DE LA RECHERCHE À L'INDUSTRIE

Mesoscopic modelling of the behaviour of interfaces between reinforcing steel and concrete

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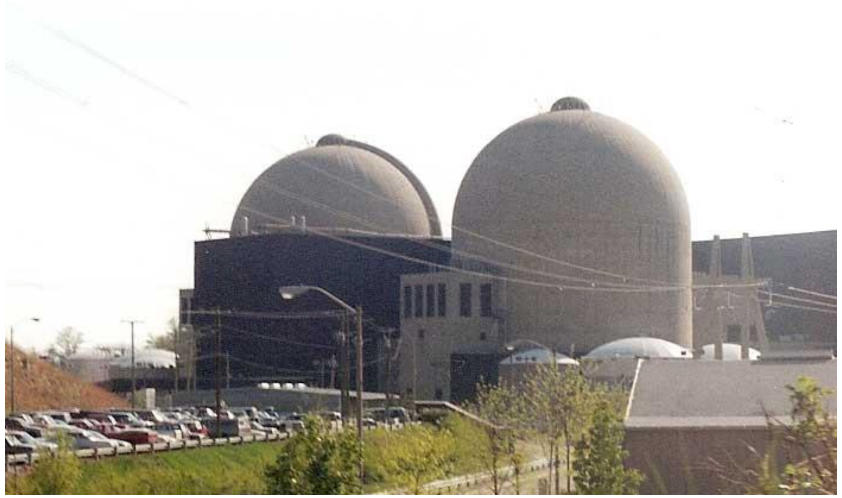
Preface

Reinforced concrete structures functions go beyond their simple mechanical resistance.

Cracking has a direct impact on the transfer properties that govern the potential **leakage** rate in containment buildings for nuclear power plants.

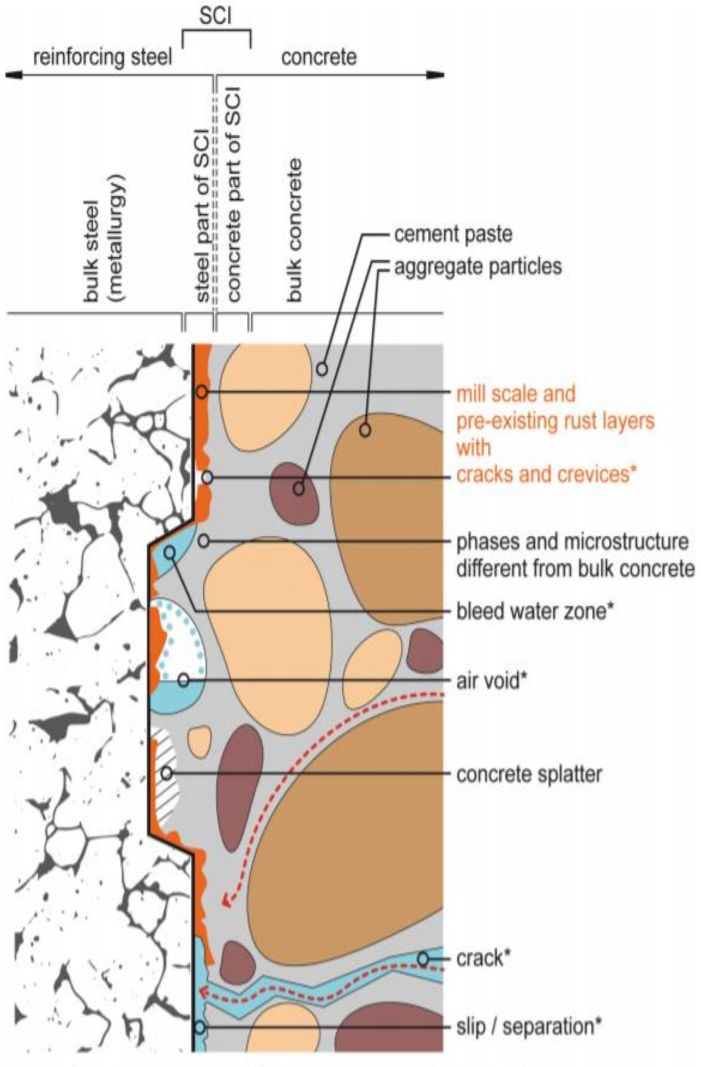
The **bond between steel and concrete** plays an essential role in determining the structural performance of reinforced concrete structures and in the **crack** properties.

This **steel-concrete interface** is very complicated due to the presence of various phenomena at this region.



Donald Cock Nuclear power plant, 1993

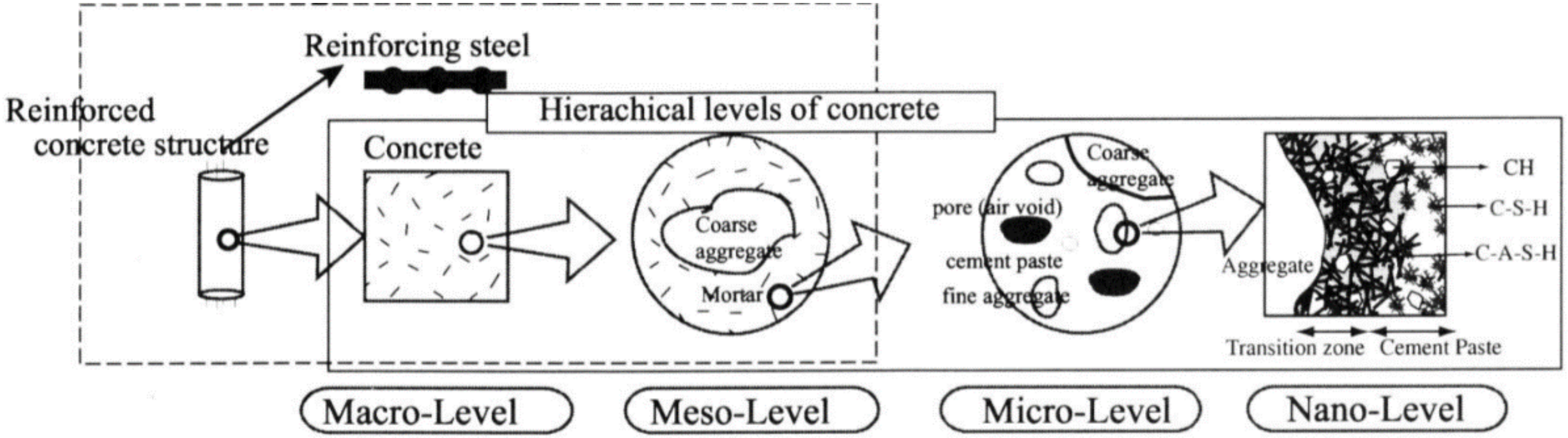
giatecscientific.com/education/cracking-in-concrete-procedures/



* possible moisture states: air filled / partly water filled / fully water filled

Angst et al., 2017

Scales



Asai et al, 2003

Macroscopic studies are already done in **LM2S**

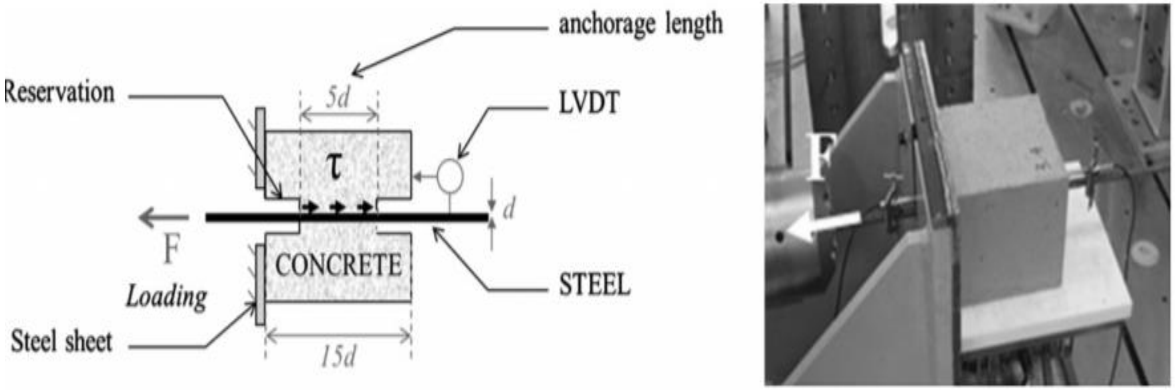
Further work be done on the **Mesoscopic scale**

Possible calibration

Difficult to use **mesoscopic** scale to models huge structures

Can be used to calibrate the **macroscopic** interface laws.

Pull-out test



Torre-Casanova et al., 2013

- The steel-concrete bond can be characterized by pull out tests (RILEM TC, 1983).
- Direct wrenching of a steel bar from a concrete specimen.
- The relation between the tensile force and the relative displacement between steel and concrete is measured.
- The load is increased up to failure of the adhesion (RILEM, 1970).

Objective

Modelling a RC sample at the **mesoscopic** scale:

- Detailed geometry of the steel bar
  - Smooth bars mostly used in previous studies or ribs having a rectangular section
  - Ribs’ shapes **control** cracking at the interface
- Including coarse aggregates:
  - Neglected in macroscopic scale
  - Simplified geometries in most of mesoscopic studies (spheres, circles)
  - **Control** the crack directions in the concrete
- 3D Study:
  - Studies used 2D approach with complex shapes
  - Studies used 3D approach with simple shapes

Pull-out tests:

- Used to study steel-concrete interface
- Aim is to apply it to any RC/PC element

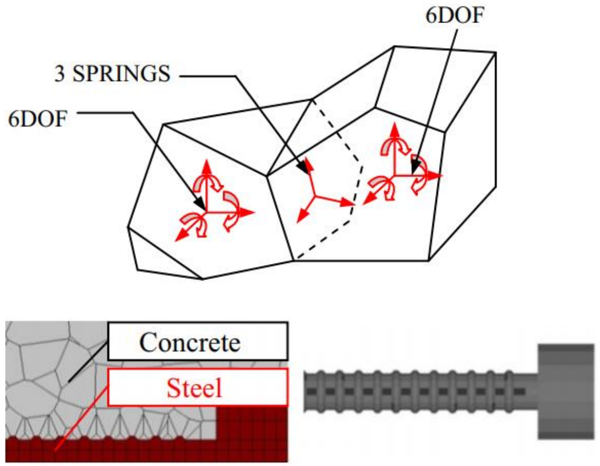
FEM:

- Solid structures
- Complex geometry (irregularities)
- Less time compared to DEM

Previous studies

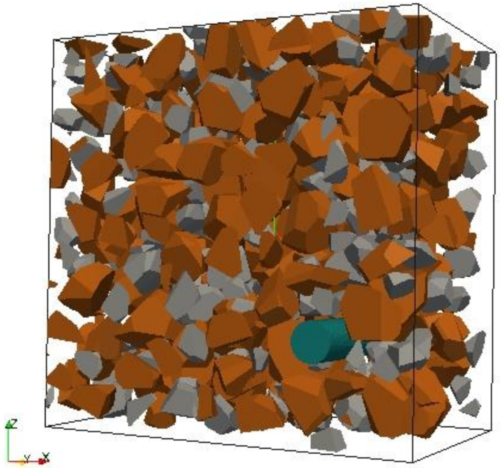
Previous studies in literature

3D DEM RBSM



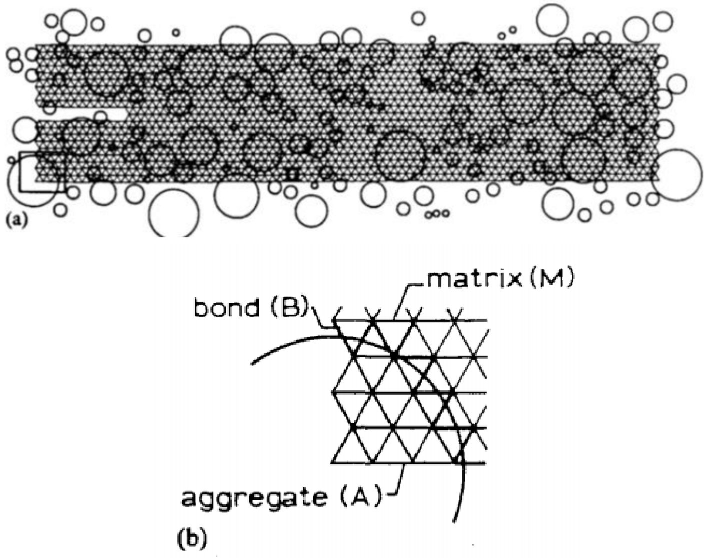
Eddy, L. and Nagai, K. 2016

3D RC sample - Corrosion



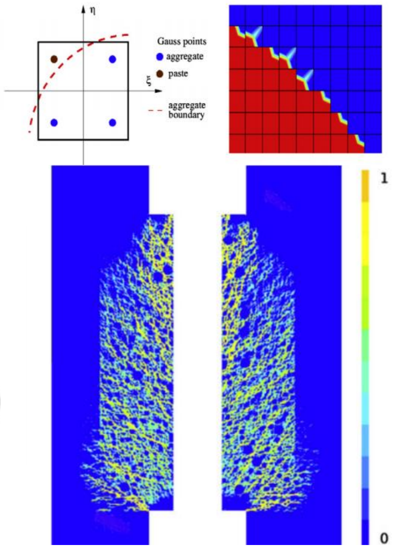
Nguyen et al, 2015

2D DEM Lattice



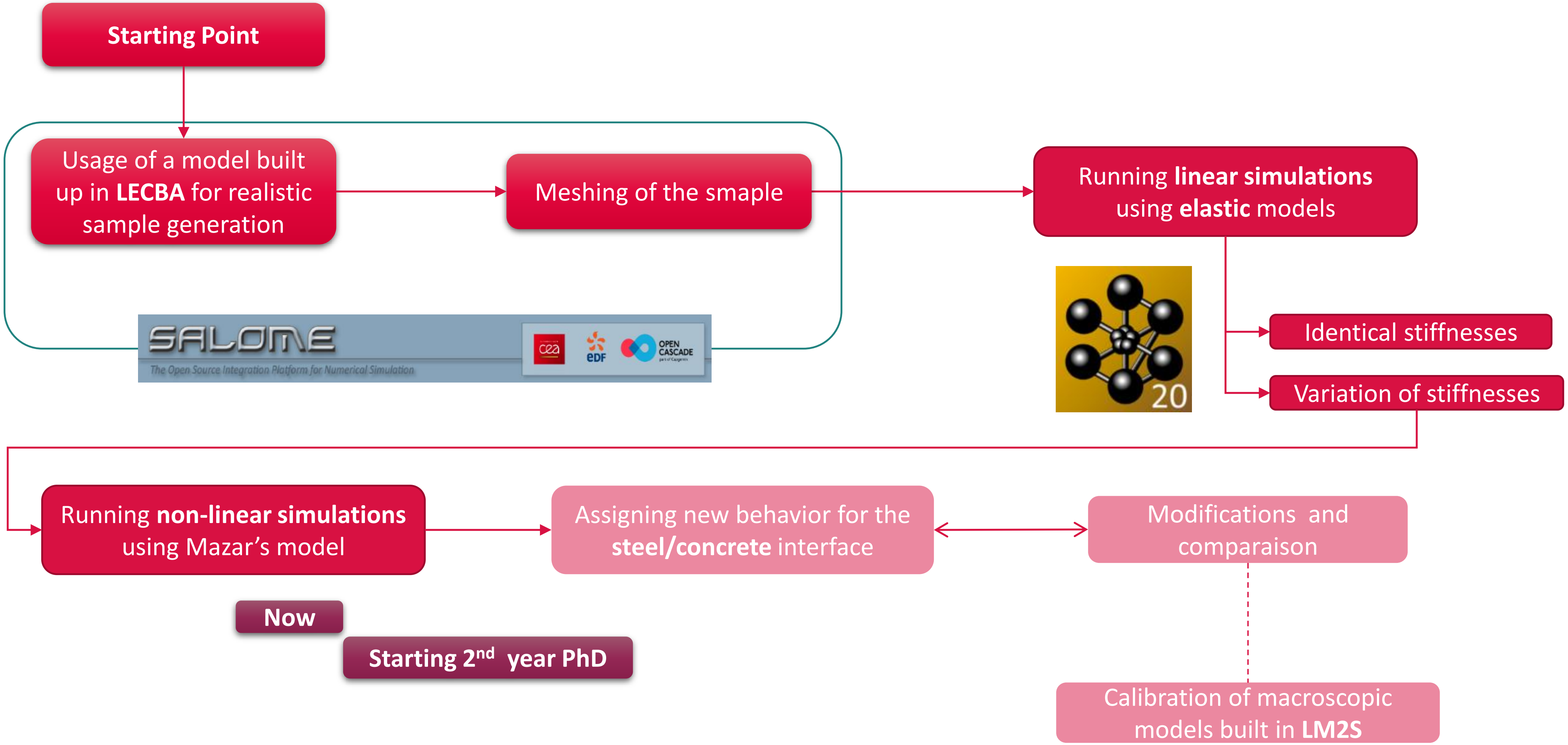
Schlangen, E. and van Mier, J. G. M 1992

2D FEM Lattice



Daoud et al, 2013

Methodology



Starting Point

Usage of a model built up in **LECBA** for realistic sample generation

Meshing of the smaple

Running **linear simulations** using **elastic** models

Identical stiffnesses

Variation of stiffnesses

Running **non-linear simulations** using Mazar's model

Assigning new behavior for the **steel/concrete** interface

Modifications and comparaison

Calibration of macroscopic models built in **LM2S**

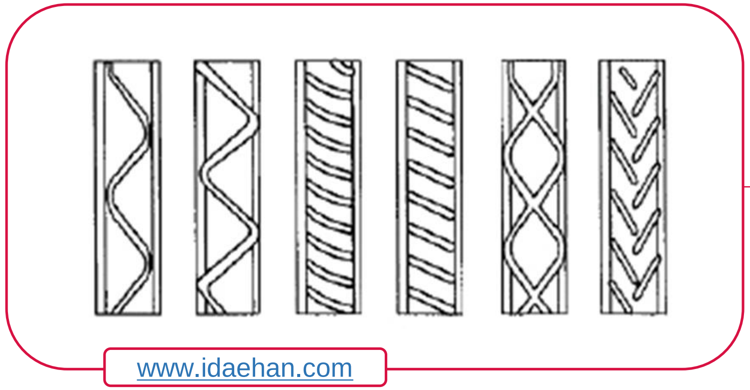
Now

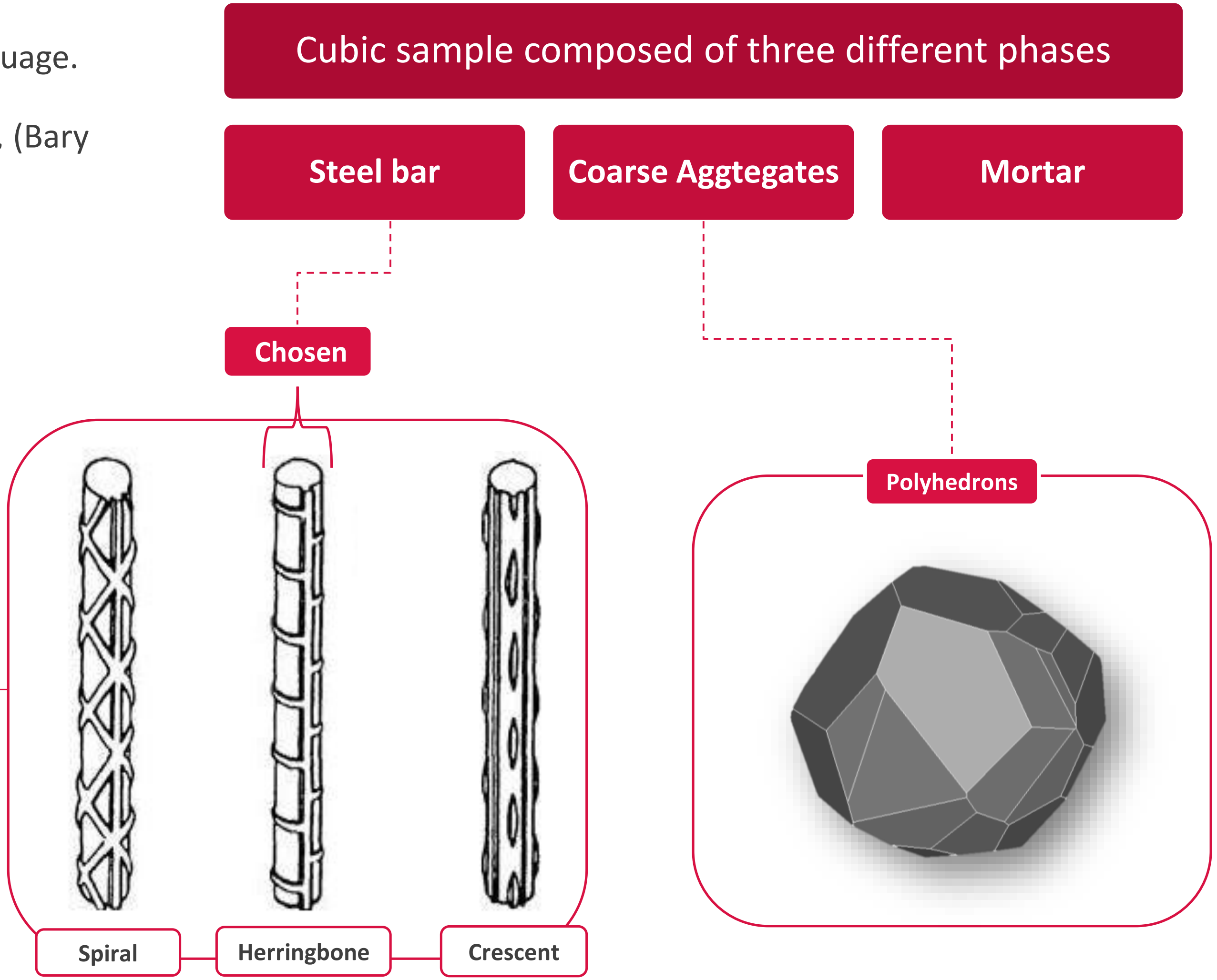
Starting 2nd year PhD

Sample Generation – General Description

- Generated via a script, Combs, developed in python language.
- Used previously in several studies: (Nguyen et al., 2015), (Bary et al., 2017) and (Bernachy-Barbe and Bary, 2019).

SALOME
The Open Source Integration Platform for Numerical Simulation


www.idaehan.com


Cubic sample composed of three different phases

Steel bar

Coarse Aggtegates

Mortar

Chosen

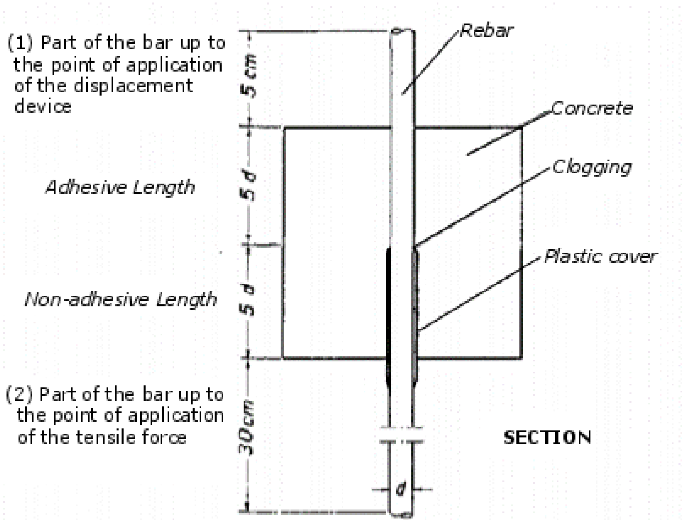
Spiral

Herringbone

Crescent

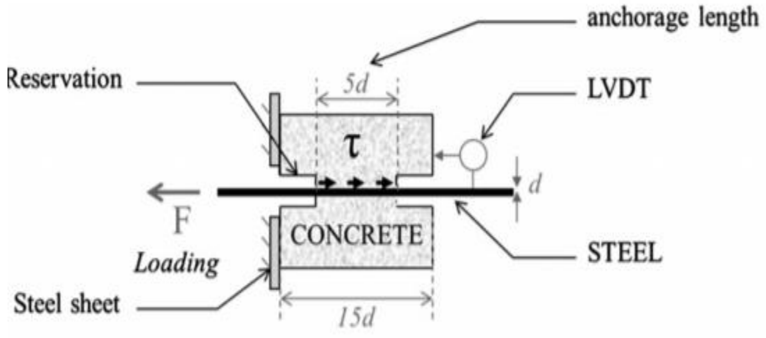
Polyhedrons

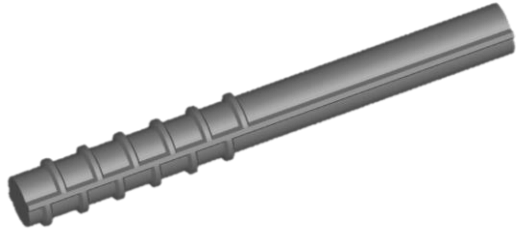
Sample Generation – Steel bar



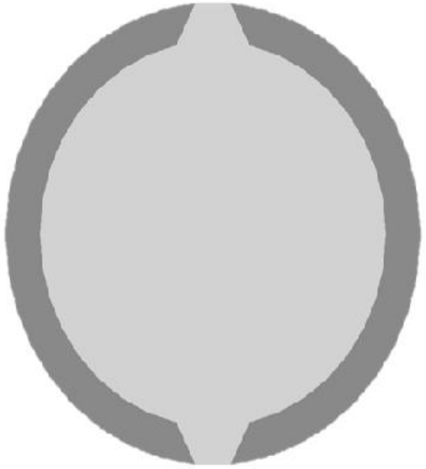
RILEM et al, 1970

Torre-Casanova et al., 2013

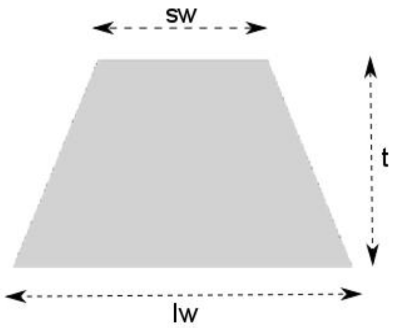




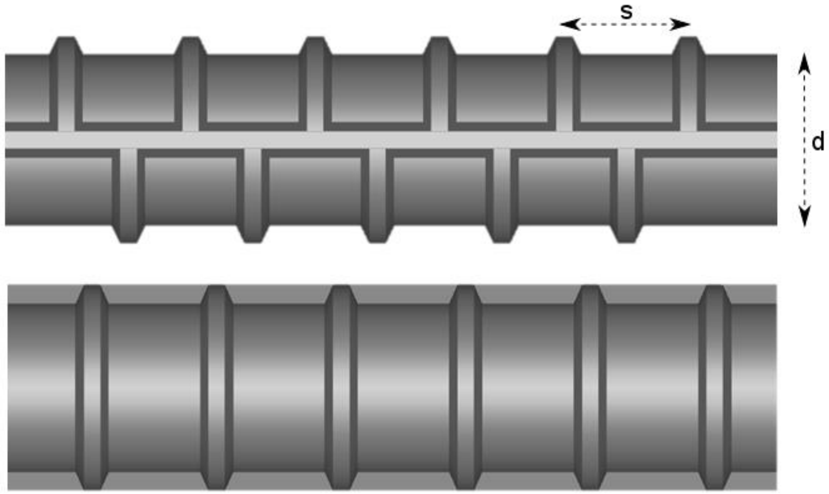
Parameters	Steel bar $\mathcal{A}$	Steel bar $\mathcal{B}$	Steel bar $\mathcal{B}^*$
Total length	150 mm	160 mm	80 mm
Adhesive length	50 mm	80 mm	40 mm
d	16 mm		8 mm
t	1.6 mm		0.8 mm
sw	1.6 mm		0.8 mm
lw	3.2 mm		1.6 mm
s	12 mm		6 mm



(a) Steel bar frontal view



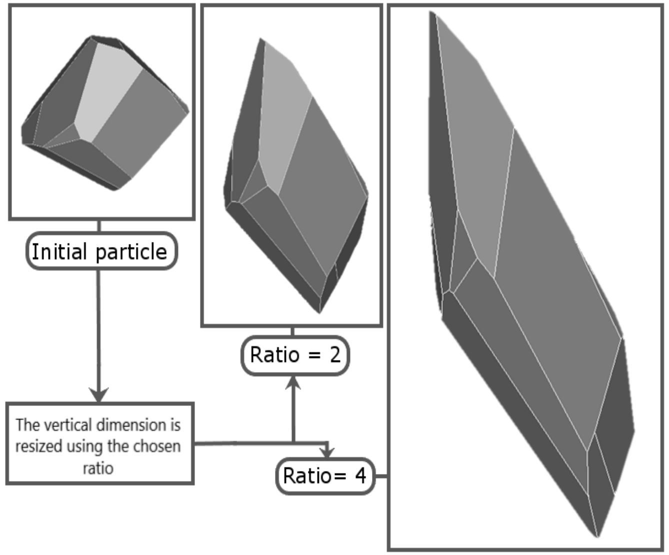
(b) Rib section

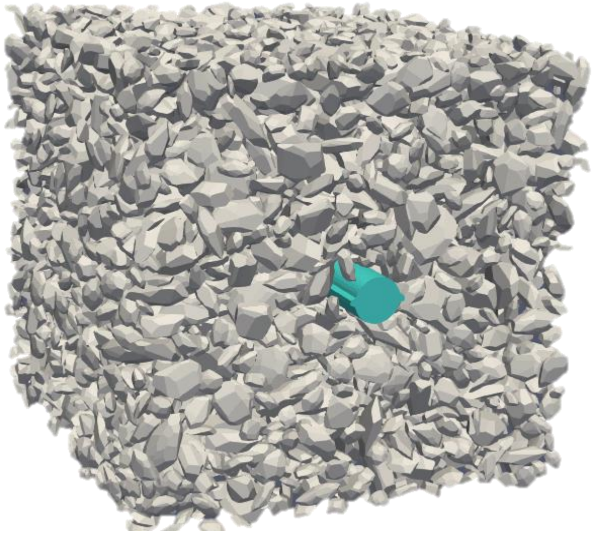


(c) Steel bar side views

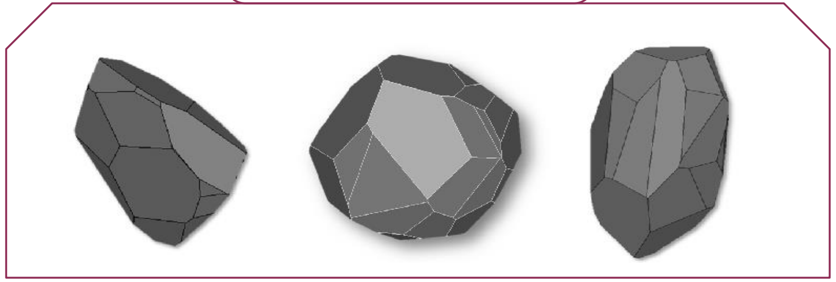
Sample Generation – Aggregates & Mortar

Aggregates



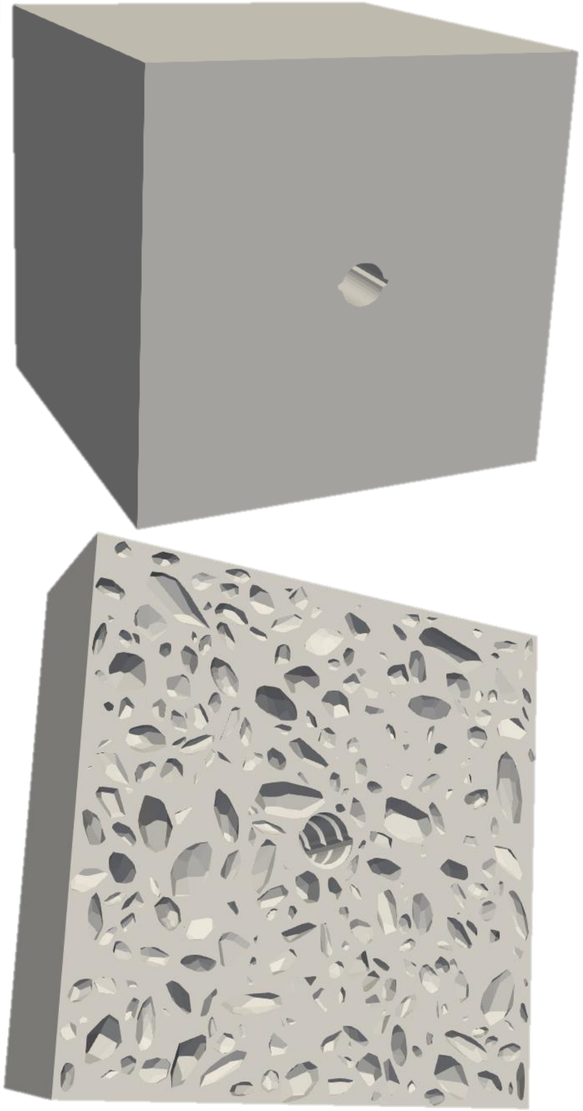


Convex Polyhedrons
Voronoi particles



Parameter	Sample $\mathcal{A}$ (Steel bar $\mathcal{A}$)	Sample $\mathcal{B}$ (Steel bar $\mathcal{B}$)	Sample $\mathcal{B}^*$ (Steel bar $\mathcal{B}^*$)
Steel bar embedded length	150 mm	160 mm	80 mm
Cubic sample side length	150 mm	160 mm	80 mm
Percentage of aggregates by volume	30%		
Aggregates minimum size	6.5 mm		
Aggregates maximum dimension	32 mm		

Mortar



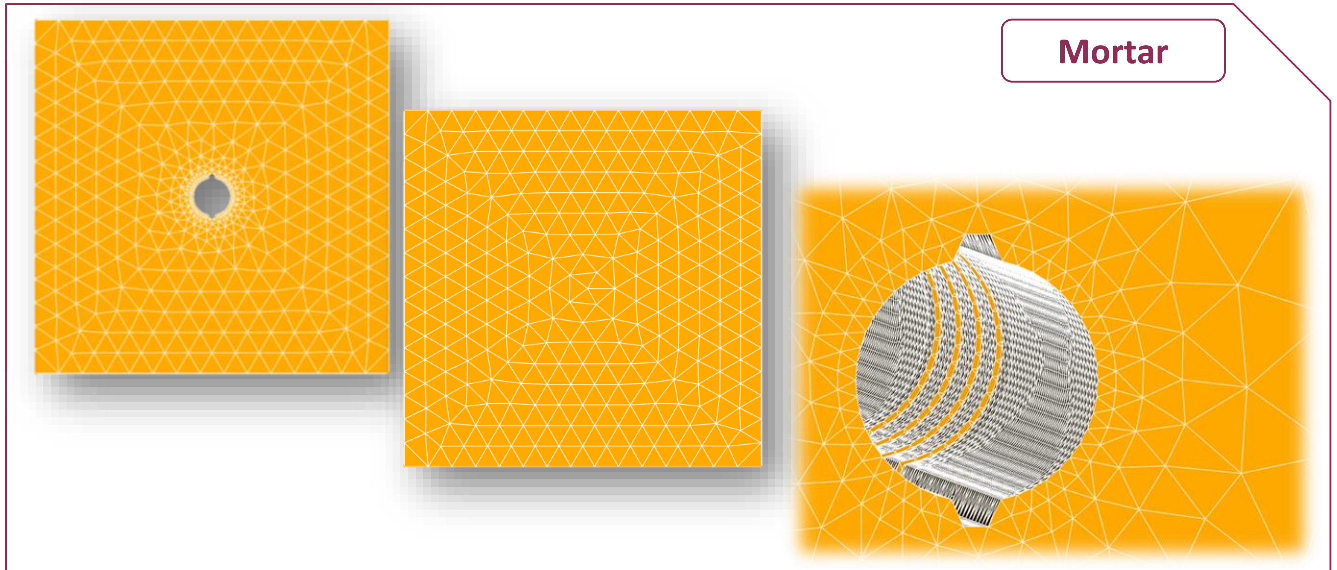
Sample Generation – Meshing

Unstructured mesh → **Linear tetrahedral**

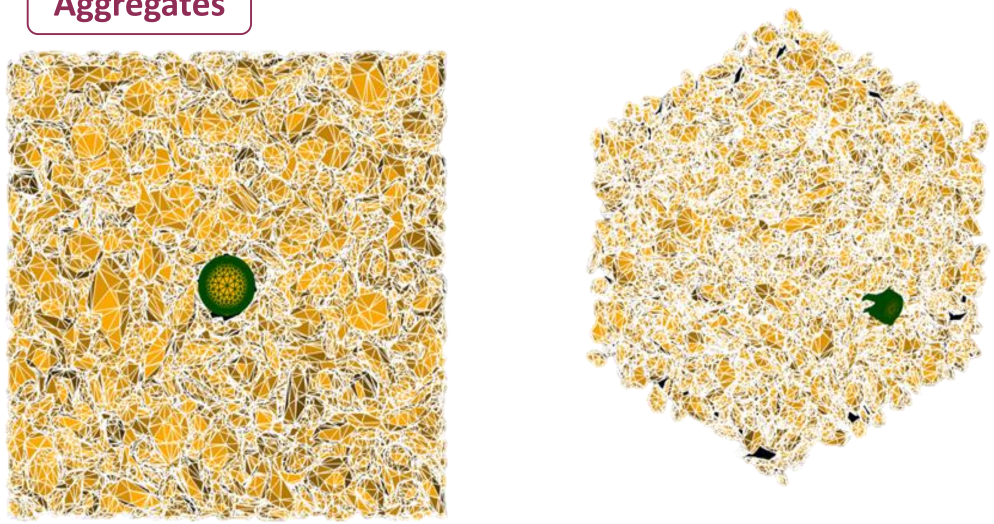
Phase	Number of Elements of		
	Sample $\mathcal{A}$	Sample $\mathcal{B}$	Sample $\mathcal{B}^*$
Steel bar	115 K	75 K	308 K
Coarse aggregates	740 K	900 K	462 K
Mortar	2 140 K	2 560 K	1 328 K
Total	**3 M**	**3.353 M**	**2.1 M**

Steel bar

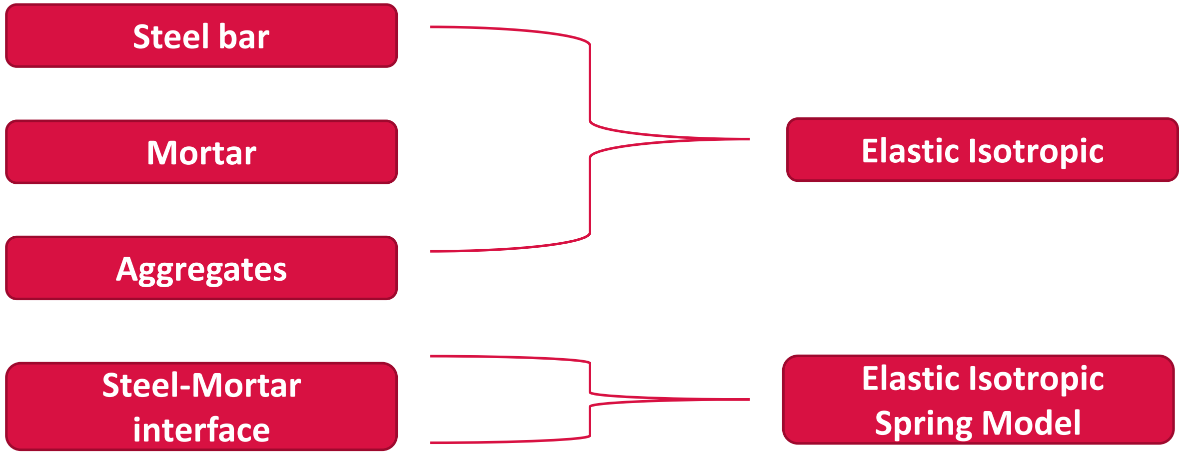
Mortar



Aggregates



Linear simulations - Models and Parameters



Steel bar

Mortar

Aggregates

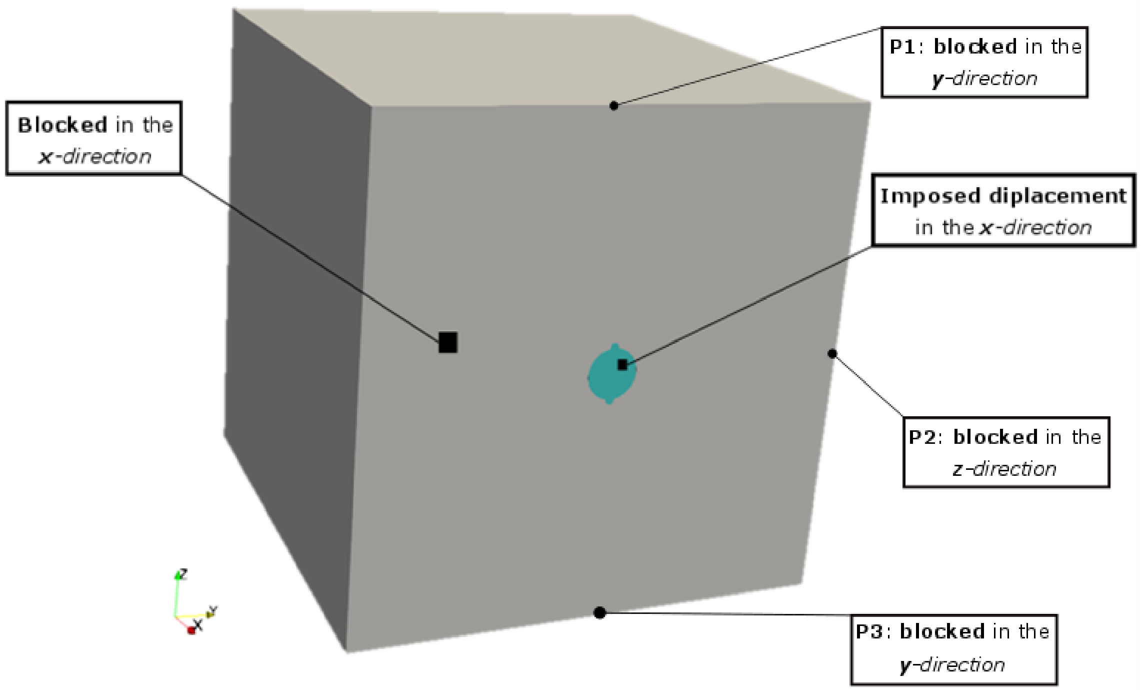
Elastic Isotropic

Steel-Mortar interface

Elastic Isotropic Spring Model

Material	Young’s modulus (GPa)	Poisson’s ratio	Density (Kg/m³)
Steel bar	210	0.3	7850
Aggregates	65	0.2	2000
Mortar	20	0.2	2500

Boundary conditions



Linear simulations – Elastic Spring model

The linear-spring interface model use described in (Duan et al., 2007):

$$K_n = \frac{2G_i(1-\nu_i)}{t(1-2\nu_i)}$$

$$K_s = K_t = \frac{G_i}{t}$$

Where for the interfacial element:

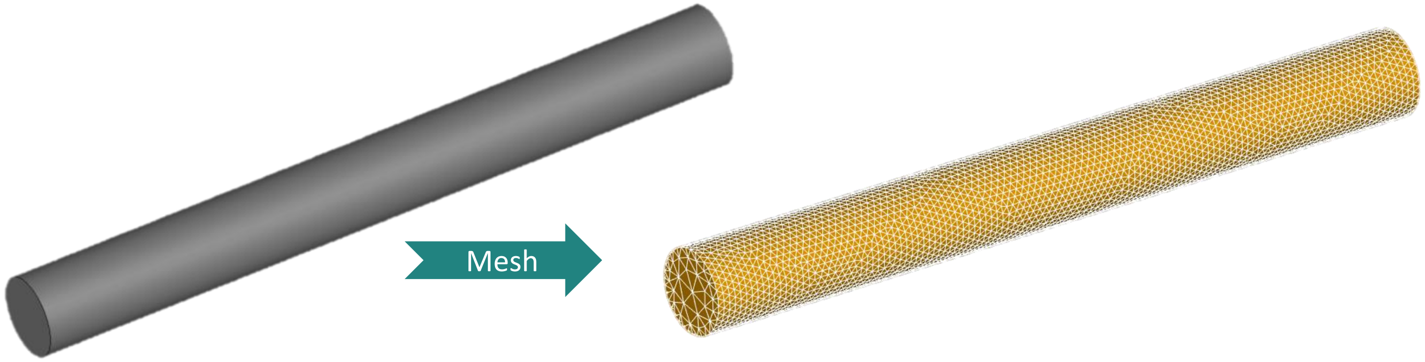
t is thickness
ν_i is Poisson's ratio
E_i is Young's modulus
G_i is shear modulus

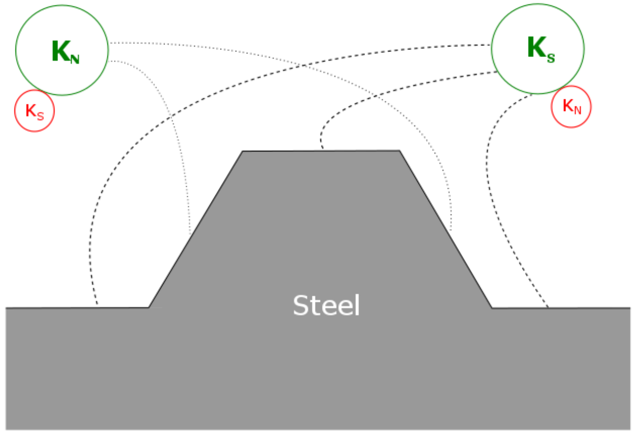
Representative especially for traction

Simple to check functionality

To be improved in the near future

Sample $\mathcal{AS}$ have the same properties of sample $\mathcal{A}$, but it has **smooth** steel bar instead of the **ribbed** steel bar



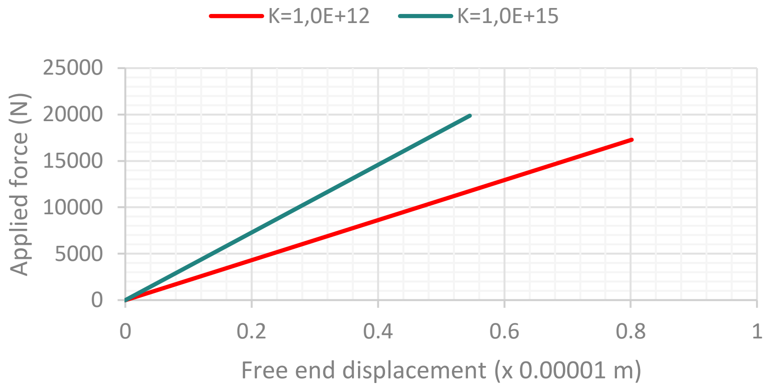


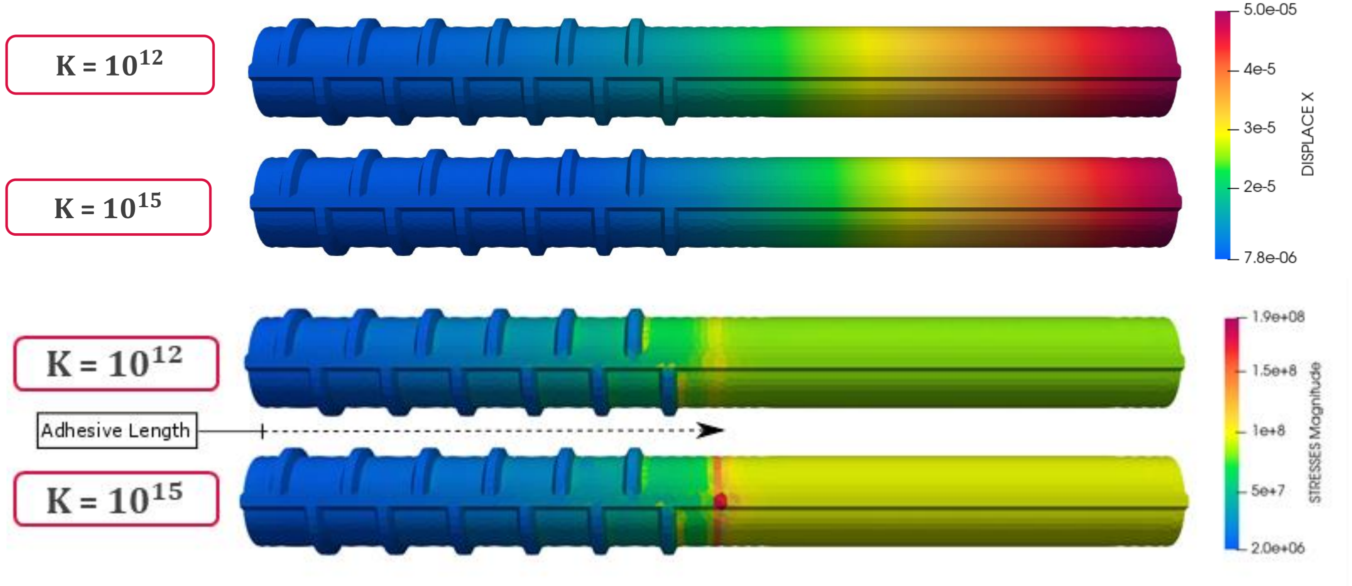
- ❖ The **normal stiffness** resembles the resistance in the normal direction.
- ❖ The **shear stiffness** resembles the resistance in the directions parallel to the surfaces.

Linear simulations – Identical stiffnesses

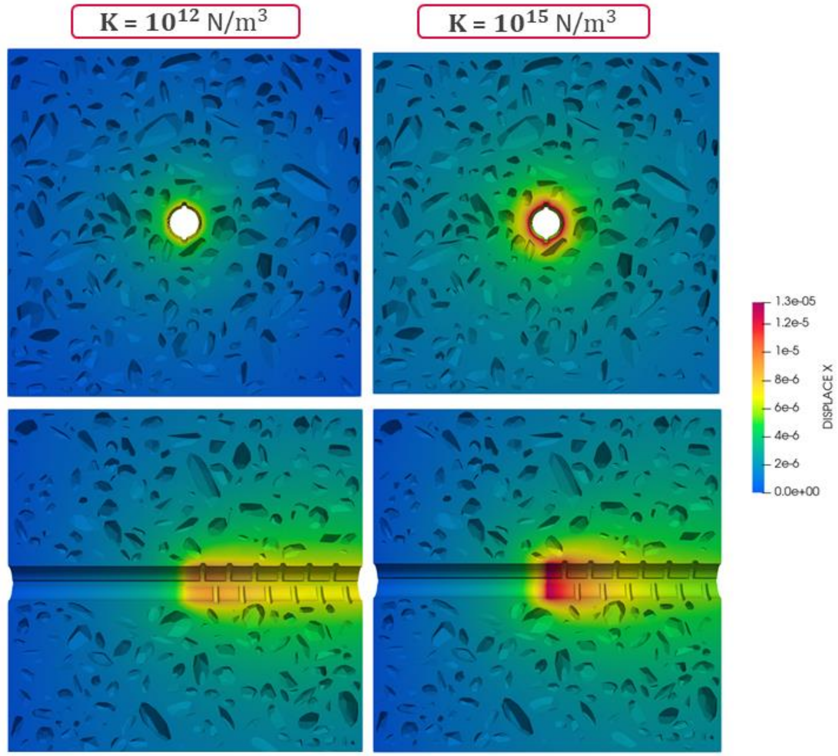
- Identical values are taken for both stiffnesses.
- Two simulations were performed on Sample $\mathcal{B}$.

Steel/mortar interface	Normal stiffness K_n (N/m^3)	Shear stiffness K_s (N/m^3)
First simulation	10^{12}	10^{12}
Second simulation	10^{15}	10^{15}



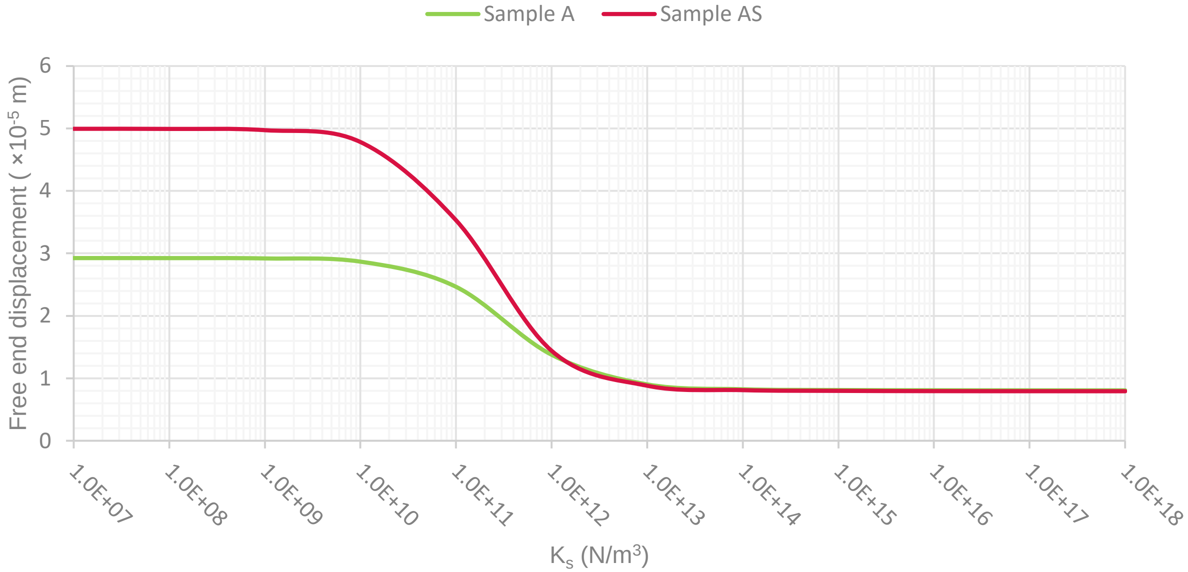


Stiffnesses are in N/m^3
Imposed displacement is 0.05 mm (5 x 10^{-5} m).

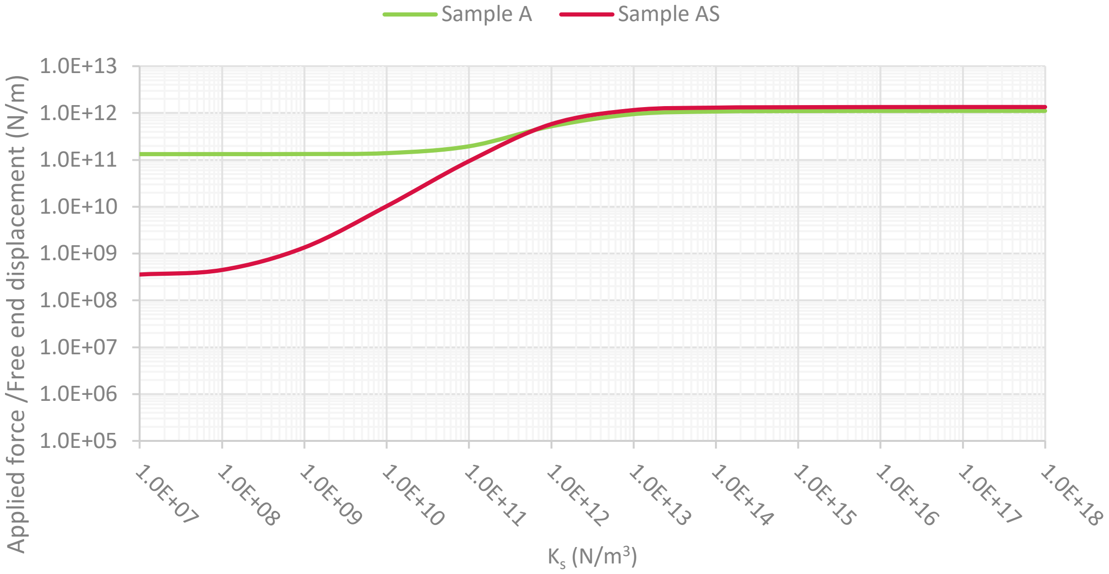


Linear simulations – Variation of the K_s

- Simulations on **sample** $\mathcal{A}$ **&** $\mathcal{AS}$
- $\mathbf{K_n} = \mathbf{10^{12}}\ \mathrm{N/m^3}$ and $\mathbf{K_s}$ varied.



Imposed displacement is 0.05 mm (5 x 10^{-5} m).

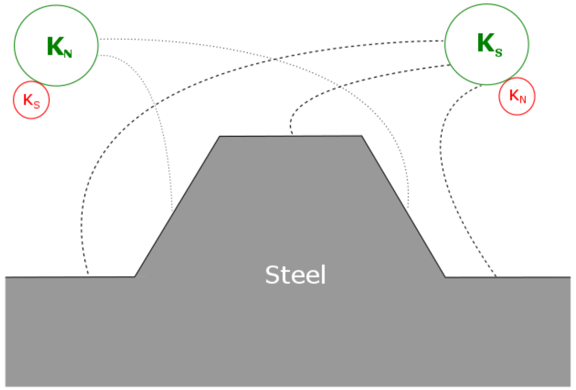


Imposed displacement is 0.05 mm (5 x 10^{-5} m).

Ribbed Bar

Low $\mathbf{K_s}$: Ribs **prevent** the bar from totally slipping

High $\mathbf{K_s}$: Ribs play **no role** in the slipping phenomena



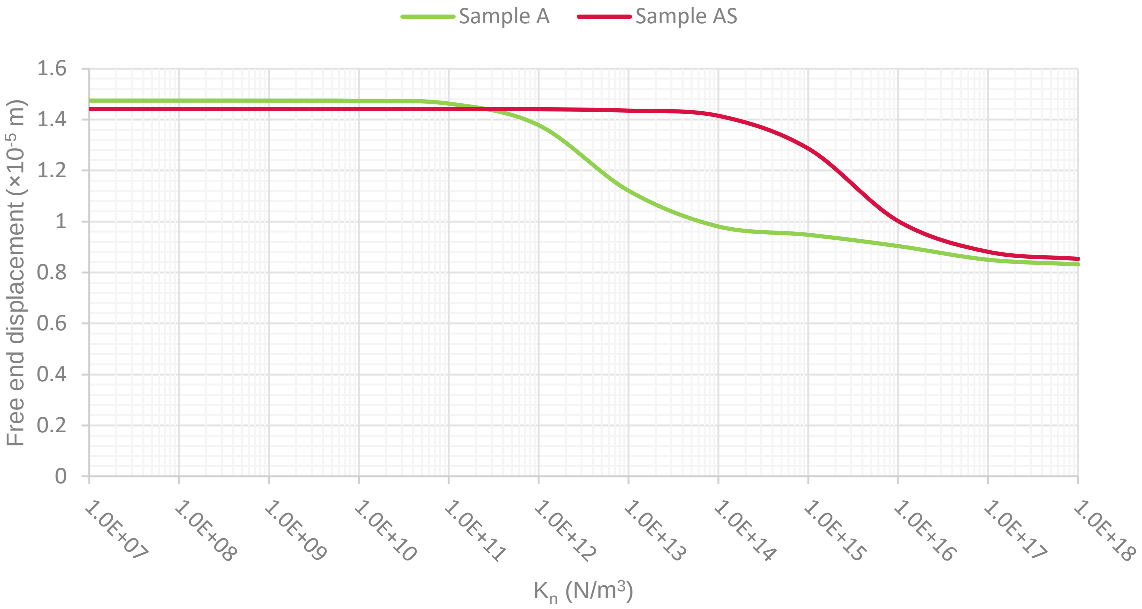
Smooth Bar

Low $\mathbf{K_s}$: **No resistance** (fully pulled)

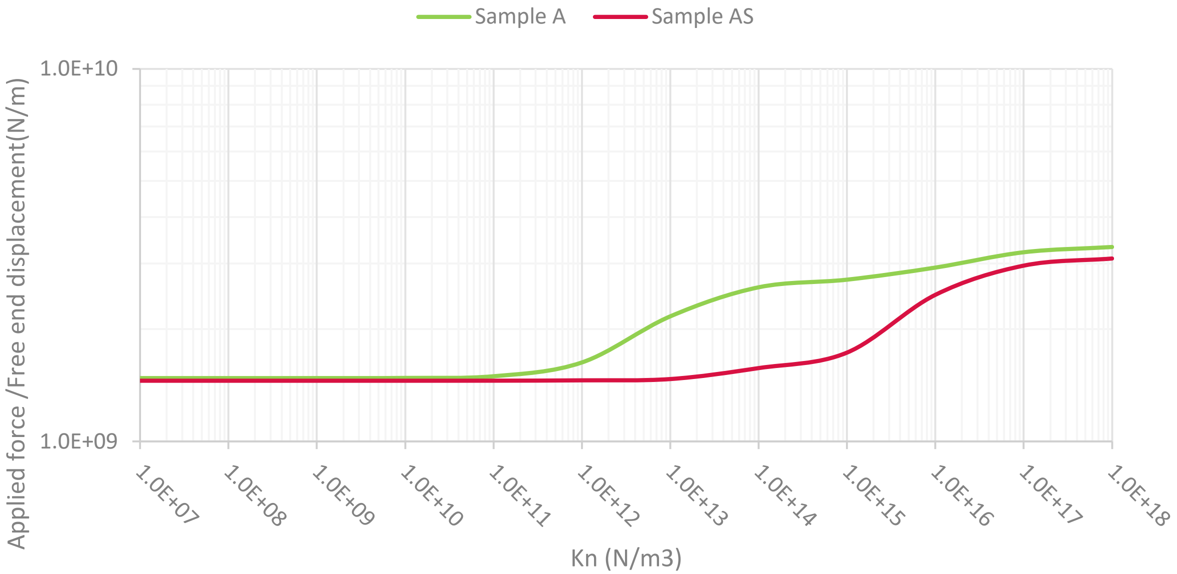
High $\mathbf{K_s}$: **Slightly** lower force to pull the bar

Linear simulations – Variation of the K_n

- Simulations on **samples $\mathcal{A}$ & $\mathcal{AS}$**
- $\mathbf{K_s = 10^{12}}$ $\mathrm{N/m^3}$ and $\mathbf{K_n}$ varied.



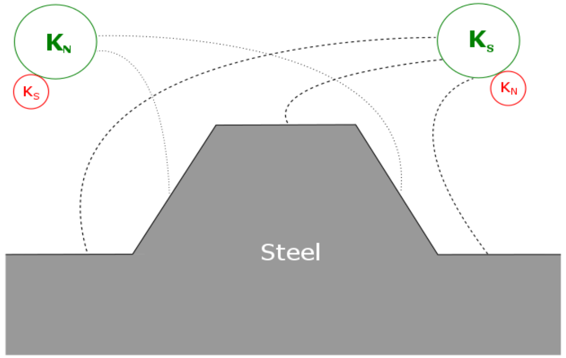
Imposed displacement is 0.05 mm (5 x 10^{-5} m).



Imposed displacement is 0.05 mm (5 x 10^{-5} m).

Similar behavior of both bars for low & high K_n

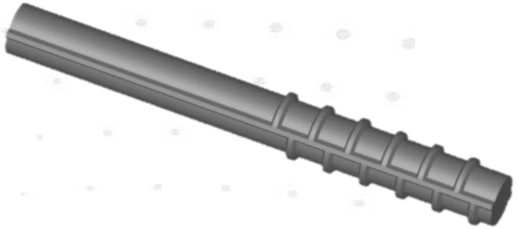
No wide difference when K_s is fixed



K_n has *a certain effect* in the smooth bar (Possibly bar **retraction** leading to **compressive stresses**)

Non-linear simulations (Early results)

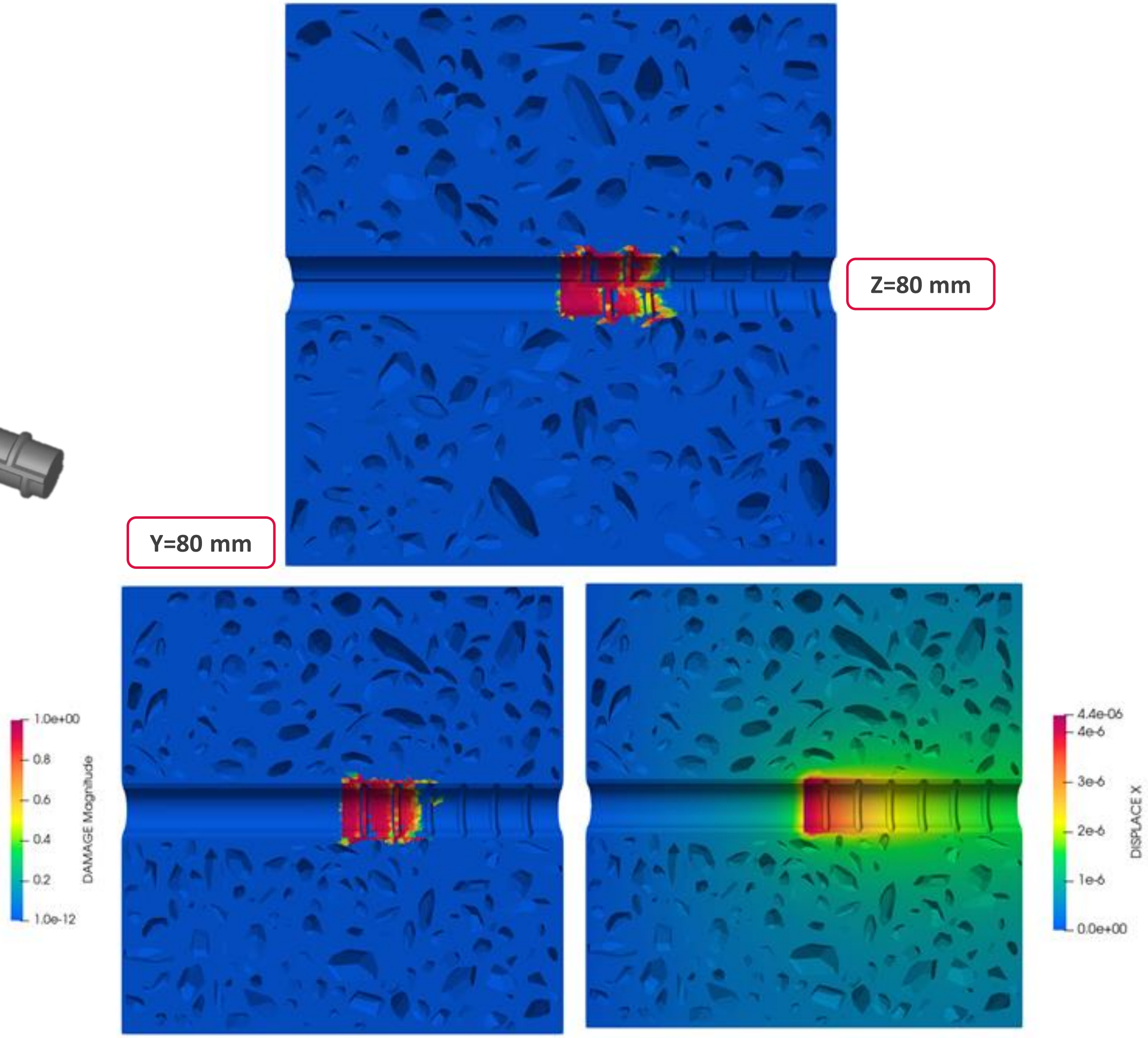
- **Mazar's classical model** (Mazars, 1984) is assigned for **mortar.**
- *Non-regularized* formulation is used in the **first try**
- $K_s = K_n = 10^{15}$ **N/m^3**
- Simulations performed on **Sample $\mathcal{B}$**



Parameters for mortar
$\varepsilon_{D_0} = 10^{-4}$
$A_t = 0.8$
$B_t = 1.7 \cdot 10^4$
$A_c = 1.4$
$B_c = 1.9 \cdot 10^3$
$\beta = 1.06$

By default in Cast3M

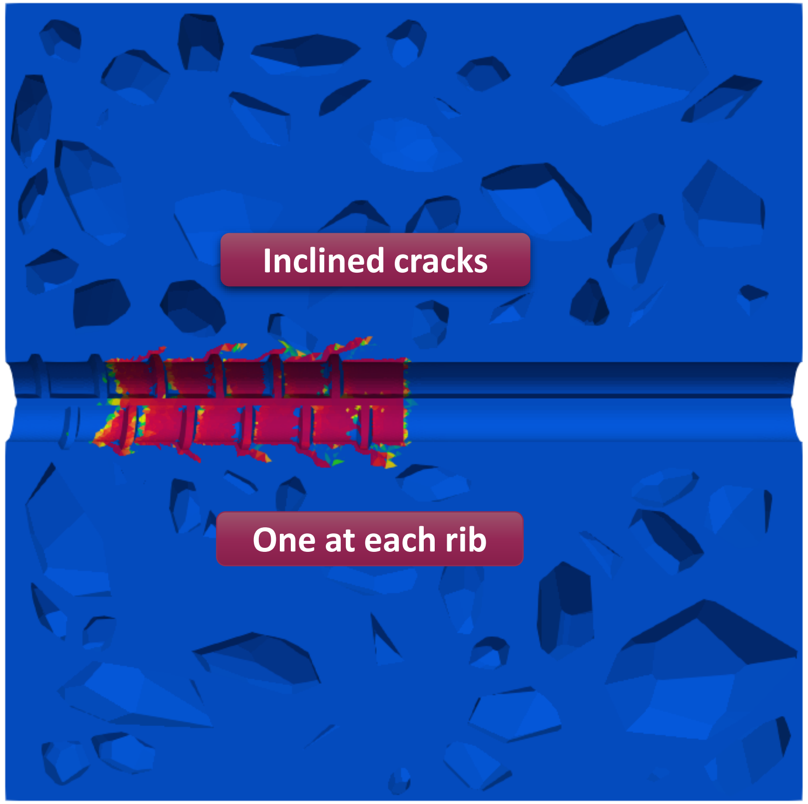
To be calibrated



Imposed displacement is 0.0125 mm (1.25×10^{-5} m).

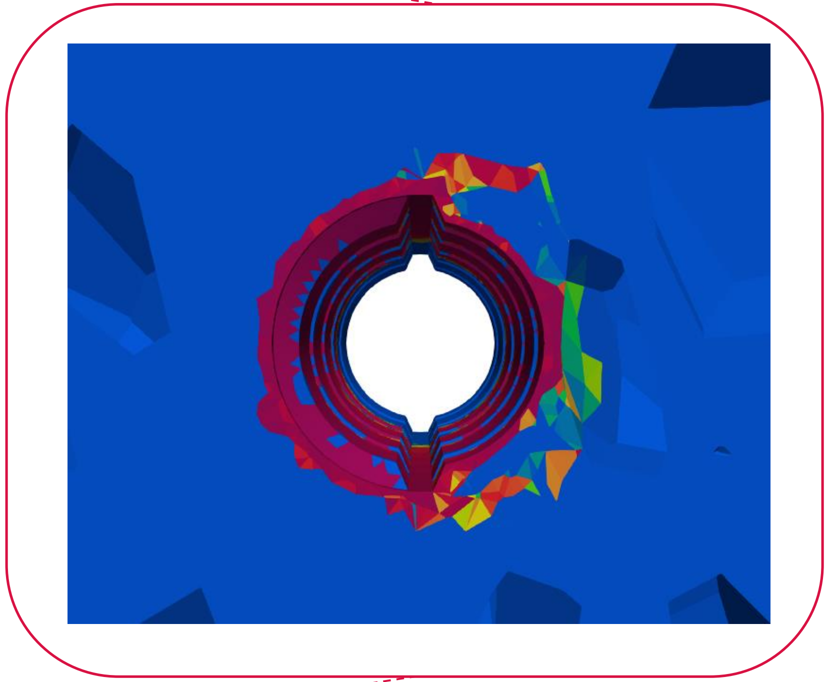
Non-linear simulations (Early results)

- A regularization is used with an exponential evolution by taking $A_t = -1$ (CAST3M)
- $\mathbf{K_s} = \mathbf{K_n} = \mathbf{10^{15}}\ \mathrm{N/m^3}$
- Simulations performed on **Sample $\mathcal{B}$***

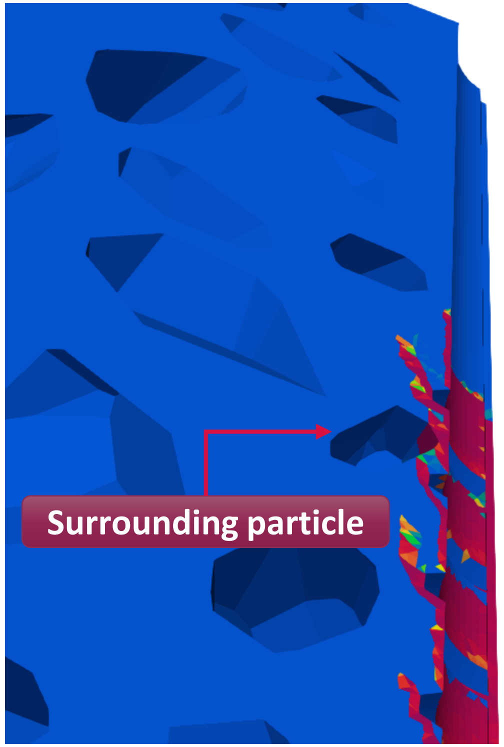

Inclined cracks

One at each rib

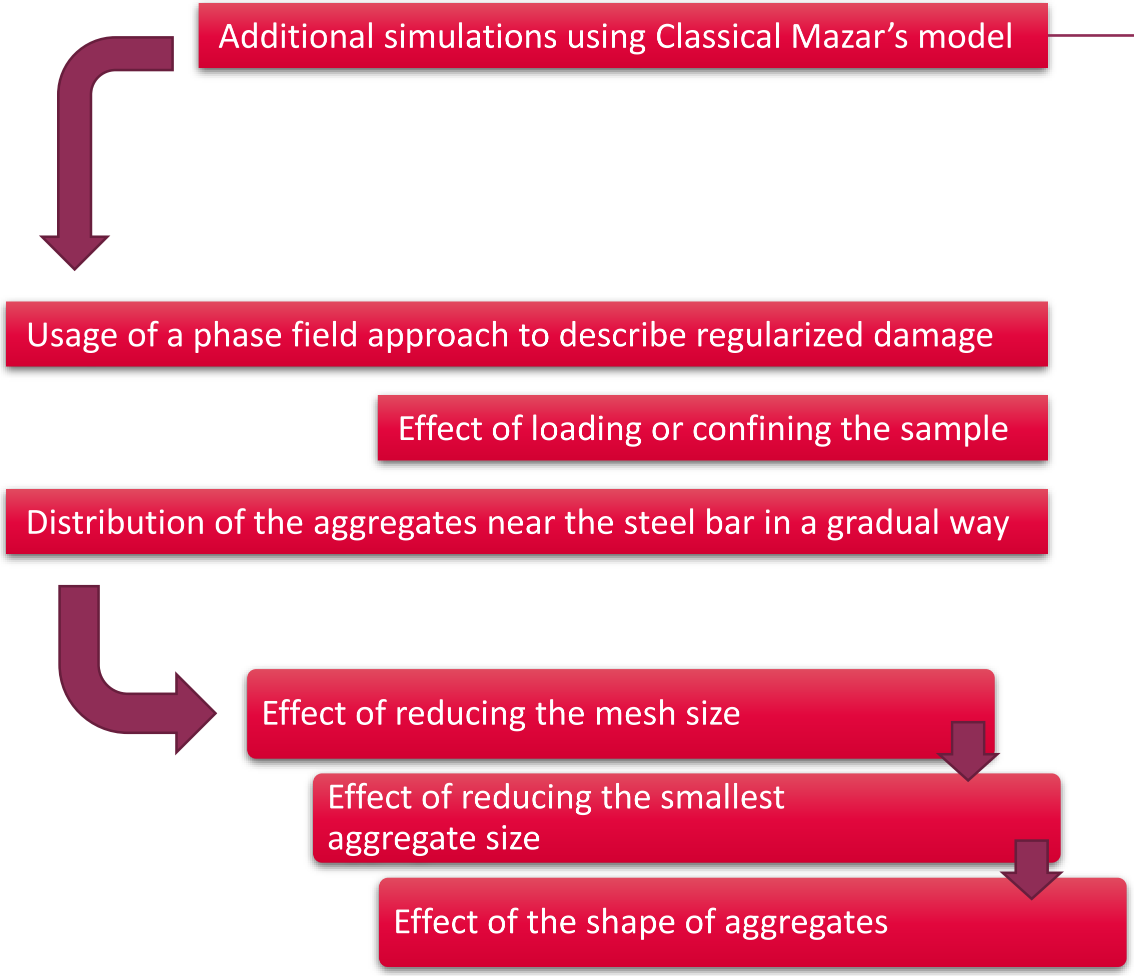
Z=40 mm


X=30 mm

Imposed displacement is 0.01 mm (10^{-5} m).


Surrounding particle

Perspectives



Additional simulations using Classical Mazar’s model

Usage of a phase field approach to describe regularized damage

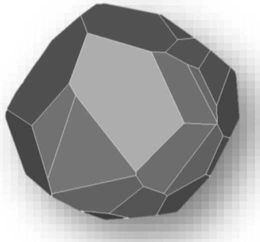
Effect of loading or confining the sample

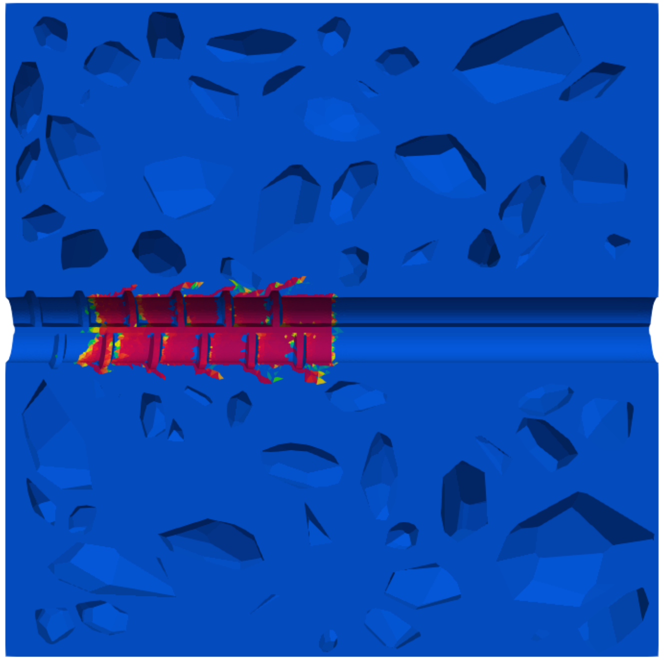
Distribution of the aggregates near the steel bar in a gradual way

Effect of reducing the mesh size

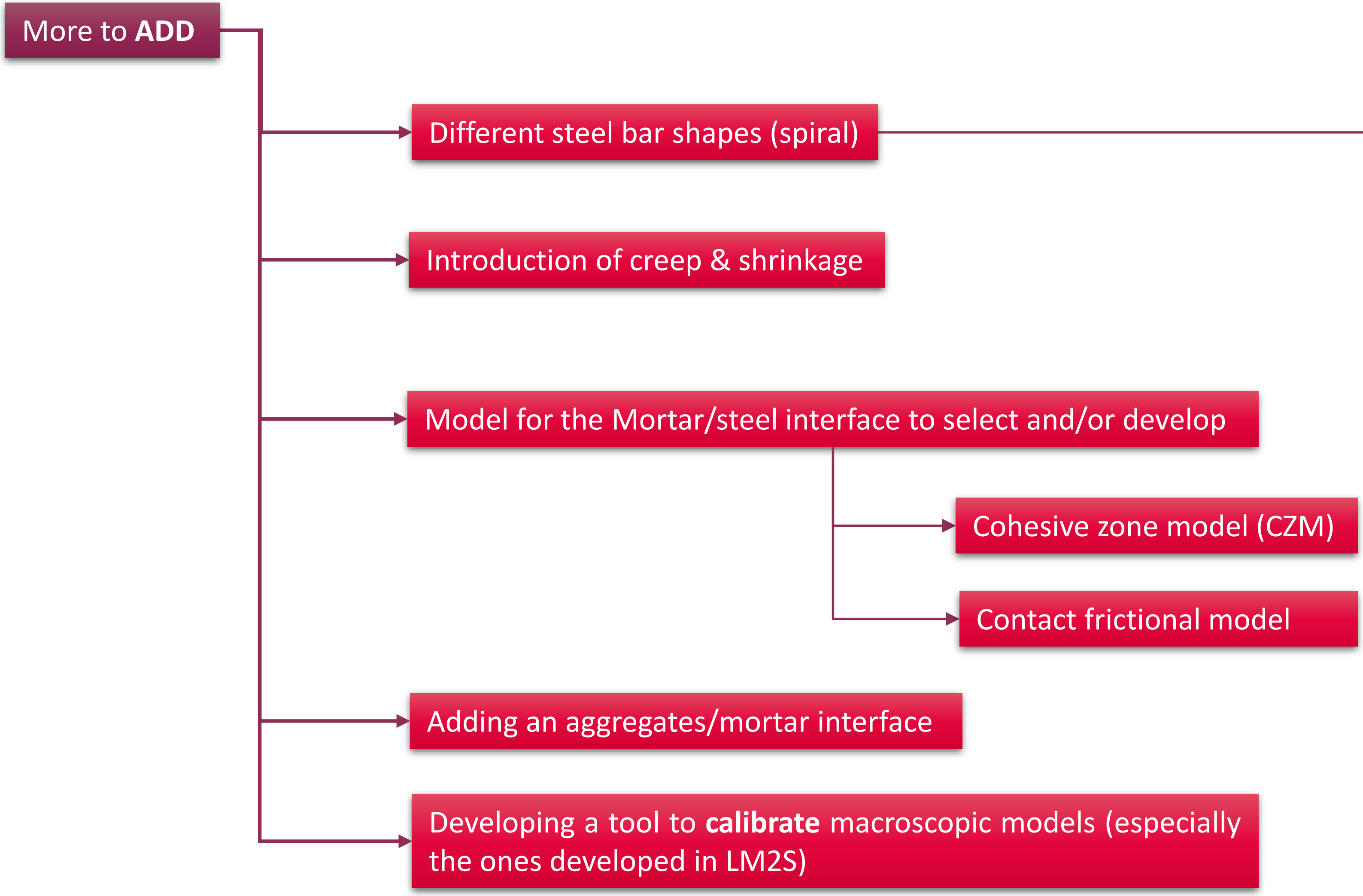
Effect of reducing the smallest aggregate size

Effect of the shape of aggregates



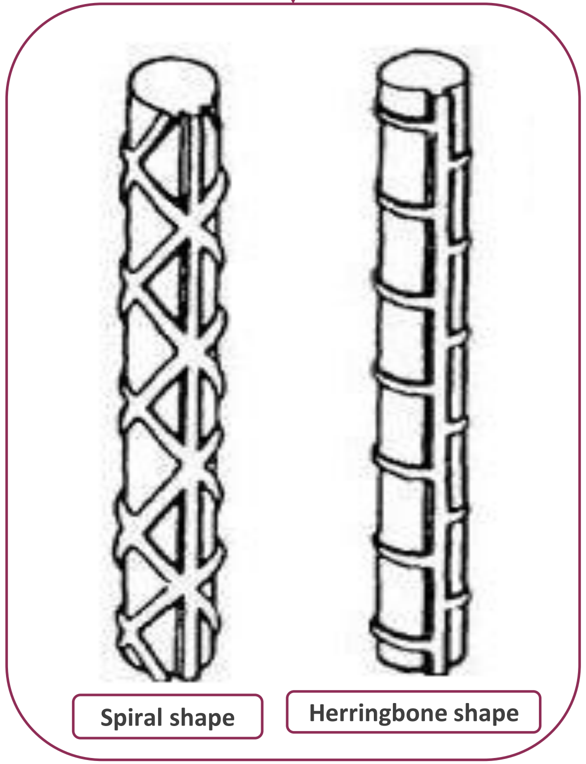


Perspectives



More to ADD

- Different steel bar shapes (spiral)
- Introduction of creep & shrinkage
- Model for the Mortar/steel interface to select and/or develop
  - Cohesive zone model (CZM)
  - Contact frictional model
- Adding an aggregates/mortar interface
- Developing a tool to **calibrate** macroscopic models (especially the ones developed in LM2S)



Merci de votre attention