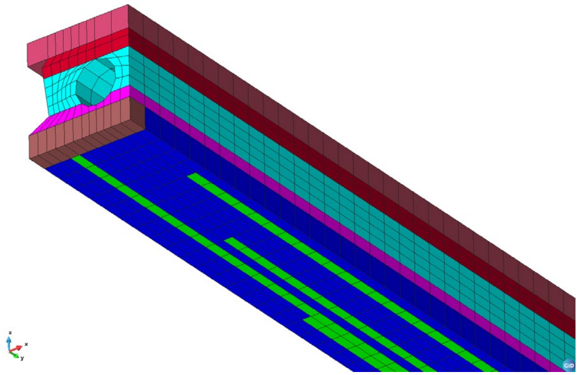






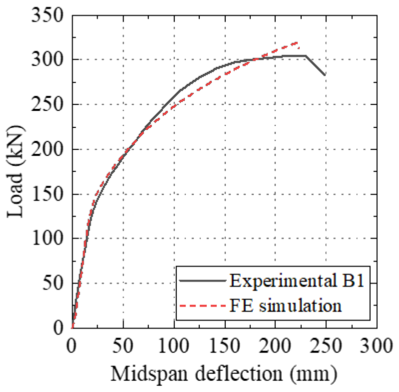
Lengths of prestressed strands

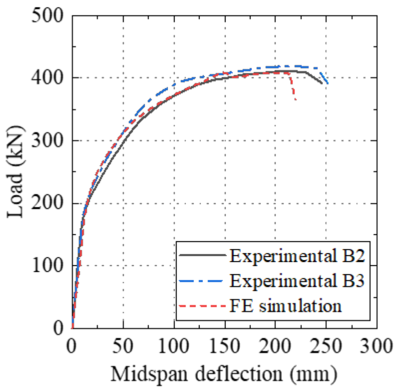
No.	Length
1	/
2	8900
3	/
4	/
5	/
6	7900
7	4700
8	9960
9	6500

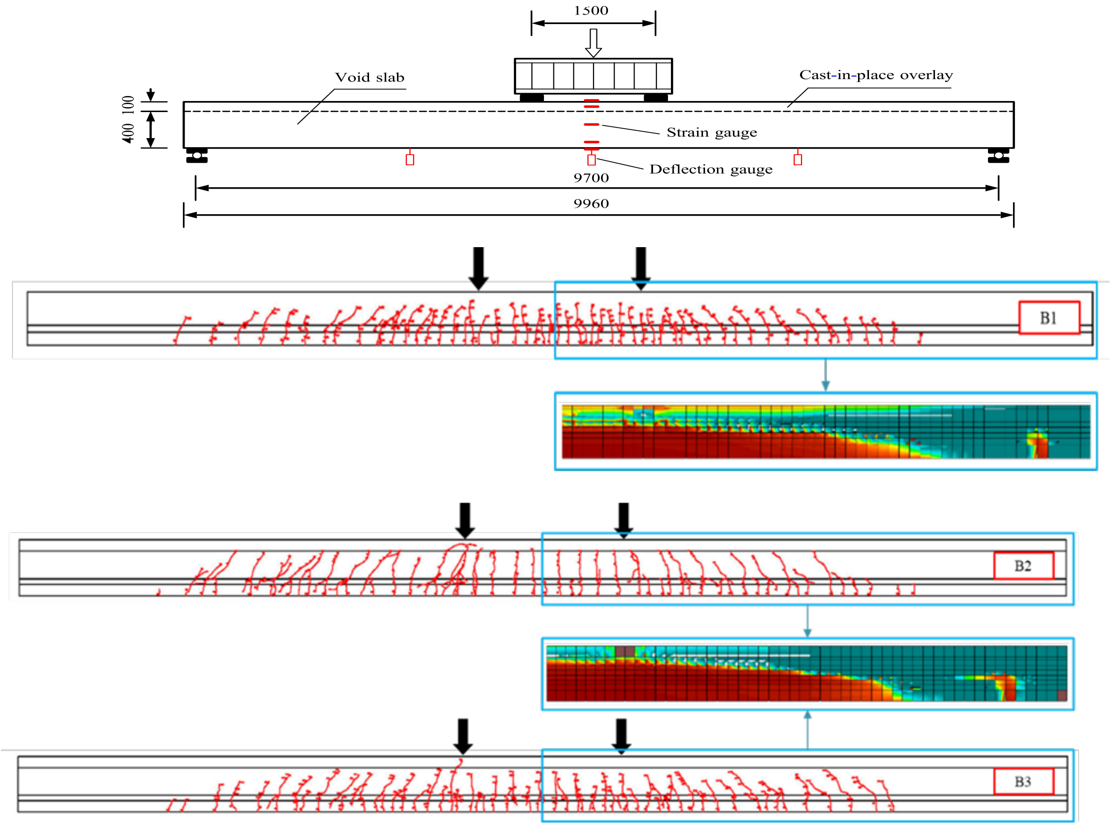


Research lines

Reinforced concrete as composite material – application to prestressed structures







Research lines

Plastic damage constitutive models for monotonic and cyclic loading

Uncoupled plastic-damage CL, $(\cdot)^{pd}_{uc}$

Model based on the RoM particularized for two "**component CLs**": damage and plasticity.

$$\boldsymbol{\sigma}^{pd}_{uc} = k^{\mathrm{d}}\,(1-d)\cdot\mathbb{C}_0\!:\boldsymbol{\varepsilon} + \left(1-k^{d}\right)\cdot\mathbb{C}_0\!:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{p})$$

Yield criteria: $\mathbb{F}^{d}_{0} = S_0 - \mathcal{K}^{d}_{0} \leq 0 \quad \wedge \quad \mathbb{F}^{p} = S - \mathcal{K}^{p} \leq 0$

Flow rule: $d \sim S_0 \quad \wedge \quad \dot{\boldsymbol{\varepsilon}}^{p} = \dot{\lambda}\dfrac{\partial \mathbb{G}^{p}}{\partial \boldsymbol{\sigma}^{p}}$

Semi-coupled plastic-damage CL, $(\cdot)^{pd}_{sc}$

Model proposed by Luccioni and latter used by Barbu for the study of LCF processes.

$$\boldsymbol{\sigma}^{pd}_{sc} = (1-d)\cdot\mathbb{C}_0\!:\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_p\right)$$

Yield criteria: $\mathbb{F}^{d} = S - \mathcal{K}^{d} \leq 0 \quad \wedge \quad \mathbb{F}^{p} = S - \mathcal{K}^{p} \leq 0$

Flow rule: $\dot{d} \wedge \dot{\boldsymbol{\varepsilon}}^{p} \sim f(\dot{\lambda})$ ➡ Damage and plasticity consistency conditions.

Coupled plastic-damage CL, $(\cdot)^{pd}_{c}$

Reinterpretation of the model proposed by Meschke et al [18] and Wu and Cervera [19] based on a normalised dissipation variable, κ_{pd}.

$$\boldsymbol{\sigma}^{pd}_{c} = \mathbb{C}_s : \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_p\right)$$

Yield criteria: $\mathbb{F}^{pd} = S - \mathcal{K}^{pd} \leq 0$

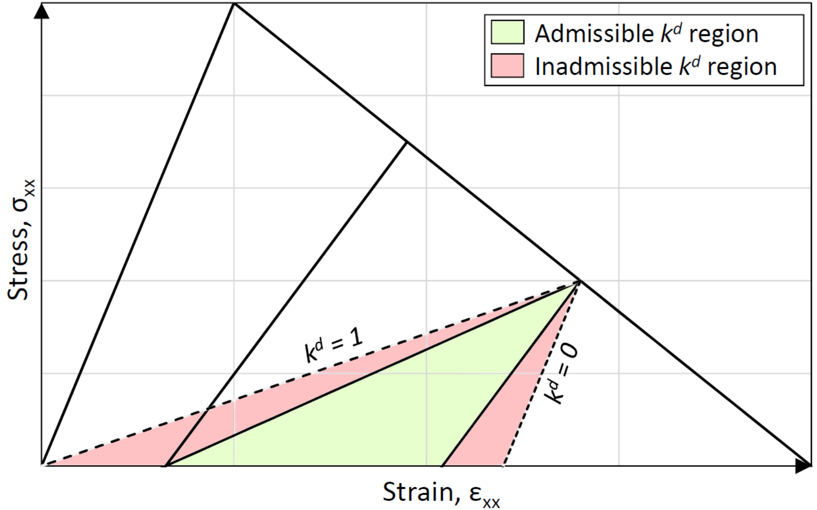
Flow rule: $\dot{\mathbb{D}} = \xi\,\dot{\phi}\,\boldsymbol{\Omega}\,\boldsymbol{\mho} \quad \wedge \quad \dot{\boldsymbol{\varepsilon}}^{p} = (1-\xi)\cdot\dot{\phi}\,\dfrac{\partial \mathbb{G}^{pd}}{\partial \boldsymbol{\sigma}^{pd}_{c}}$

Research lines

Fluctuating (un)coupled plastic-damage model

- **Objective:** adapting the material response (plasticity-damage) along the simulation.
- First step in the direction of the **unified analysis**. $k^d \longrightarrow k^d(?) \quad \wedge \quad \xi \longrightarrow \xi(?)$
- **Uniqueness condition**. This affects both models, where the **material stress state** is $\boldsymbol{k^d}$**-dependent** in the **uncoupled** case and the **threshold** is $\boldsymbol{\xi}$**-dependent** in the **coupled** case.

$$k^d \longrightarrow k^d(d) \quad \wedge \quad \xi \longrightarrow \xi(\kappa_{pd})$$



- **Irreversibility condition** (only affecting the uncoupled model).

$$: \frac{d_{ref}}{d}\, k^d_{ref}$$

$k^d_{min} \longrightarrow$ Stop damage

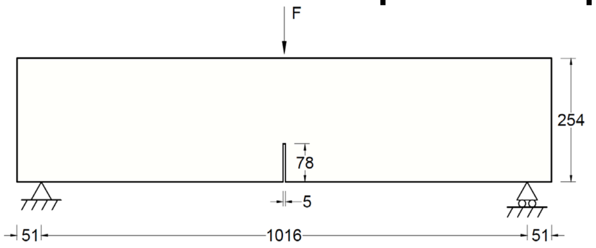
$k^d_{max} \longrightarrow$ Stop plasticity

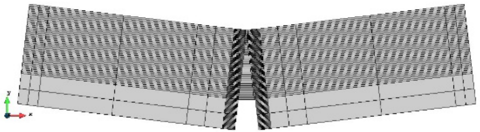
$$\frac{\left(1-k^d_{ref}\right)E_p\left(\kappa_{p,ref}\right)-\left(1-k^d_{ref}\,d_{ref}\right)E_p\left(\kappa_p\right)}{d\left(1-k^d_{ref}\right)E_p\left(\kappa_{p,ref}\right)-\left(1-k^d_{ref}\,d_{ref}\right)E_p\left(\kappa_p\right)}$$

Research lines

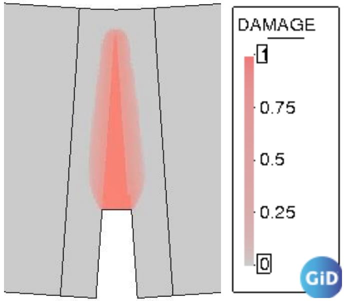
Fluctuating (un)coupled plastic-damage model

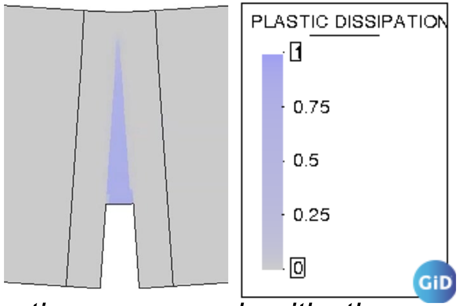
Numerical examples. Three point cyclic bending test



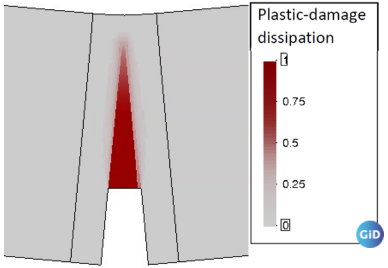


Three point bending test (a) geometry in [mm] and (b) FE mesh used (7376 hexahedra).

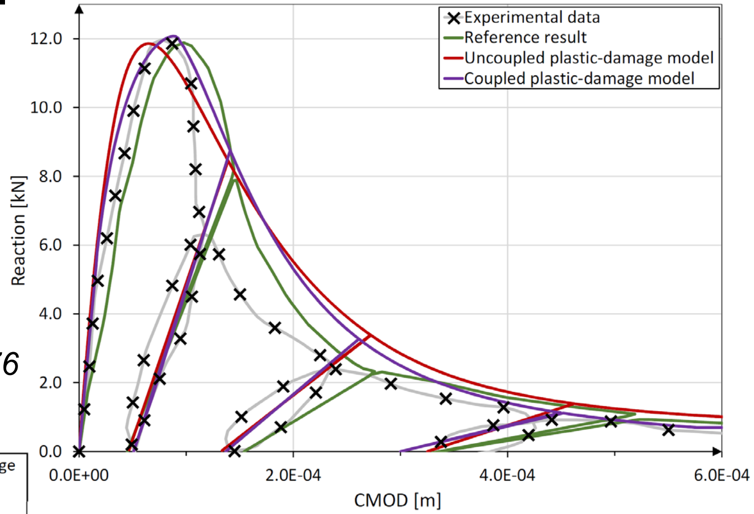




Envelope deterioration measured with the uncoupled plastic-damage CL: (a) damage and (b) plastic dissipation.



Envelope deterioration measured with the coupled plastic-damage CL



CMOD-reaction response. Numerical-experimental comparison.

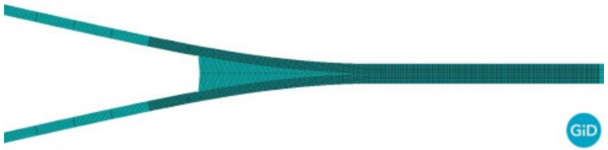
- **Uncoupled plastic-damage model.**
  - ► Exponential softening.
  - ► Fluctuating version, $k^d \in [0.5, 1.0]$.
- **Coupled plastic-damage model.**
  - ► Exponential softening.
  - ► Steady version, $\xi = 0.5$.

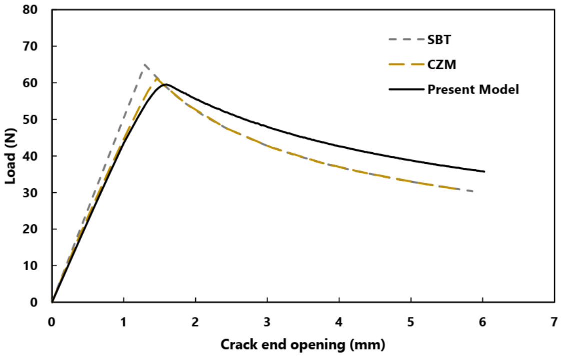
Research lines

Monotonic

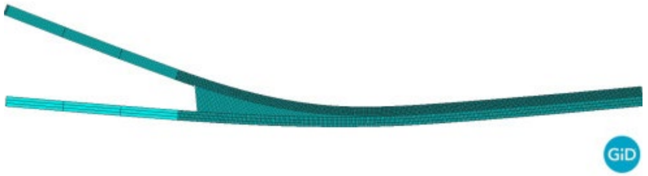
Delamination modelling without explicit interface representation

- Double Cantilever Beam (DCB)

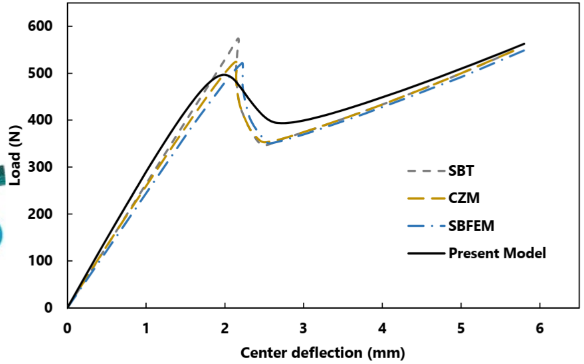


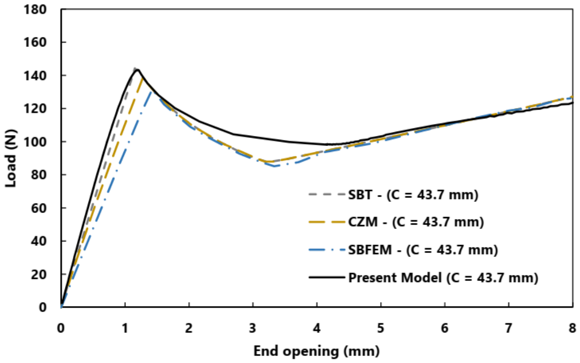


- Mixed Mode Bending (MMB)



- End Notch Flexure (ENF)



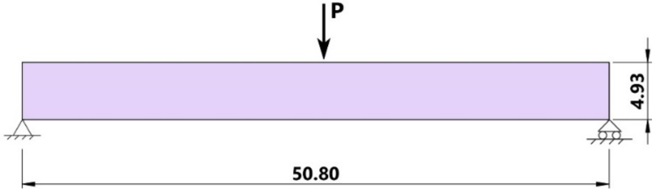


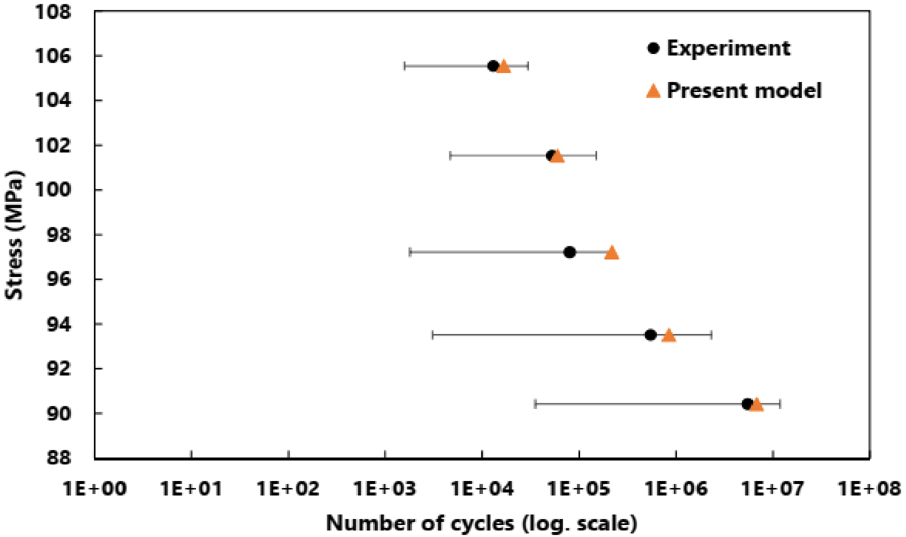
Taherzadeh-Fard A, Cornejo A, Jiménez S, Barbu LG. A rule of mixtures approach for delamination damage analysis in composite materials. Composites Science and Technology. 2023 Sep 29;242:110160.

Research lines

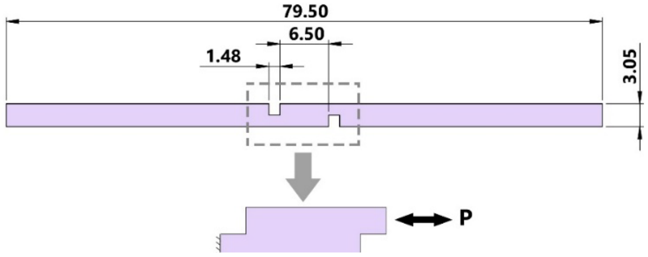
Cyclic

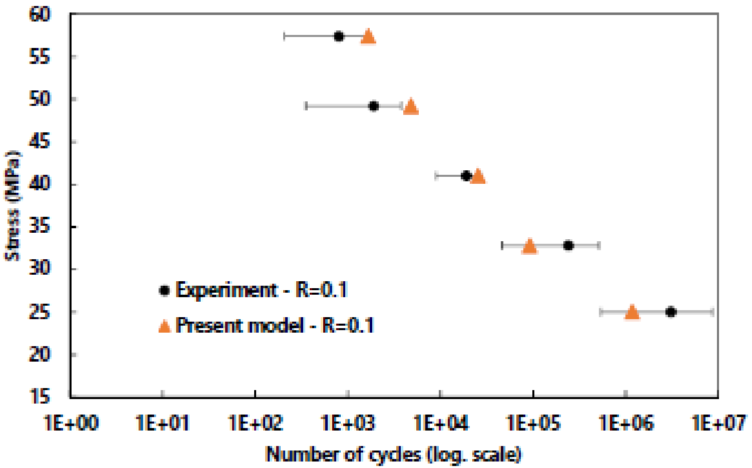
Delamination modelling without explicit interface representation





Initiation of the fatigue crack in the three-point bending configuration under mode I loading compared with the experimental data at R = 0.1





Initiation of the fatigue crack in double-notch shear configuration in R = 0.1

CIMNE
EXCELENCIA SEVERO OCHOA

Research lines

CAMMS

KRATOS MULTI-PHYSICS

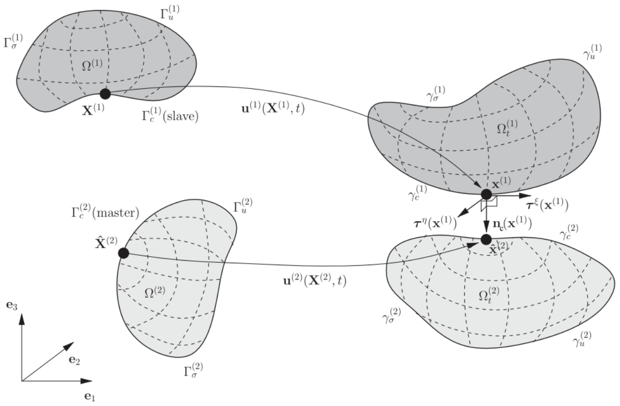
Contact and tire mechanics

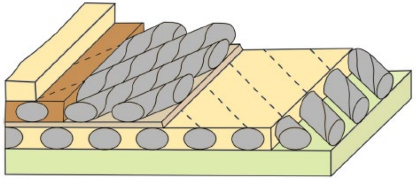
Methodologies to model implicit frictional contact and tire mechanics

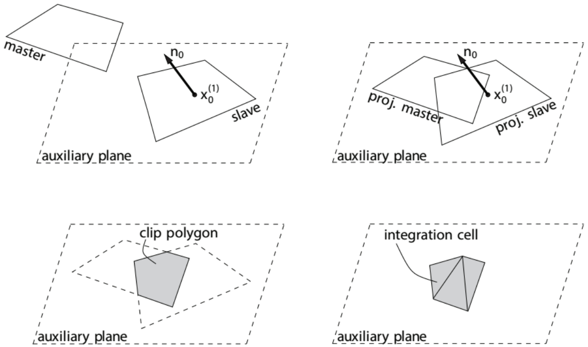
- Dual Augmented lagrangian Method
- Mortar Method for estimating the gap
- Implicit frictional contact
- Mixed u-p TL elements to deal with incompressibility and finite strains
- Modified SP-RoM to be used for tires

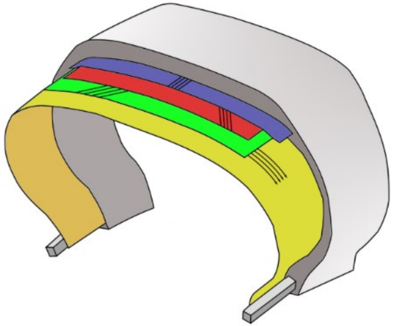
Leibniz Universität Hannover

Prof. Wriggers









Research lines

Contact and tire mechanics

Methodologies to model implicit frictional contact and tire mechanics

- Dual Augmented lagrangian Method
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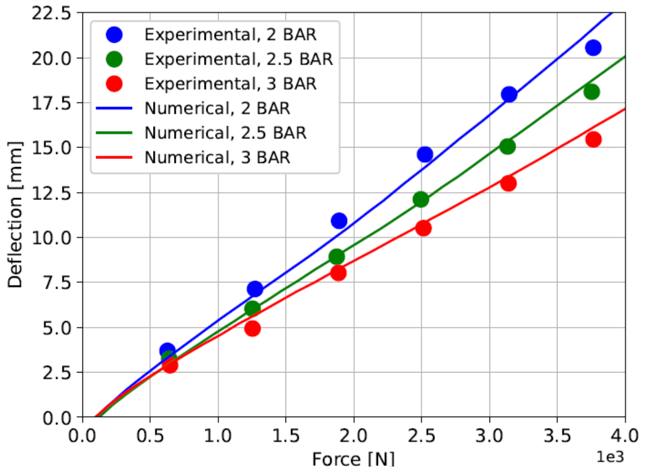
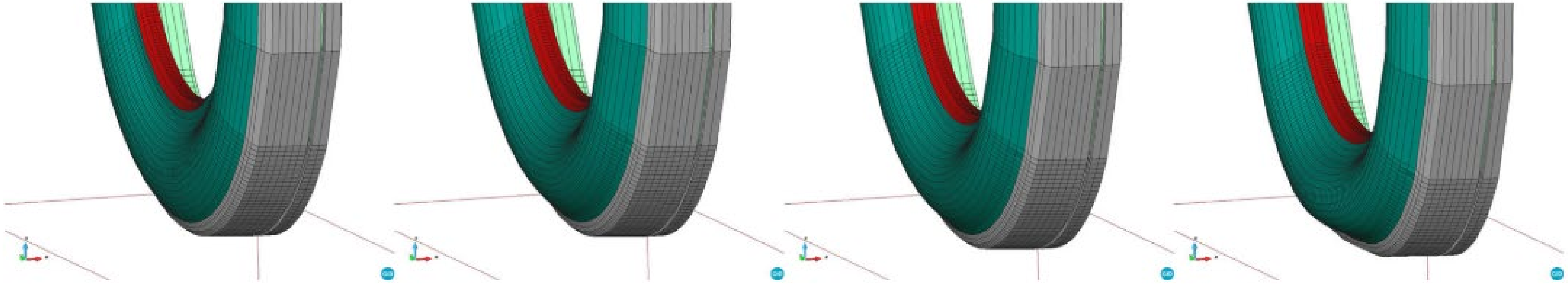




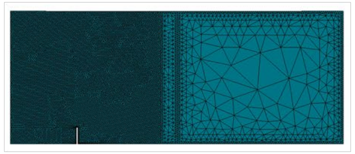
(a) No internal pressure (b) Internal 2.5 Bar pressure (c) 2000 N force (d) 4000 N force

Research lines

Fluid – Structure Interaction

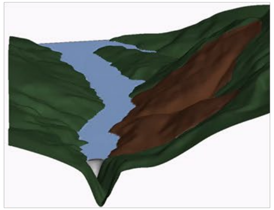
Finite Element Method (FEM)

- ✓ **Large displacement** (Total Lagrangian)
- ✓ **Fracture** mechanics
- ✓ Element **removal**

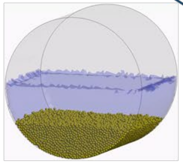


Particle Finite Element Method (PFEM)

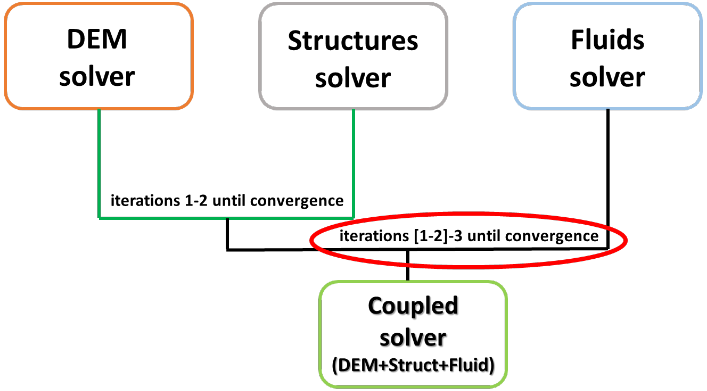
- ✓ **Lagrangian method** for large deformations problems
- ✓ Massive **remeshing**
- ✓ Time step solution with FEM



- ✓ **Explicit** method
- ✓ **Unbalanced** forces produce accelerations
- ✓ **Different** contact laws can be used

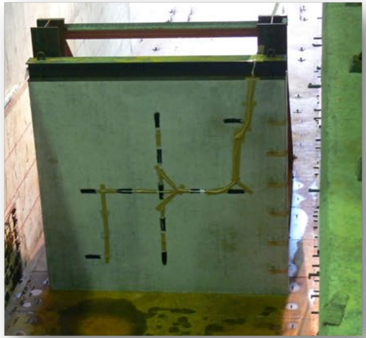


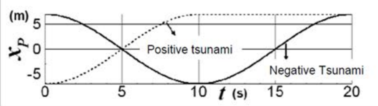
Discrete Element Method (DEM)

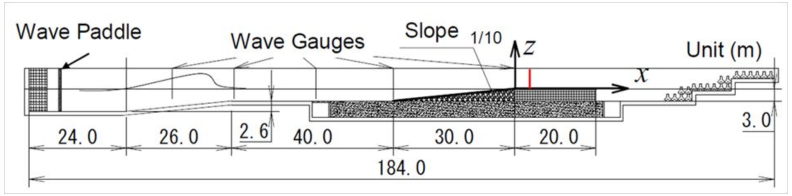


Research lines

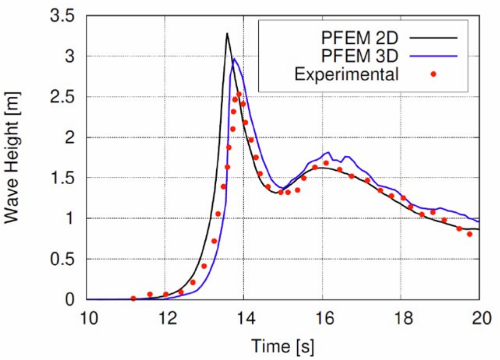
Fluid – Structure Interaction

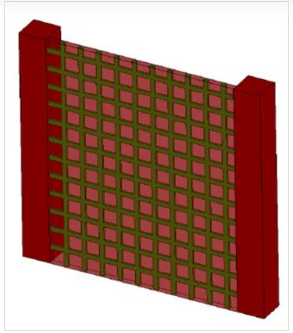


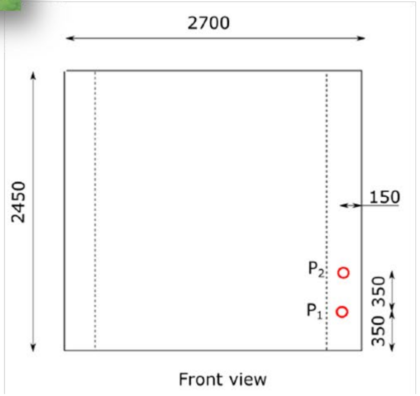


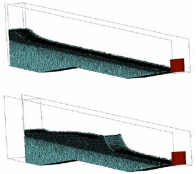


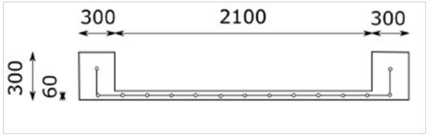
Prof. T. Arikawa, K. Shimosako and N. Ishikawa

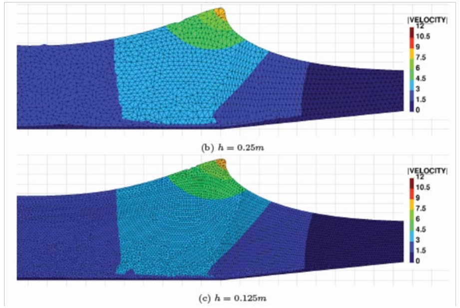






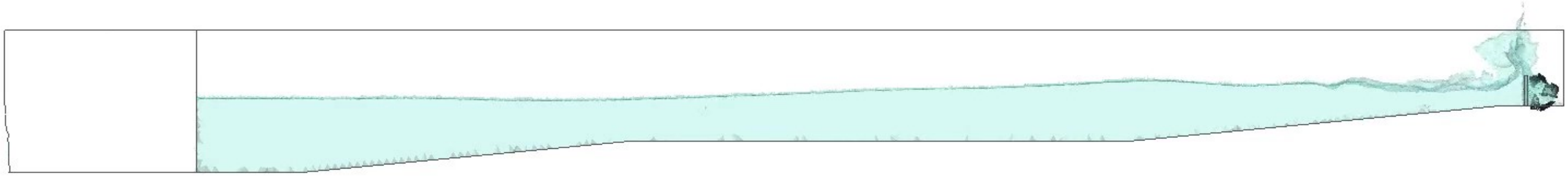


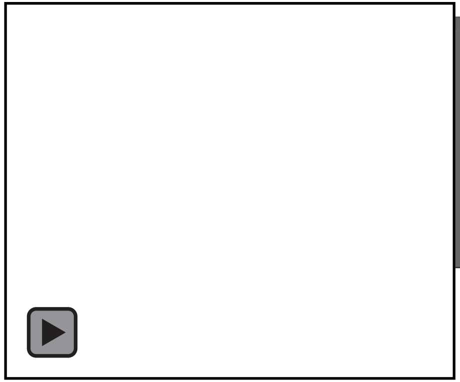




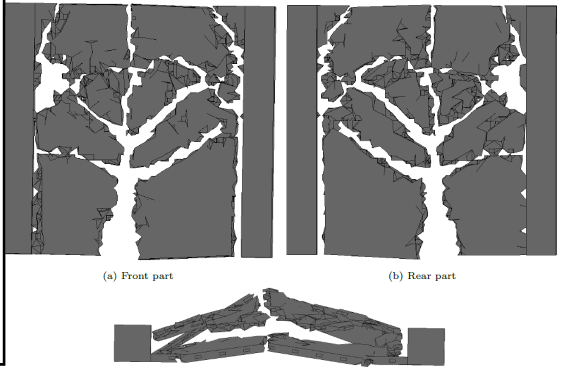
Research lines

Fluid – Structure Interaction





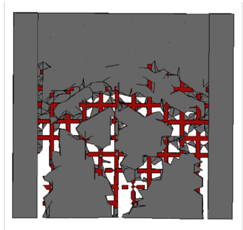
Non reinforced!



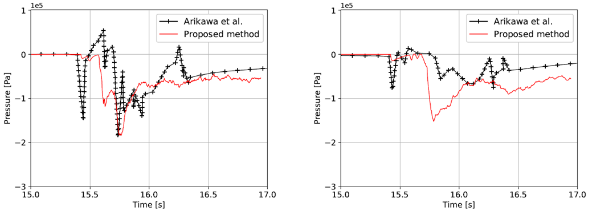
(a) Front part

(b) Rear part

(c) vertical view



(a) Front part

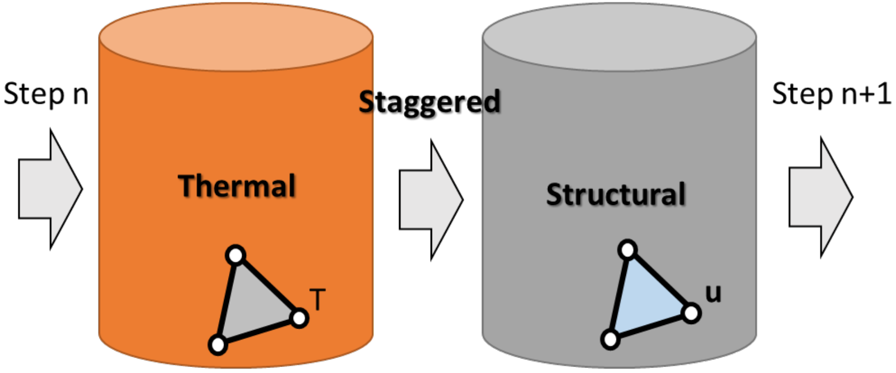


(a) P1 pressure gauge

(b) P2 pressure gauge

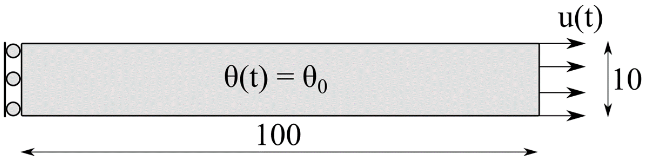
Research lines

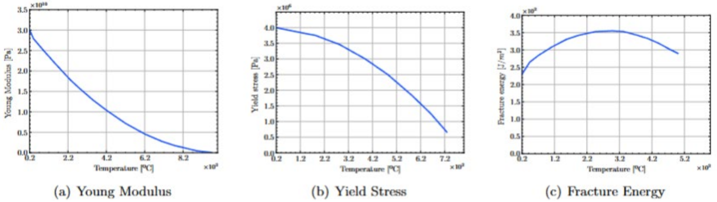
Thermomechanical calculations

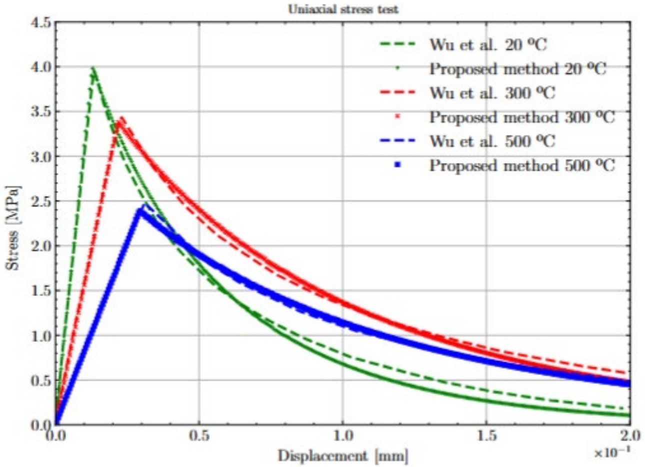


Convection-Diffusion

Static/Dynamic Solid solver
E(T), yield(T), G(T), etc







Monotonic

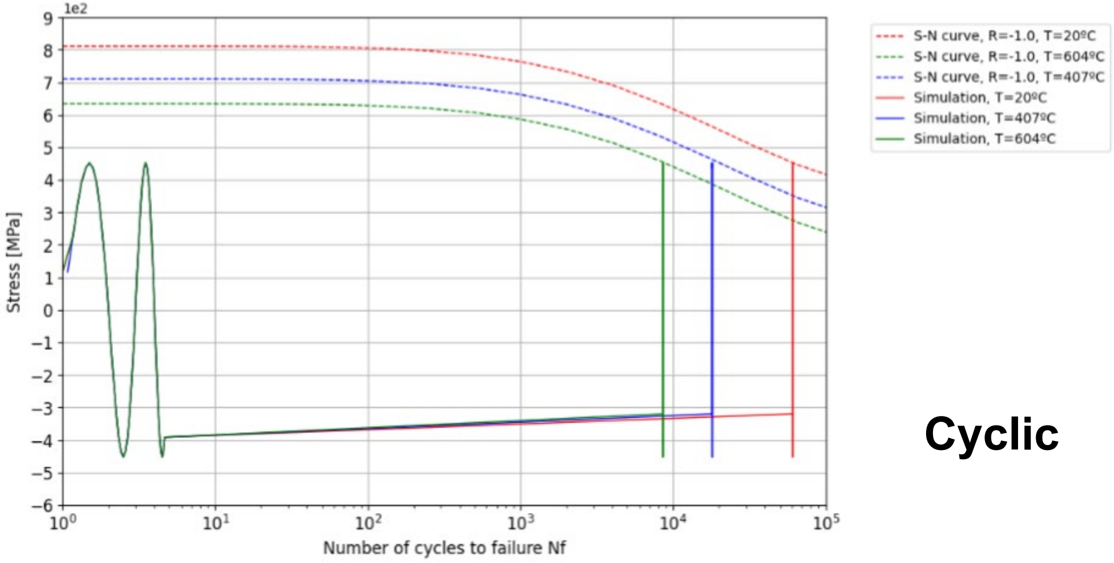
Research lines

Thermomechanical calculations

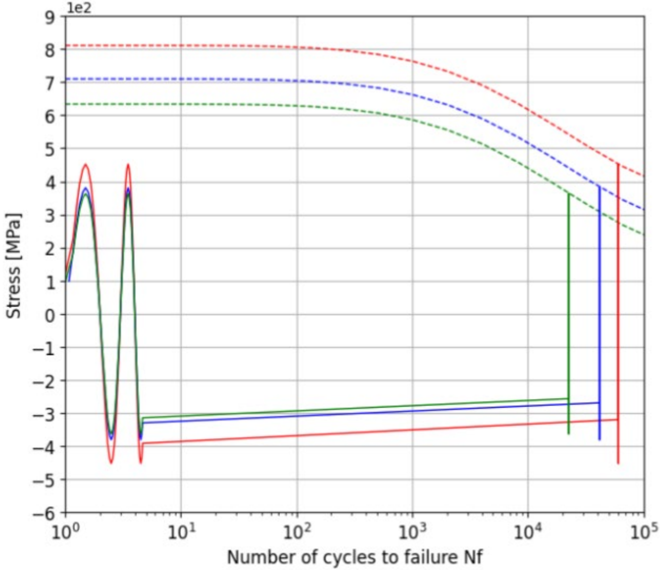
Thermomechanical HCF!

Only affecting the S-N curve according to T

Affecting S-N and E according to T

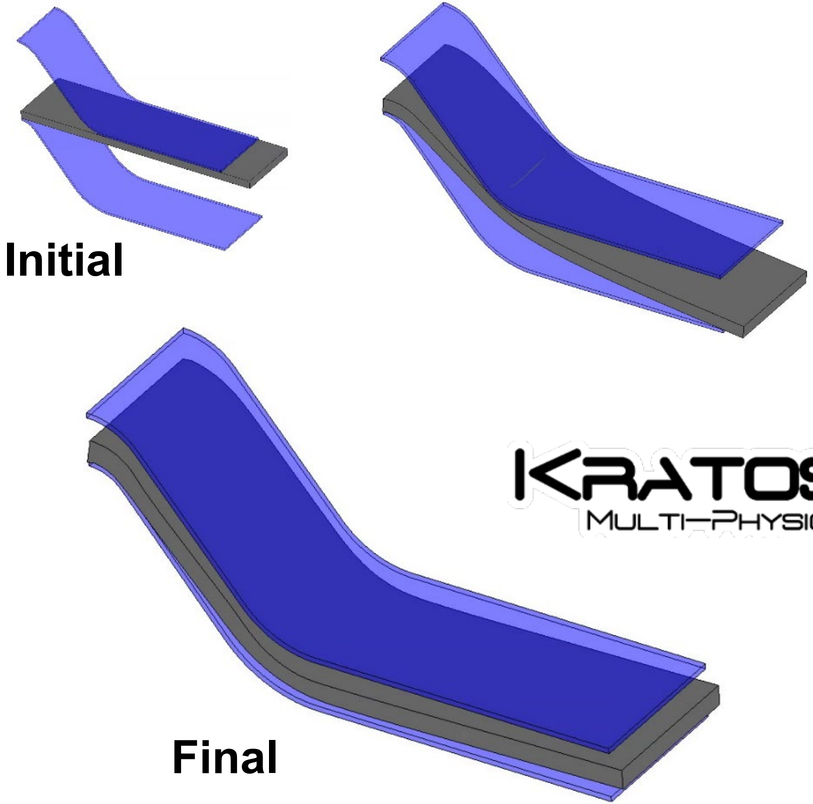


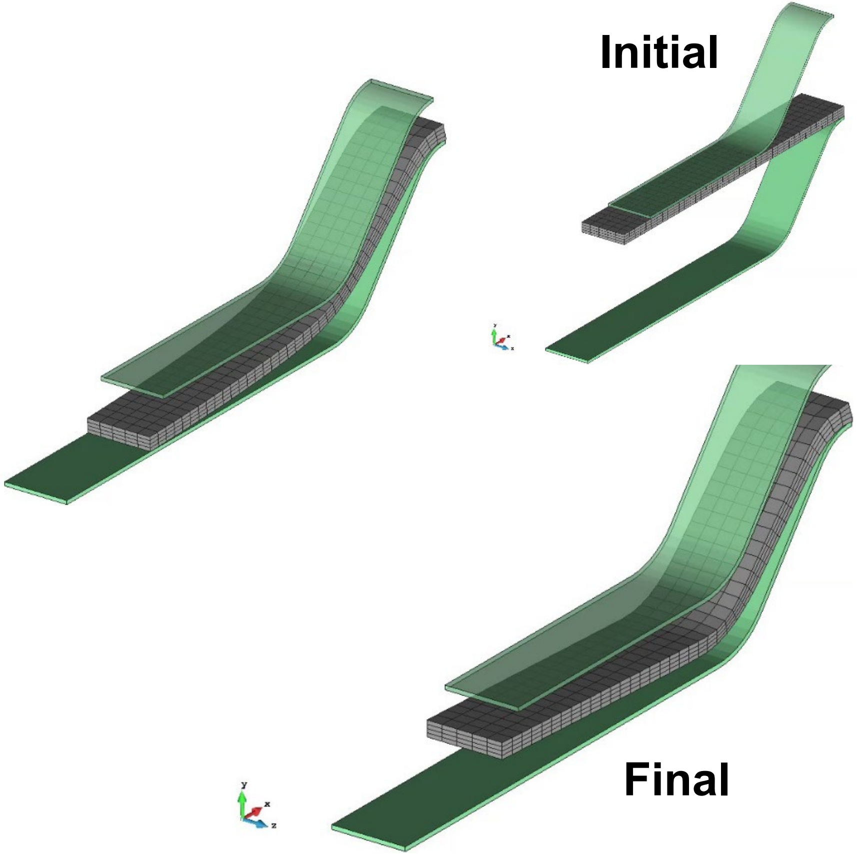
Cyclic



Research lines

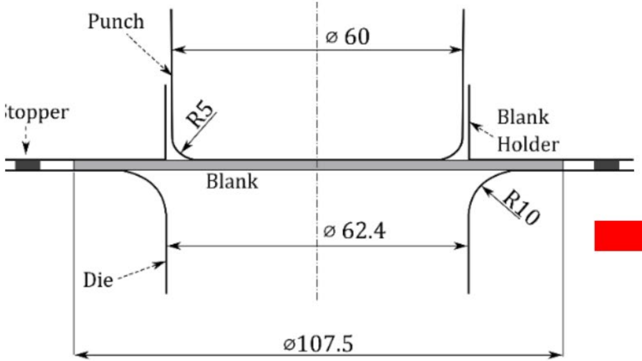
Contact Mechanics – forming simulations

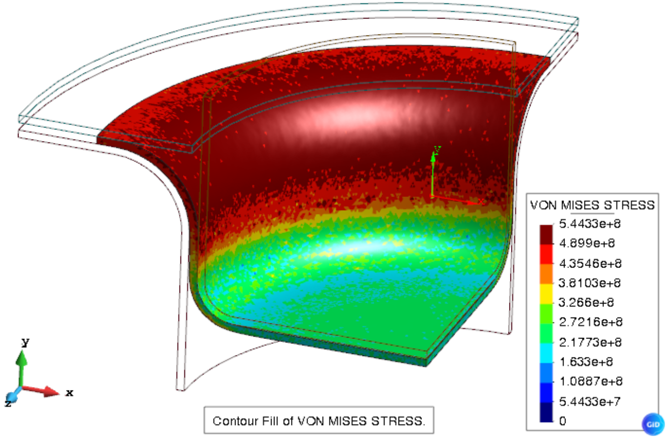


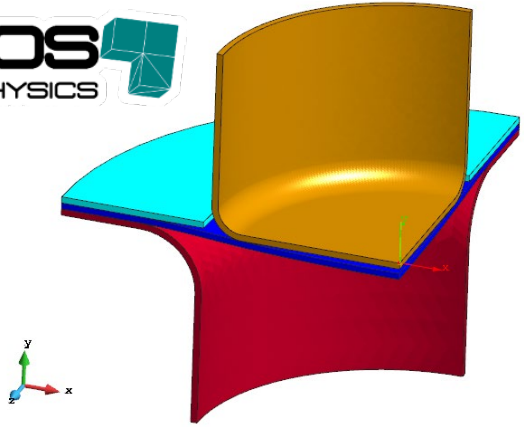


Research lines

Contact Mechanics – forming simulations





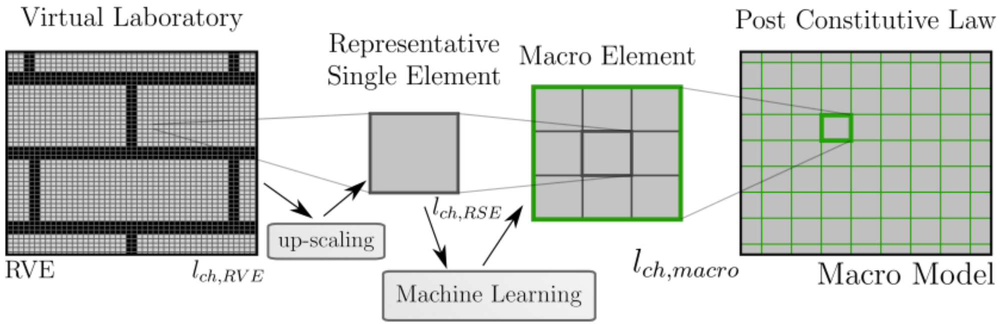


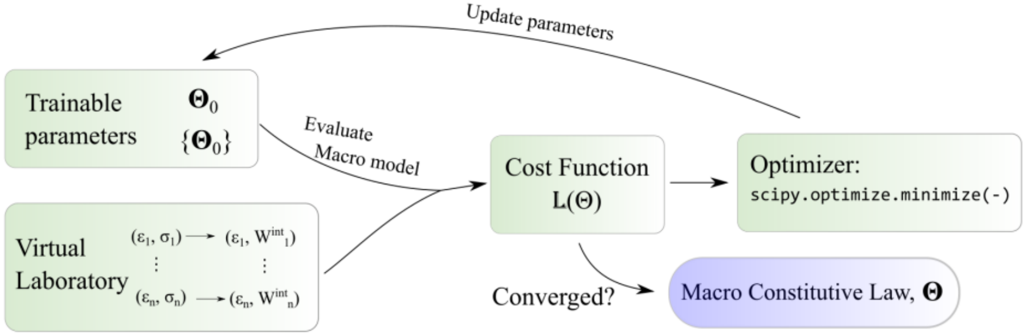
- Finite strain combined kinematic and isotropic plasticity
- Augmented Lagrangian contact mechanics
- Total and Updated Lagrangian elements, mixed u-ϵ_{vol} for incompressibility

Research lines

Multiscale homogenization for masonry

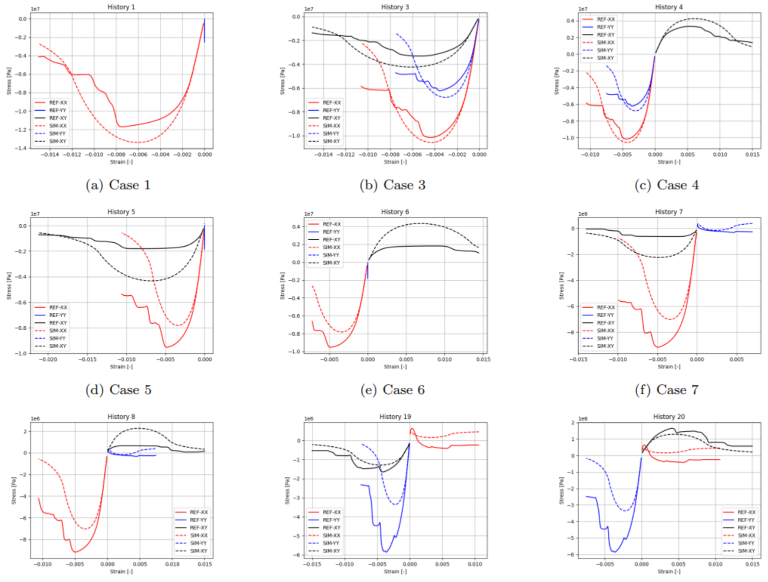
- Optimize macro model parameters to match micro scale masonry





$$\mathcal{L}(\Theta) = \sum_{k=1}^{n} \left| (\tilde{W}_{int,k}(\Theta) - W_{int,k}) \right|$$

Optimized model comparison



(a) Case 1 (b) Case 3 (c) Case 4

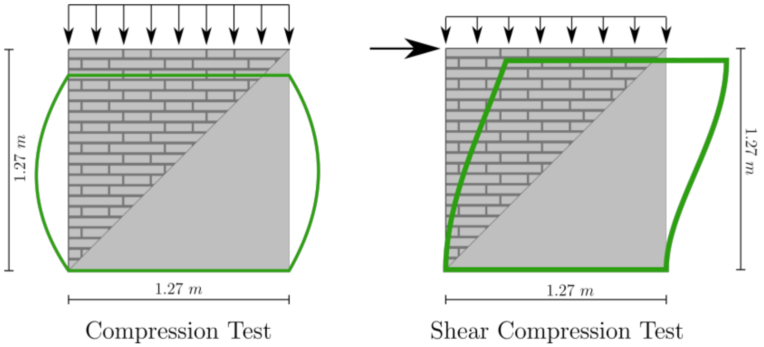
(d) Case 5 (e) Case 6 (f) Case 7

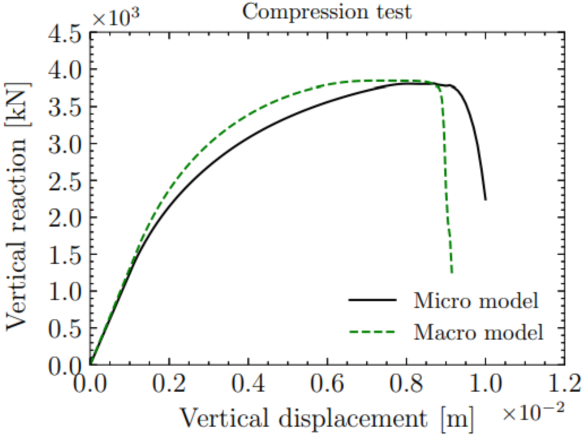
(g) Case 8 (h) Case 19 (i) Case 20

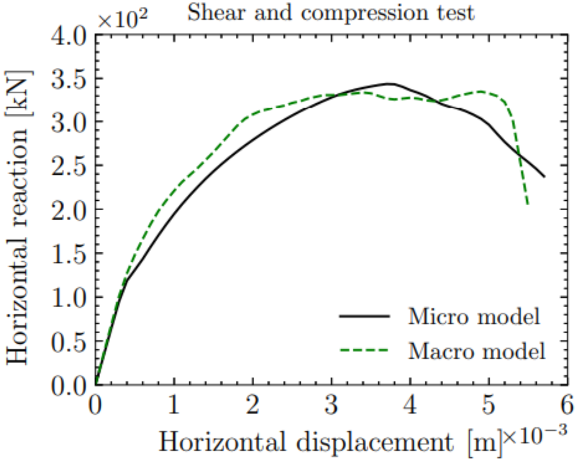
Research lines

Multiscale homogenization for masonry

- Optimize macro model parameters to match micro scale masonry







Optimized macro model results

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Thank you!