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LIÈGE université
Sciences Appliquées

MSM Materials and Solid Mechanics

Fatigue crack prediction in Multiphasic-Phasic Material

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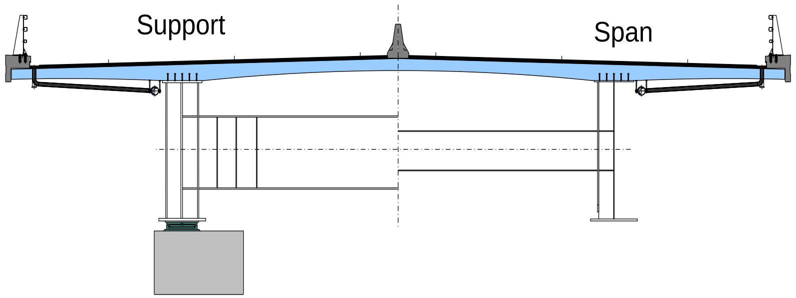
Motivation: Applications



Road bridges
RFCS OPTIBRI project

Replace standard S355 NL by HSS S690 QL in a welded steel bridge
-save ressources (material, welding meters)

Use lighter materials like AlSi10Mg and process like LPBF
-save ressources (fuel)

LongLifeAM RW project

Design of civil engineering structures, or transport vehicules

without fatigue cracks

→ Damage modelling at different scales

Lemaitre and Chaboche model

Old fashion (?) but robust model

Many extensions…

Coupled or uncoupled…

For crack initiation: uncoupled model can do the job

Always: need of a carefull identification and validation

Lemaitre, J., Chaboche, J.-L., 1996. Mécanique des matériaux solides, Dunod

Lemaitre and Chaboche model

$$\frac{\partial D}{\partial N} = 0 \quad \text{if } f_D < 0$$

or

$$\frac{\partial D}{\partial N} = \left[1-(1-D)^{\beta+1}\right]^{\alpha} \left(\frac{\tilde{A}_{II}}{M}\right)^{\beta} \quad \text{if } f_D \geq 0$$

$$f_D = A_{II} - A_{II}^*$$

$$\hat{\sigma}_{ij} = \sigma_{ij} - \sum_k \frac{1}{3}\sigma_{kk}$$

$$A_{II} = \frac{1}{2}\sqrt{\frac{3}{2}(\hat{\sigma}_{ijmax} - \hat{\sigma}_{ijmin})(\hat{\sigma}_{ijmax} - \hat{\sigma}_{ijmin})}$$

$$A_{II}^* = \sigma_{l0}\,(1 - 3.b.\sigma_{Hm}) \quad \text{(Sines' criterion)}$$

$$\tilde{A}_{II} = \frac{A_{II}}{1-D} \qquad \sigma_{Hm} = \frac{1}{3}\left[\frac{1}{T}\int_T Tr\left(\underline{\underline{\sigma}}(t)\right)dt\right]$$

$$\alpha = 1 - a\left\langle\frac{A_{II} - A_{II}^*}{\sigma_u - \sigma_{eqmax}}\right\rangle \qquad M = M_0\,(1 - 3.b.\sigma_{Hm})$$

D: damage value

N: number of cycles

A_{II}: 2nd stress amplitude invariant

A_{II}^*: fatigue limit

f_D: damage yield locus

σ_{Hm}: mean hydrostatic stress

σ_{eqmax}: maximum VM stress / cycle

<x> = x if x > 0 else = 0

$b = 1/\sigma_u$

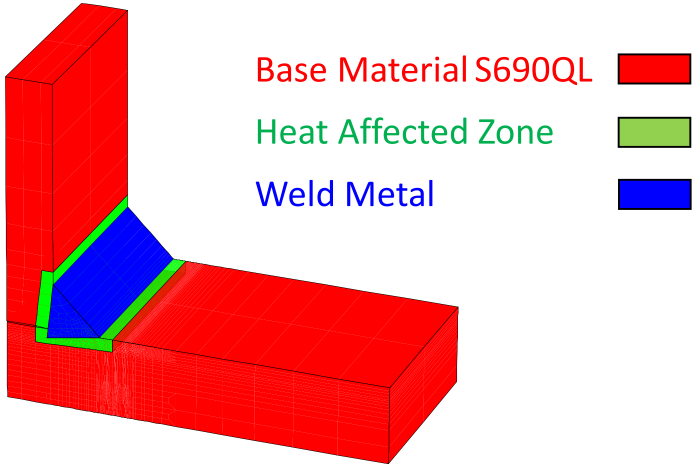
σ_u: ultimate tensile stress

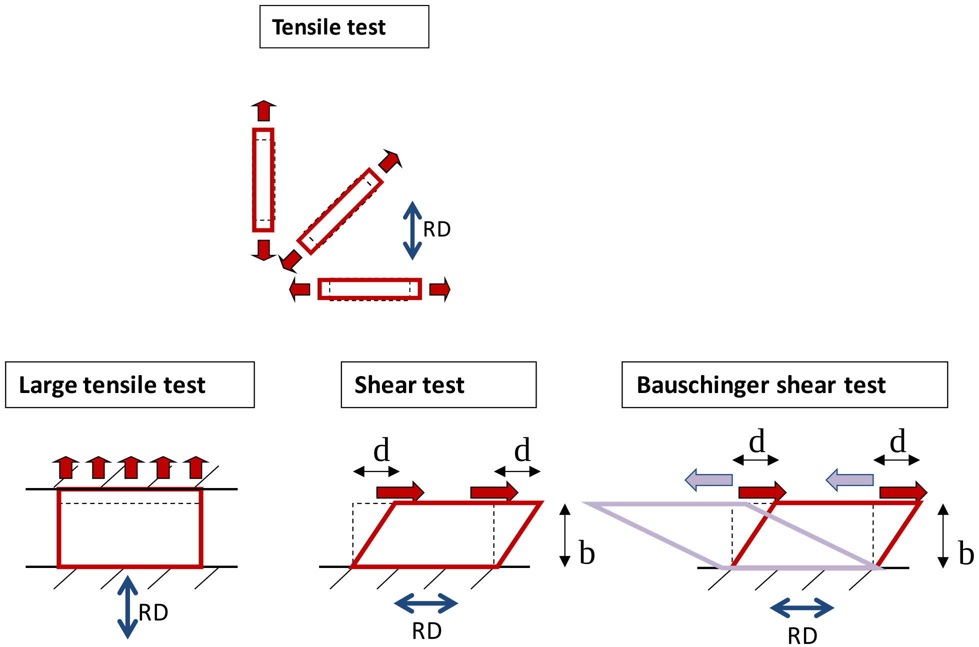
σ_{l0}: fatigue limit if $\sigma_{Hm}=0$

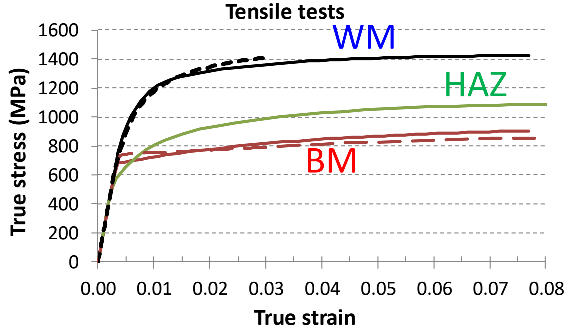
a, M_0, β: material parameters

Contents

Material parameter identification (STATIC)





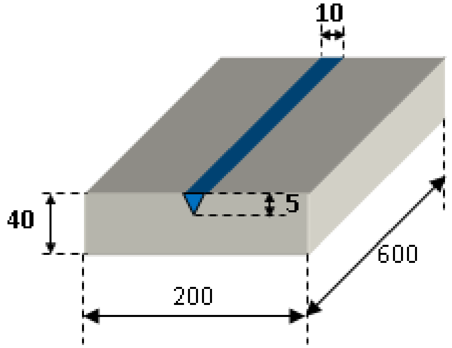


---Experiment in RD
__Model

Material tests -- Small samples (

Data for Hooke, Hill, Voce and Armstrong-Frederick laws (units: MPa, s)													
Material	Ultimate tensile strength		Elastic data		Yield locus				Isotropic hardening			Kinematic hardening	
	$\sigma_{u,eng}$	$\sigma_{u,true}$	E	ν	F	G	H	*N=L=M*	*K*	σ_0	*n*	C_X	X_{sat}
BM (S690QL)	838	905	210 116	0.3	1	1	1	*3.9*	*0*	*674*	*0*	*31.9*	*167*
HAZ	1338	1424	210 000	0.3	1	1	1	*4.45*	*371*	*827*	*511*	*52.5*	*152*
WM	1008	1101	210 000	0.3	1	1	1	*3.2*	*241*	*531*	*285*	*42.6*	*218*

BM bulk sample with WM



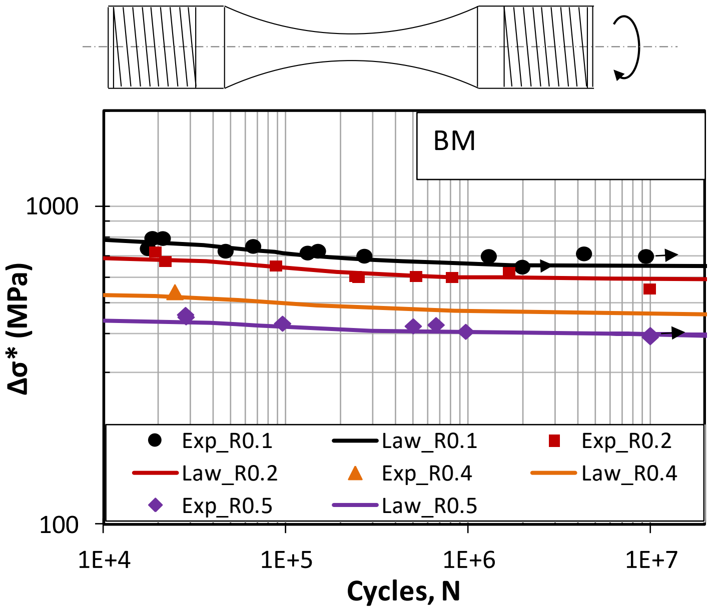
Validation of Lemaitre and Chaboche (vgrad LC) model

Small samples, Ra= 0.8 µm,
Length: 96 mm
Diameter: 5 mm

- **Tests on a vibrophore**
- **Axial loading**

Material	Smooth	Notch
BM	3 R	3 geom.
HAZ1	1 R	1 geom.
HAZ2	2 R	1 geom.
WM	2 R	1 geom.

BM: smooth samples

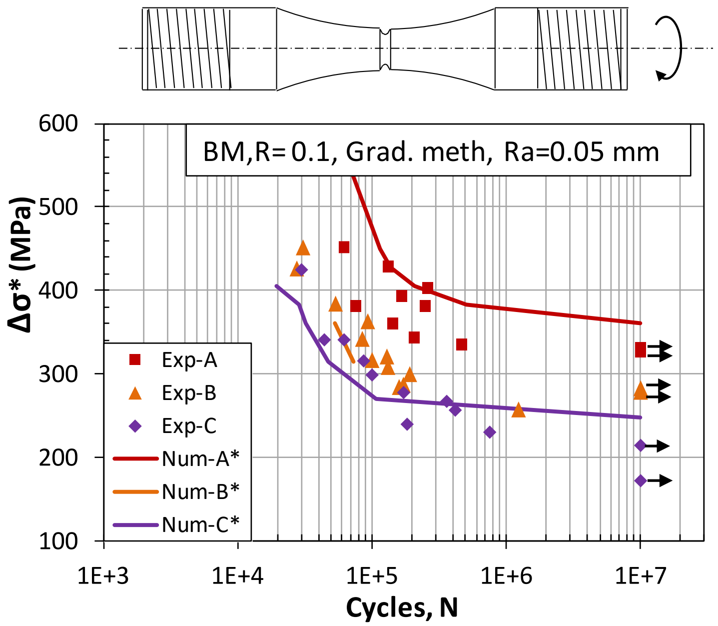


Notch radius:
A: 1.2 mm
B: 0.3 mm
C: 0.15 mm

Vgrad LC
↘ mesh dependency

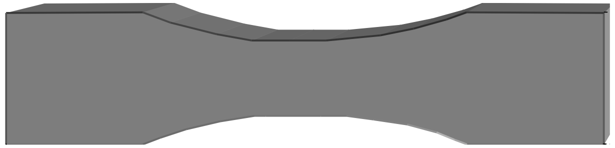
Additional parameter
Length scale Ra : 0.06 mm

BM: notched samples

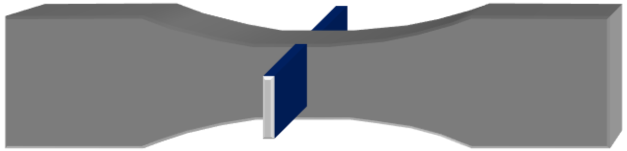


Experimental campaign on representative parts

Plates



Welded plates + PIT or Tig rem. or nothing

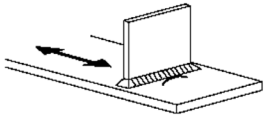


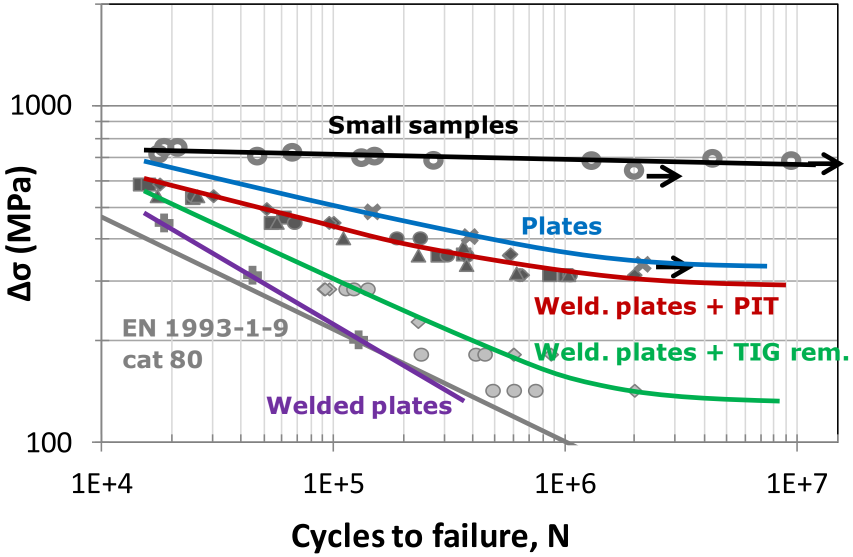
Effect of:

- **size, surface roughness**
- **welding (HAZ, σ concentration, σ_{res})**
- **post-treatment Pneumatic Impact Treatment (PIT) or Tungsten Inert Gas remelting (TIG rem.)**
- **Almost no geometrical effect (plate thickness 1.5- 4 cm, stiffener length 4-6 cm and thickness 6-15 mm)**

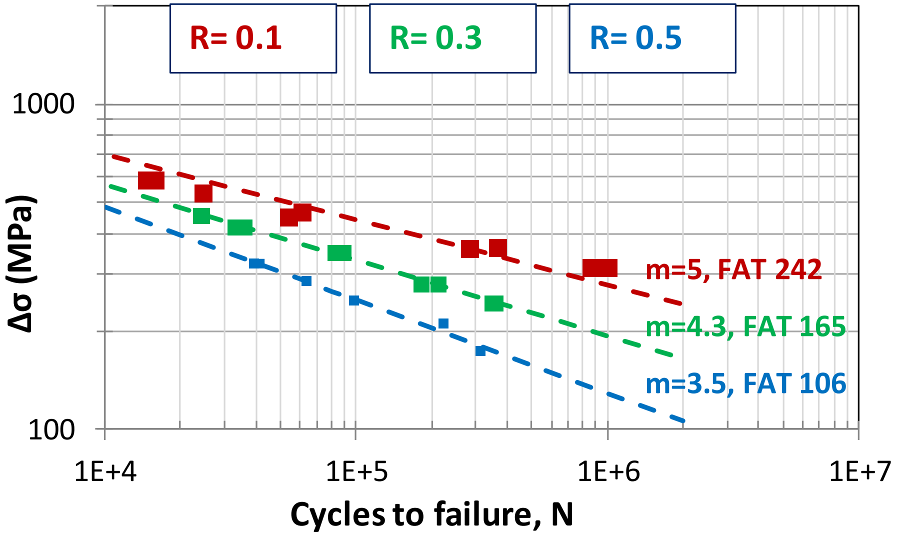
Comparison with

EN 1993-1-9 cat 80





Effect of stress range on welded plates + PIT



Identified material parameter - Scale effect (FATIGUE)

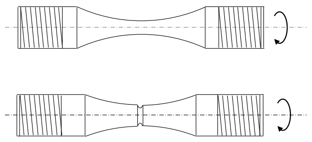
σ_u: ultimate tensile stress

σ_{l0}: fatigue limit

a, M_0, β: material data

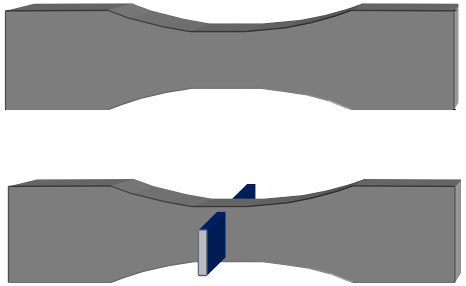
Lemaître Chaboche multiaxial fatigue model improved by stress gradient method

Length 96 mm
Diameter 5 mm



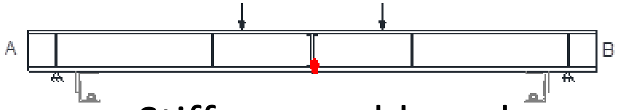
Material	σ_U (Mpa)	σ_{l0} (Mpa)	b	β	a	M_0	Ra (mm)
BM – small	905.0	580.0	1.10 E-03	0.17	1	5.385 E+30	0.06
HAZ - small	1424.0	428.4	7.02E-04	2.094	1	4.410E+05	0.06
WM - small	1101.0	319.4	9.08E-04	0.161	1	7.245E+32	0.00

Length 1 m
Thickness 4 cm



Material	σ_U (Mpa)	σ_{l0} (Mpa)	b	β	a	M_0	Ra (mm)
BM - plate	905.0	**203.0**	1.10 E-03	0.17	1	5.385 E+30	0.06
HAZ - plate	1424.0	**149.9**	7.02E-04	2.094	1	4.410E+05	0.06

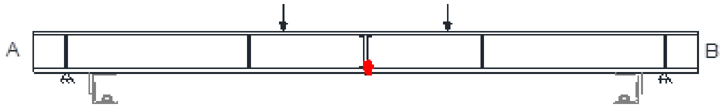
Length 4 m



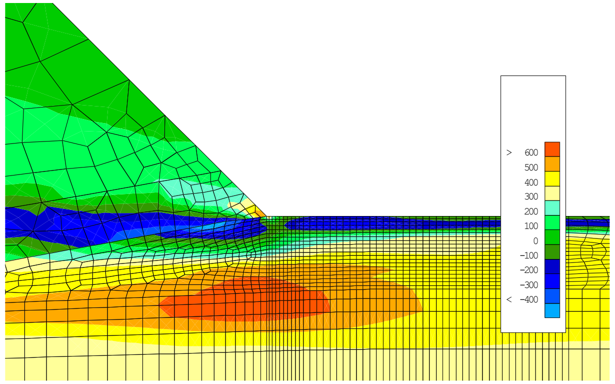
Stiffener weld crack

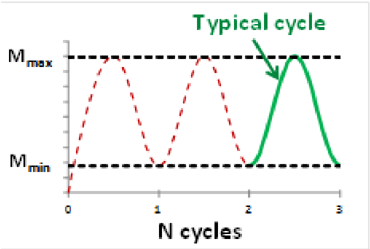
Material	σ_U (Mpa)	σ_{l0} (Mpa)	b	β	a	M_0	Ra (mm)
BM – large plate	905.0	203.0	1.10 E-03	**0.159**	1	5.385 E+30	0.06
HAZ – large plate	1424.0	149.9	7.02E-04	**1.965**	1	4.410E+05	0.06

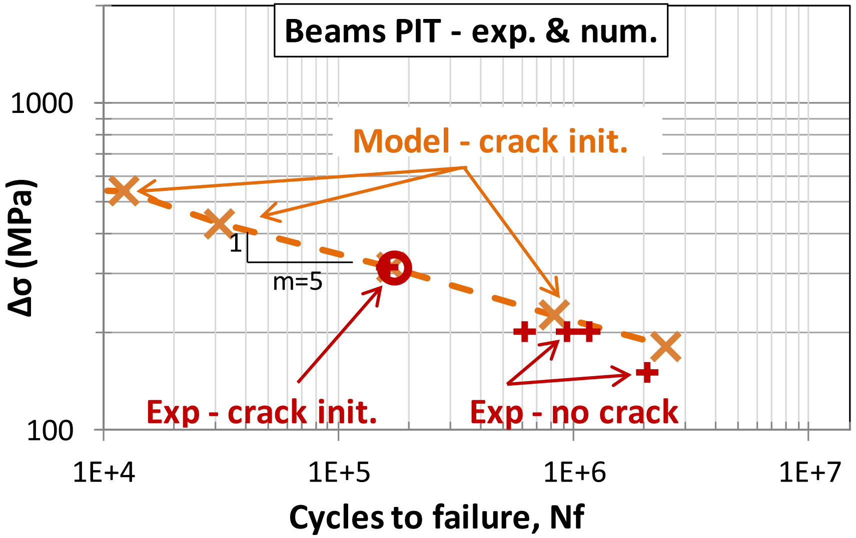
Validation of Lemaitre and Chaboche model



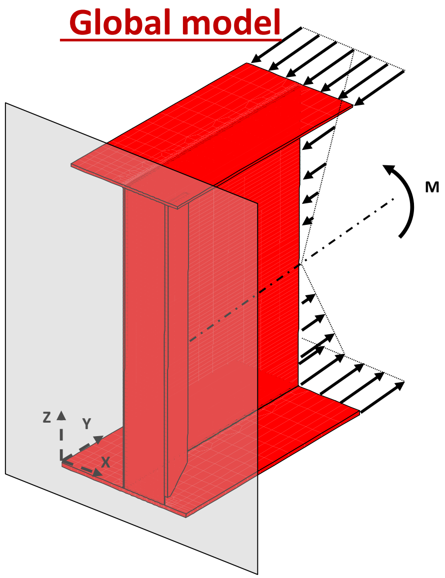
Crack initiation on PIT treated welded joints → **Large scale reduction factor on fatigue data**

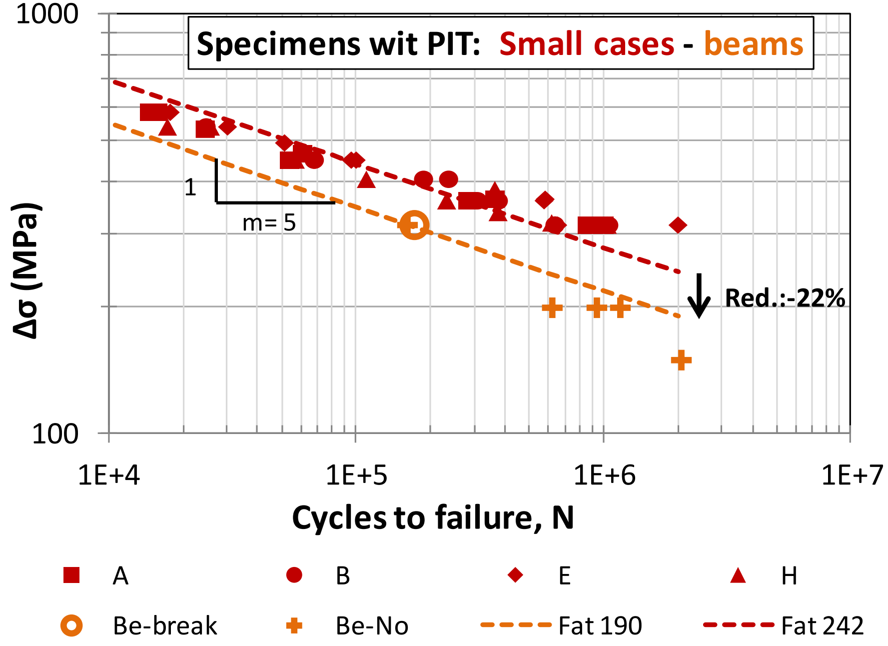


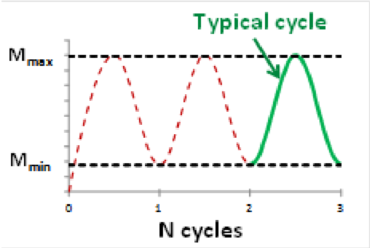


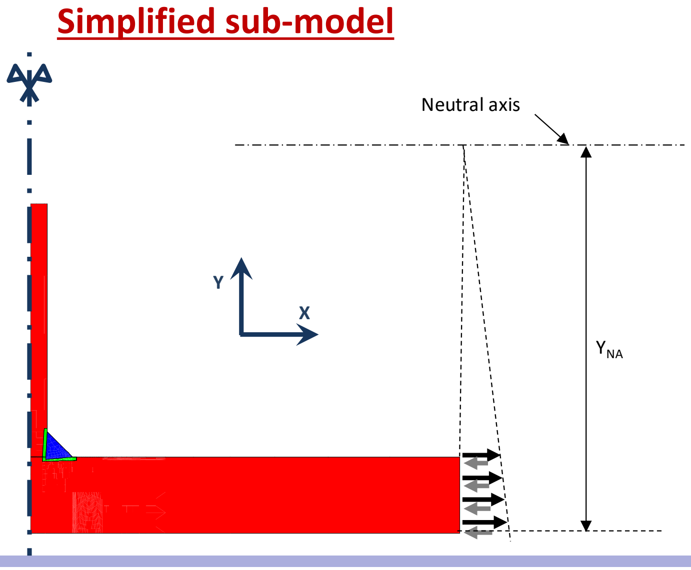


Application of Lemaitre and Chaboche model









Conclusion about damage model in welded bridges

Clear scale effect between laboratory samples and civil engineer structure

Predictions of Vgrad Lemaitre and Chaboche model validated,
however tuning parameter is required when scale varies
very heavy experimental campaign

'User guided multi-scale simulations':

- *FE simulations identify stress cycles in hot points or mandatory check point from civil engineer Standard*
- *Modeling of weld joint*

OPTIBRI project proves interest to replace S355 NL by HSS S690 QL from
LCA analysis + cost analysis
(impact of decrease of material but mostly weld multipass process thanks to plate reduction

Optimal use of high strength steel grades within bridge (**OPTIBRI**) Habraken A.M., Duchêne L., Bouffioux C. 2019 (**EUR 29546 EN**) doi: 10.2777/93807

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Introduction

- Motivation
- Lemaitre and Chaboche model

Welded structures

- Material parameter identification
- Results

Bi-Phasic material

- RVE definition
- Results

Concluding remarks

- Conclusions
- Future prospects

What about work at a smaller scale ?

Assumptions about AlSi10Mg

post processing of LPBF samples to suppress the porosity

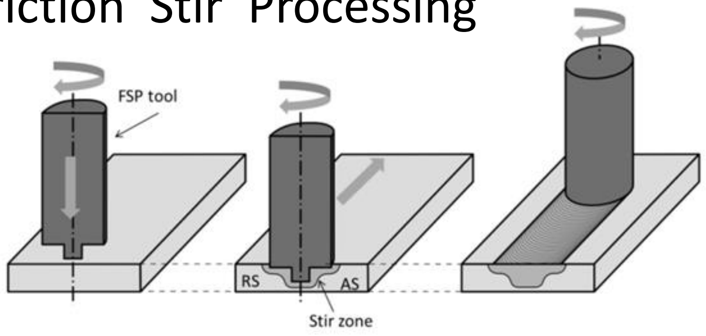
→ the microstructure itself defines the mechanical behavior

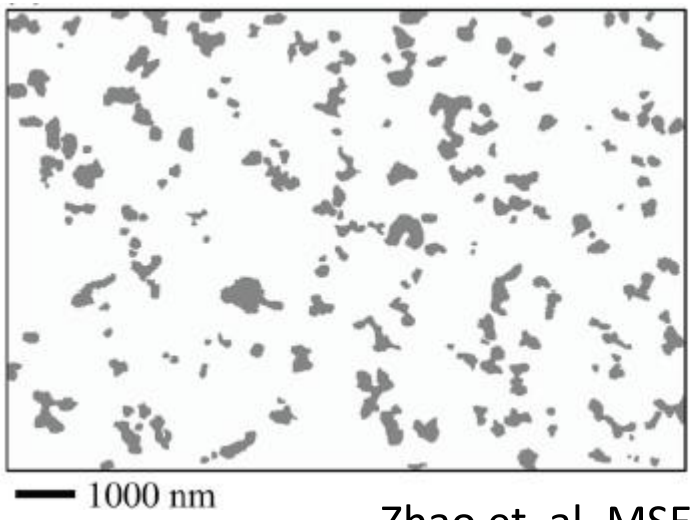
→ definition of a representative volume element: Al α phase matrix + Si precipitates

→ RVE validation 1 : static behaviour

→ fatigue ?

post processing Friction Stir Processing





Zhao et al. MSEA 2019

Representative Volume Element RVE - Geometry

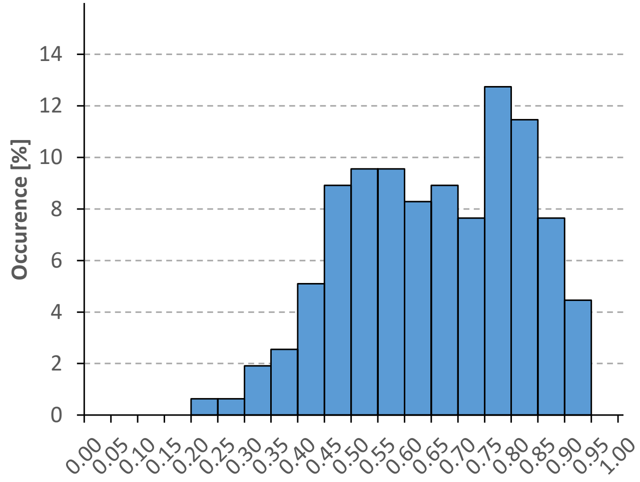
AR vs. $\varnothing_{eq}$	α vs. $\varnothing_{eq}$	α vs. AR
-0.336	0.042	0.066

Analysis of precipitate distribution $r_{mn} = \frac{cov(m,n)}{\sigma_m . \sigma_n}$

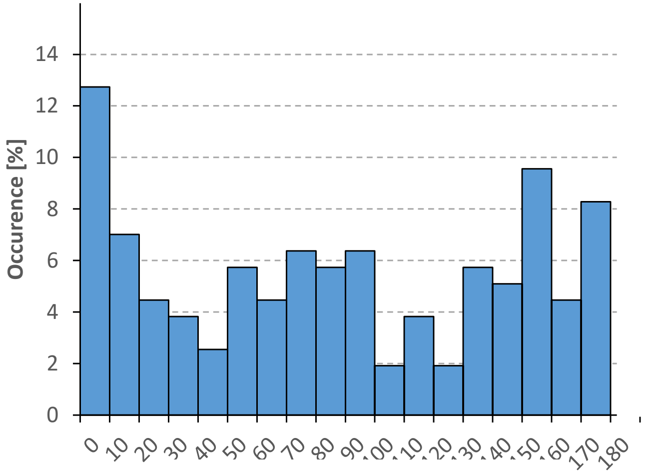
No correlation r_{mn}=0 strong |1|

Pearson correlation coefficient

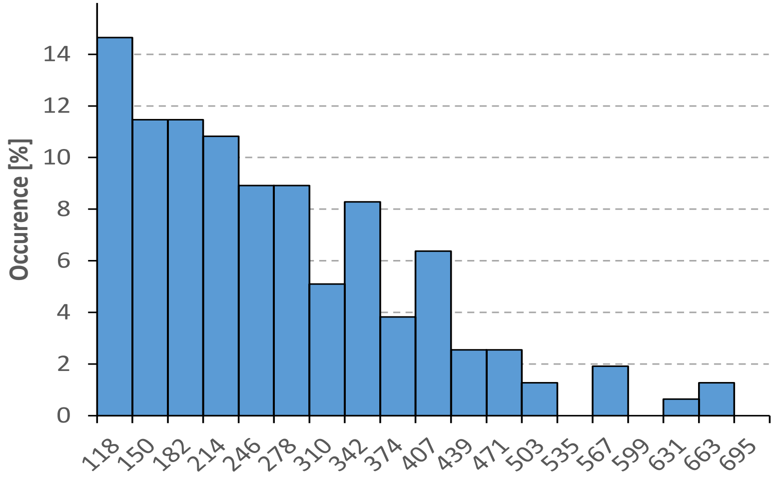
Similar in RVE and measured microstructure



Aspect ratio



Angle α to x axis in degree



Equivalent Diameter $\varnothing_{eq}$

Si volume meets Si composition in Al α phase matrix + Si precipitate → statistical representativity of images and RVE

Representative Volume Element RVE - Phase properties

Si : literature + nano-indentation of big particles

(Young modulus, mostly elastic behavior, fracture stress very high)

α-Al matrix:

1. nano-indentation of α-Al matrix with 3 indenters → info on hardening curve (σ_0 still multiple solutions)[1]

2. inverse modelling of Berkovich nano-indentation[2]

→tensile curve = validation)

3. analytical formulas (many parameters, microscopic experiment validations) [3,4]

+ links with data driven approach

In the idea to go to material design
no dependence on experiment
on large sample or any sample is searched

[1] Dedry et al. *Proc. ESAFORM 2021 (PoPuPs)*
[2] Tran Song Hoang et. al *Int.Journal of Mec.Sciences 2022*
[3] PhD J. Delahaye ULiege 2022
[4] ongoing Master thesis V. Borlaf and PhD H. Spulveda

Experimental method with 3 indenters

a representative point ($\varepsilon_{r,\theta}$, $\sigma_{r,\theta}$) by indenter characterized by its angle α

- **K.L. Johnson (J. Mech. Phys. Solids, 1970)** → $\varepsilon_{r,\theta} = K \cdot cotan(\theta)$

θ: angle of the equivalent cone, K = 0,105 (Bucaille, Acta Mat. 51, 2003) with α: angle of indenter

→ the characteristic strain $\varepsilon_{r,\theta}$

$$\theta = arctan\left(\sqrt{\frac{3.\sqrt{3}}{\pi}}.tan(\alpha)\right)$$

- **Dao's method (Acta Mat. 49, 2001) + Bucaille method (Acta Mat. 51, 2003)**

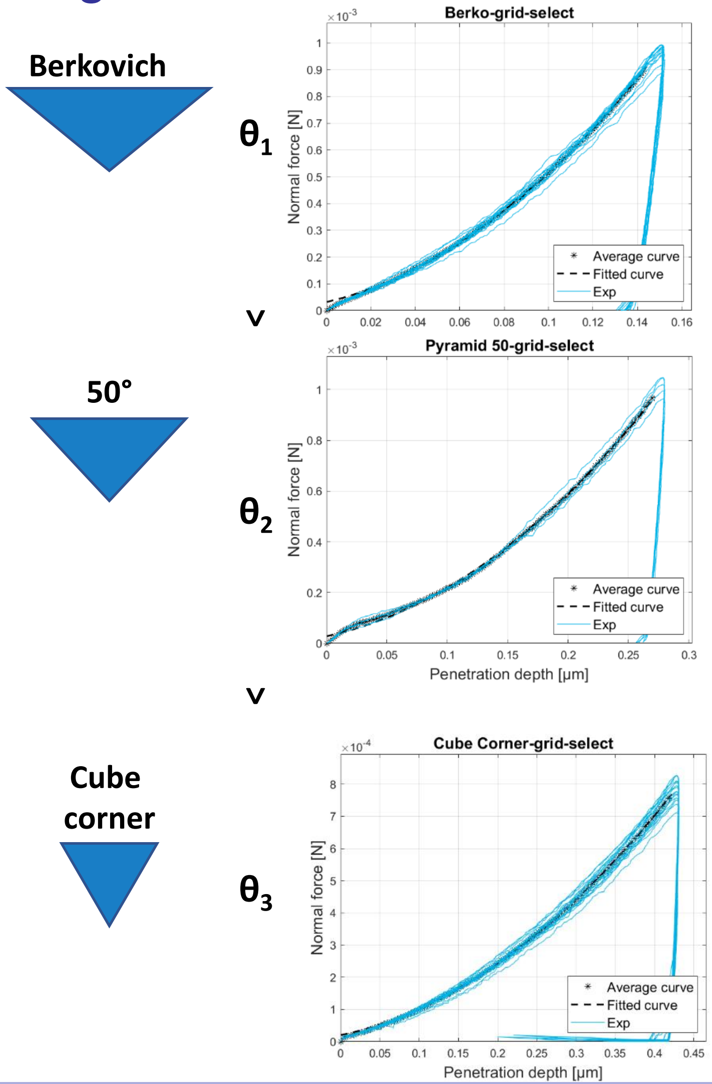
$$\Pi_{1\theta} = \frac{C_\theta}{\sigma_{r,\theta}} = tan^2(\theta).\left\{P1.\left[ln\left(\frac{E^*}{\sigma_{r,\theta}}\right)\right]^3 + P2.\left[ln\left(\frac{E^*}{\sigma_{r,\theta}}\right)\right]^2 + P3.\left[ln\left(\frac{E^*}{\sigma_{r,\theta}}\right)\right] + P4\right\}$$

E*: reduced modulus of the nano-indentation curve

→ the characteristic stress $\sigma_{r,\theta}$

P1	P2	P3	P4
0.02552	- 0.72526	6.34493	- 6.47458

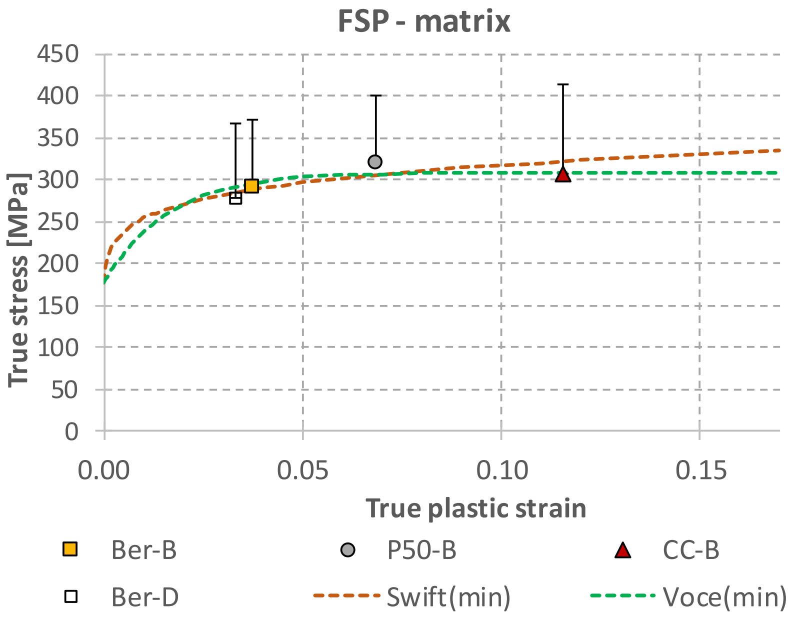
Indentations on grids with 3 different indenters: lowest curves for matrix = **assumption**



→ Swift or Voce hardening law fitting infinite solution

if σ_y not defined

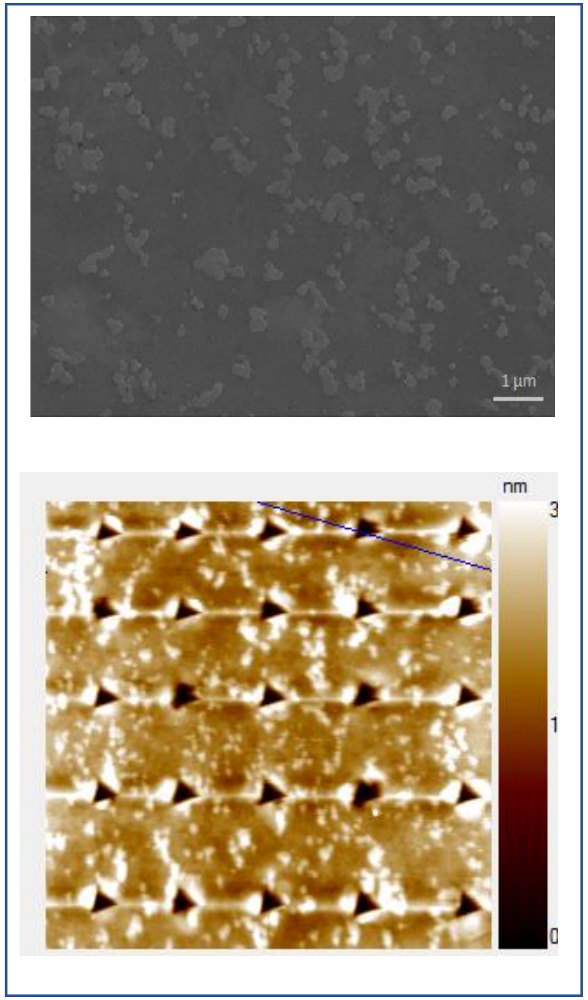
→ σ_y from macro tensile macro

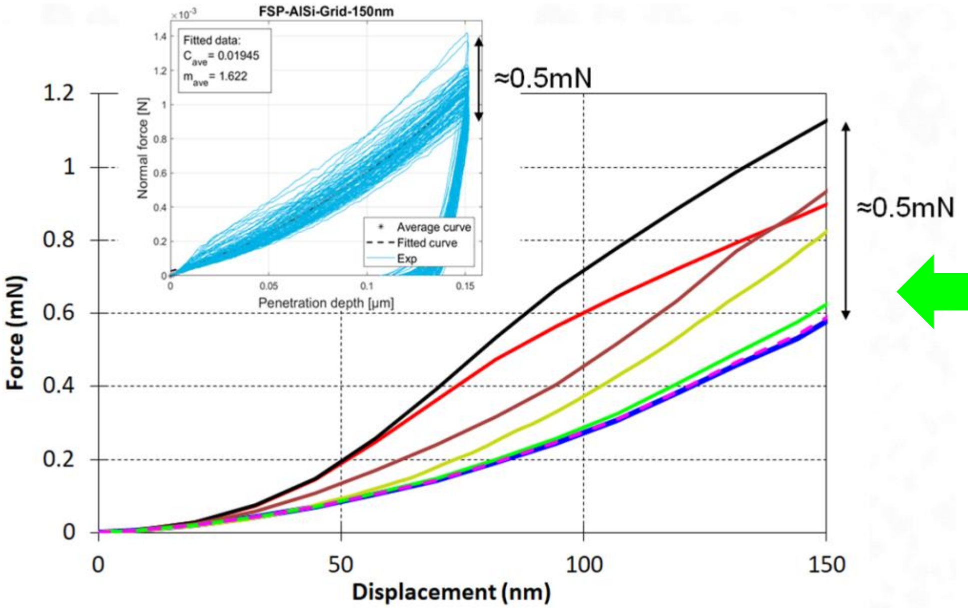


O. Dedry,et al. , (2021) ESAFORM proceedings (PoPuPs)

Representative Volume Element RVE - Phase properties 2

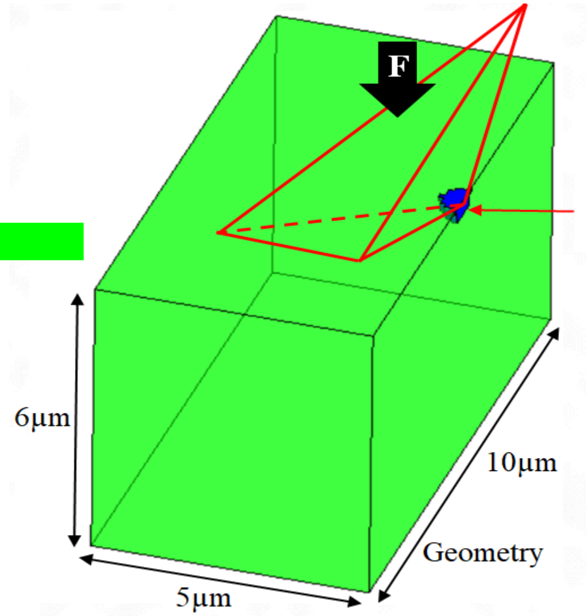
Berkovich nanoindentation + Finite Element Method to identify plastic behavior of the α-Al matrix in FSP- LPBF AlSi10M





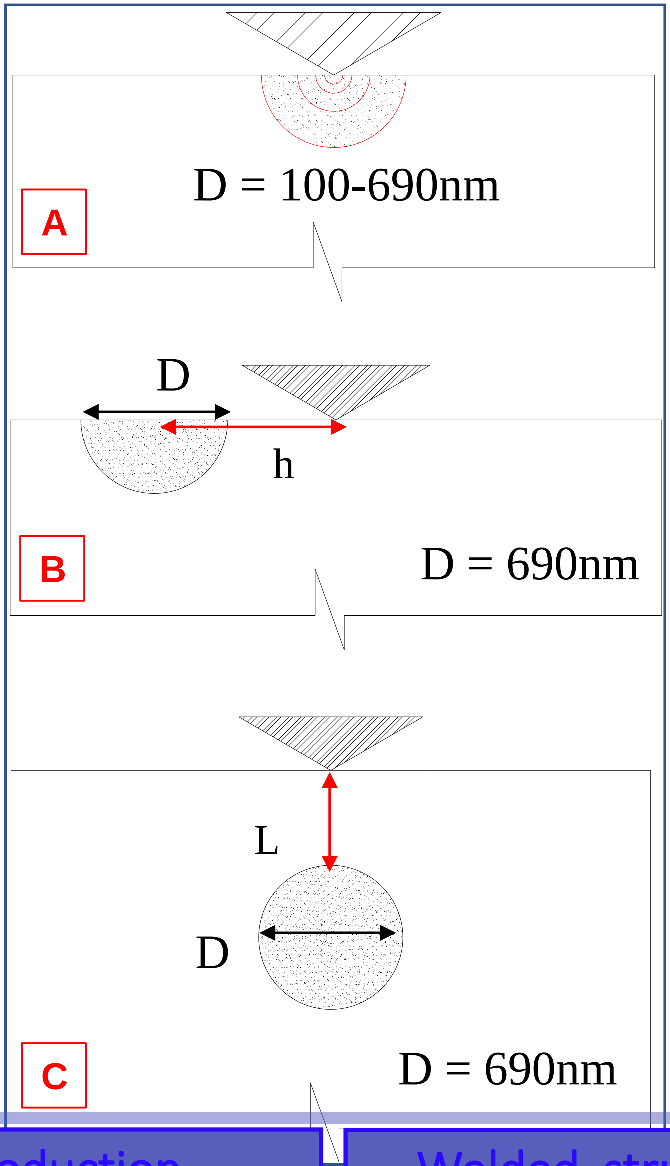
Large scattering
α-Al and Si

Identification the mechanical behavior of α-Al ?



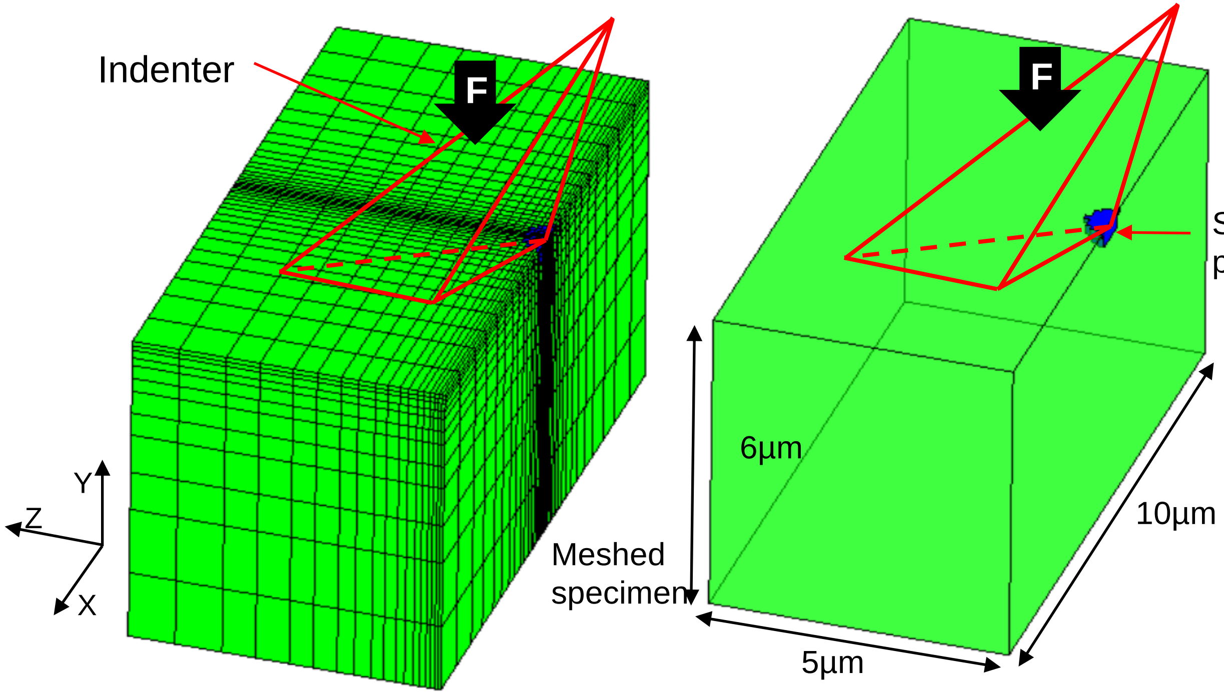
3D finite element model

Representative Volume Element RVE - Phase properties 2

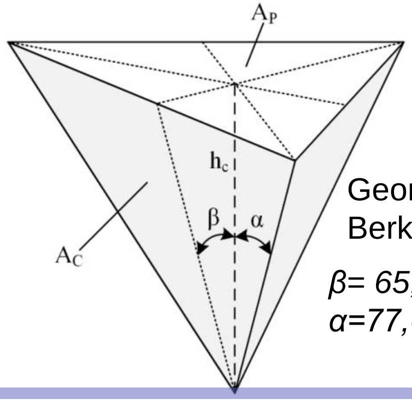


Inclusion embedded in the matrix

Three cases studied by simulations



Symmetric FE-model



Geometry of the Berkovich indenter

β= 65,3°
α=77,05°

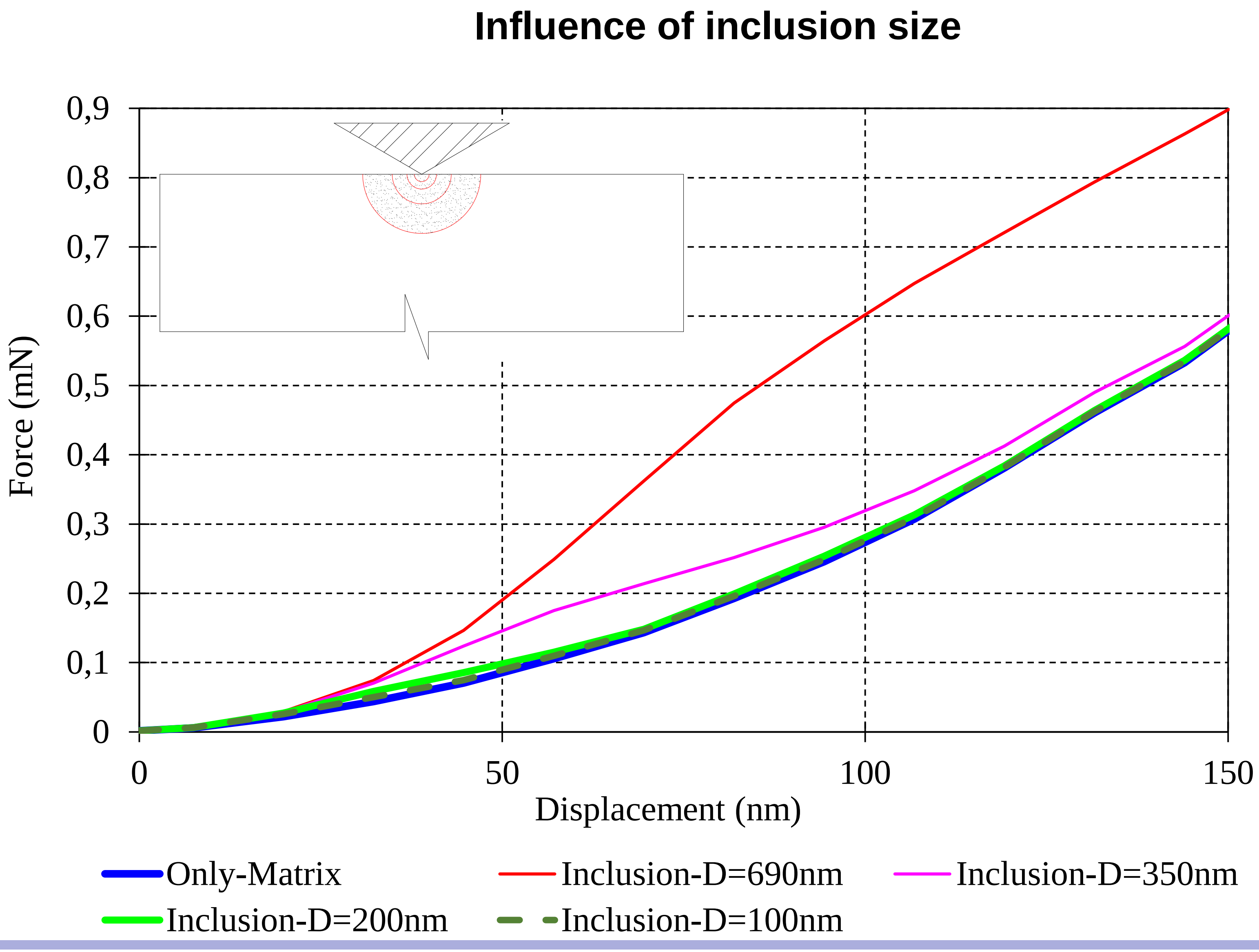
Voce law for Matrix

$$\sigma_F = \sigma_0 + K(1 - exp(-n.\varepsilon^{pl}))$$

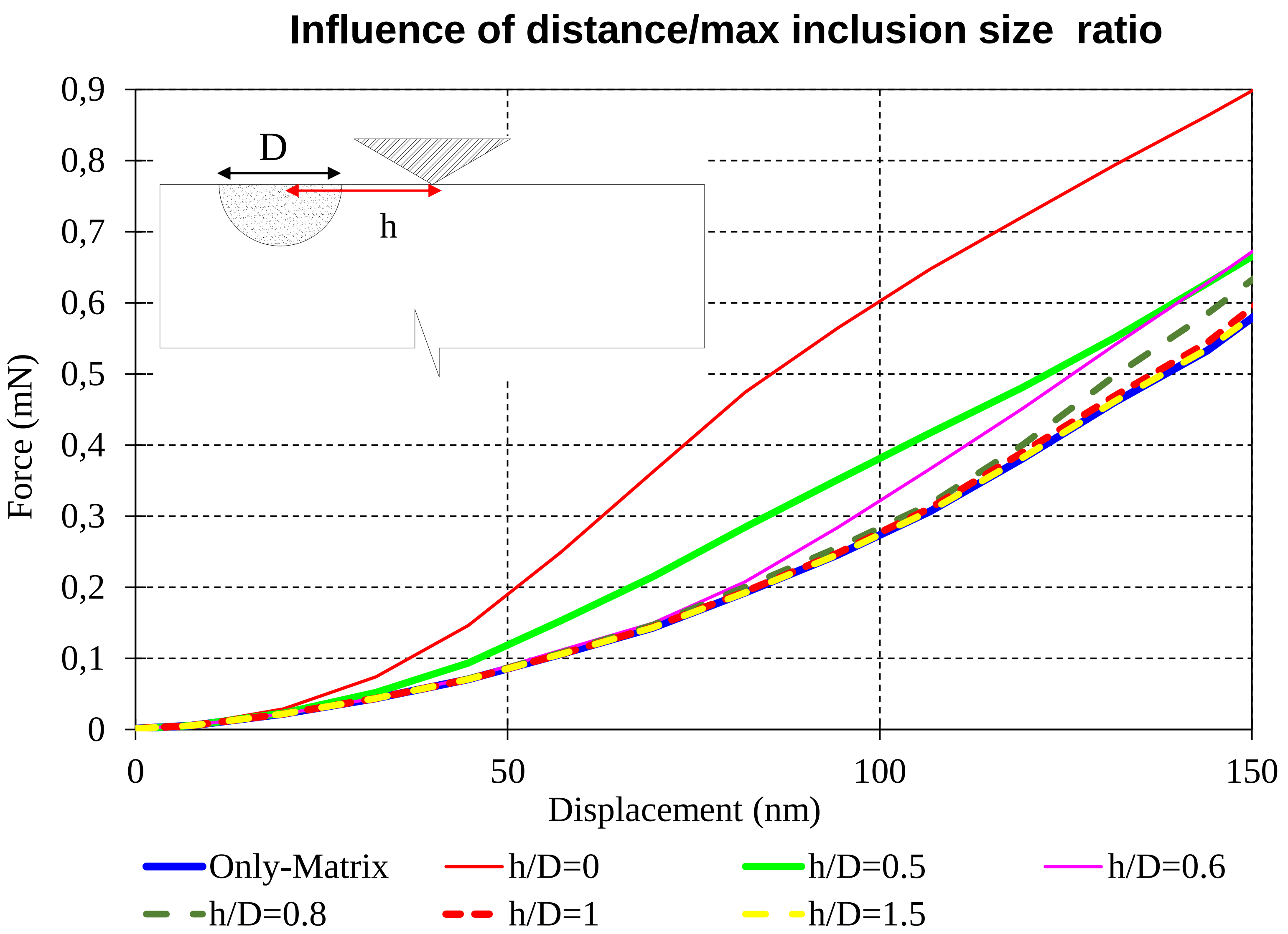
	Inclusion	Matrix
E (Gpa)	138	83.74
µ	0.3	0.3

Typical geometry case A

Simulation assumption: Matrix law based on lowest measured Forece Displ. Curve+ inverse model

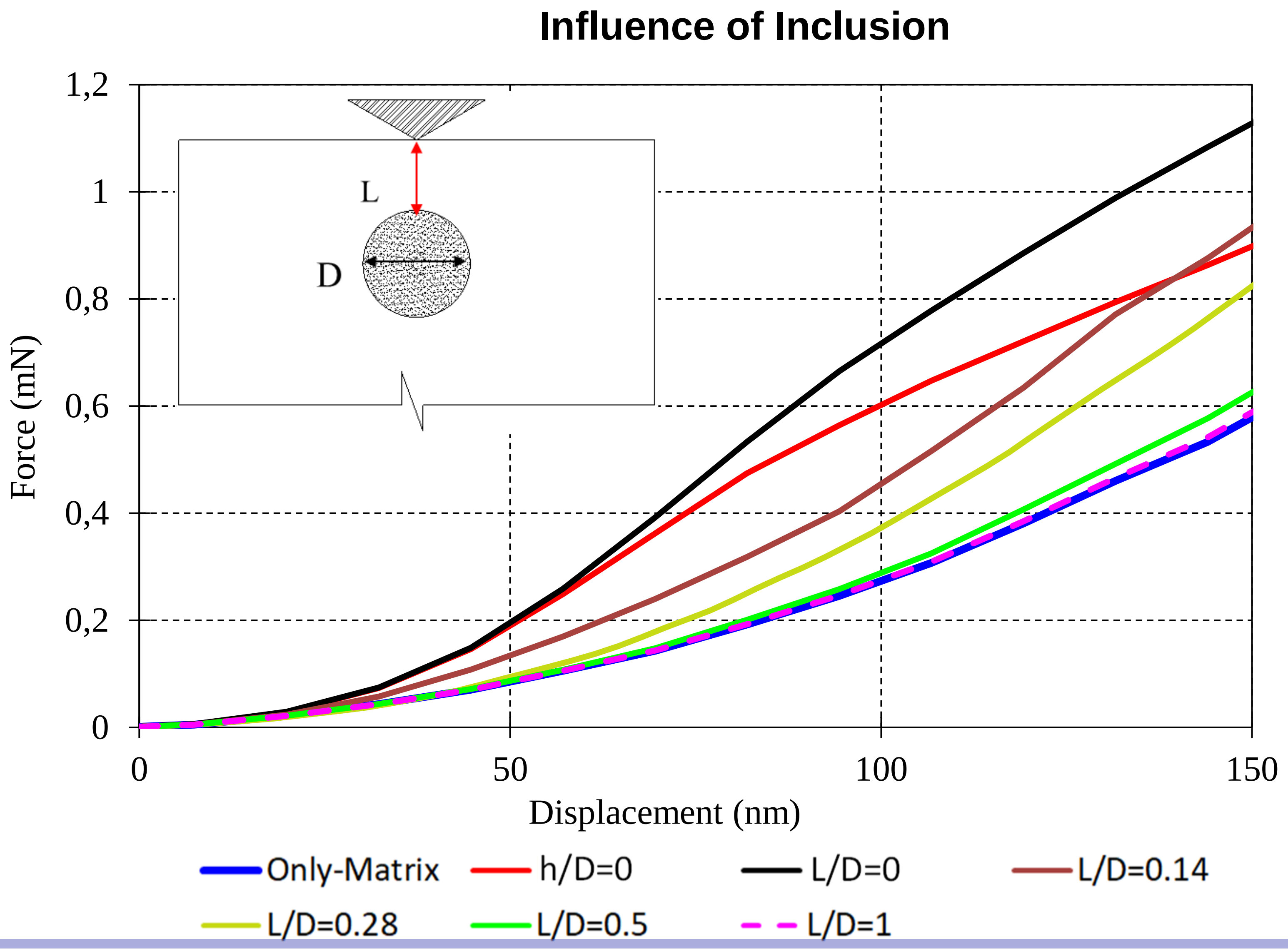


Typical geometry case B



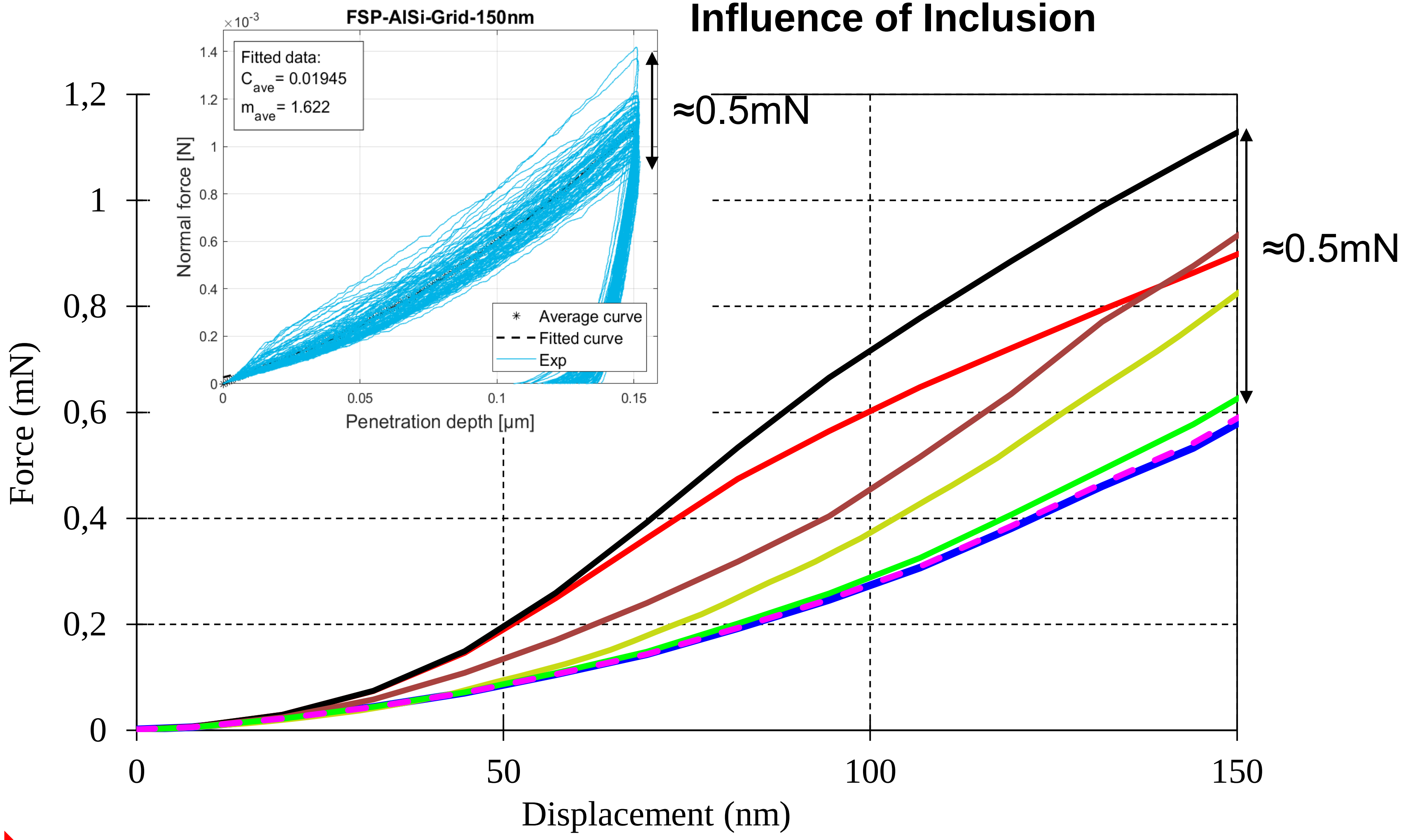
Representative Volume Element RVE - Phase properties 2

Typical geometry case C



Representative Volume Element RVE - Phase properties 2

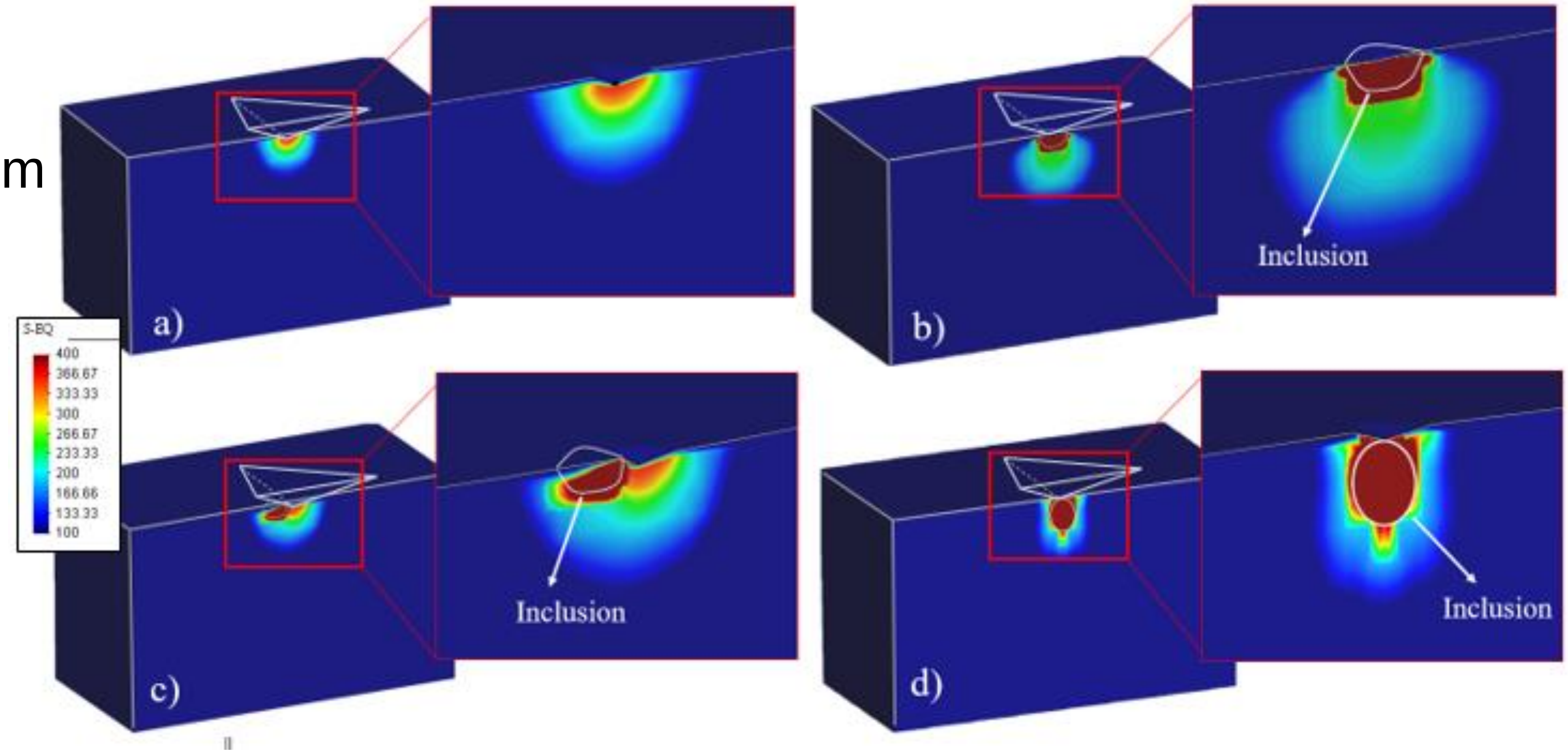
Cases A, B, C recover Experim. scattering range



➡ **Possibility to find the α-Al matrix properties : lower curves**

Von Mises field

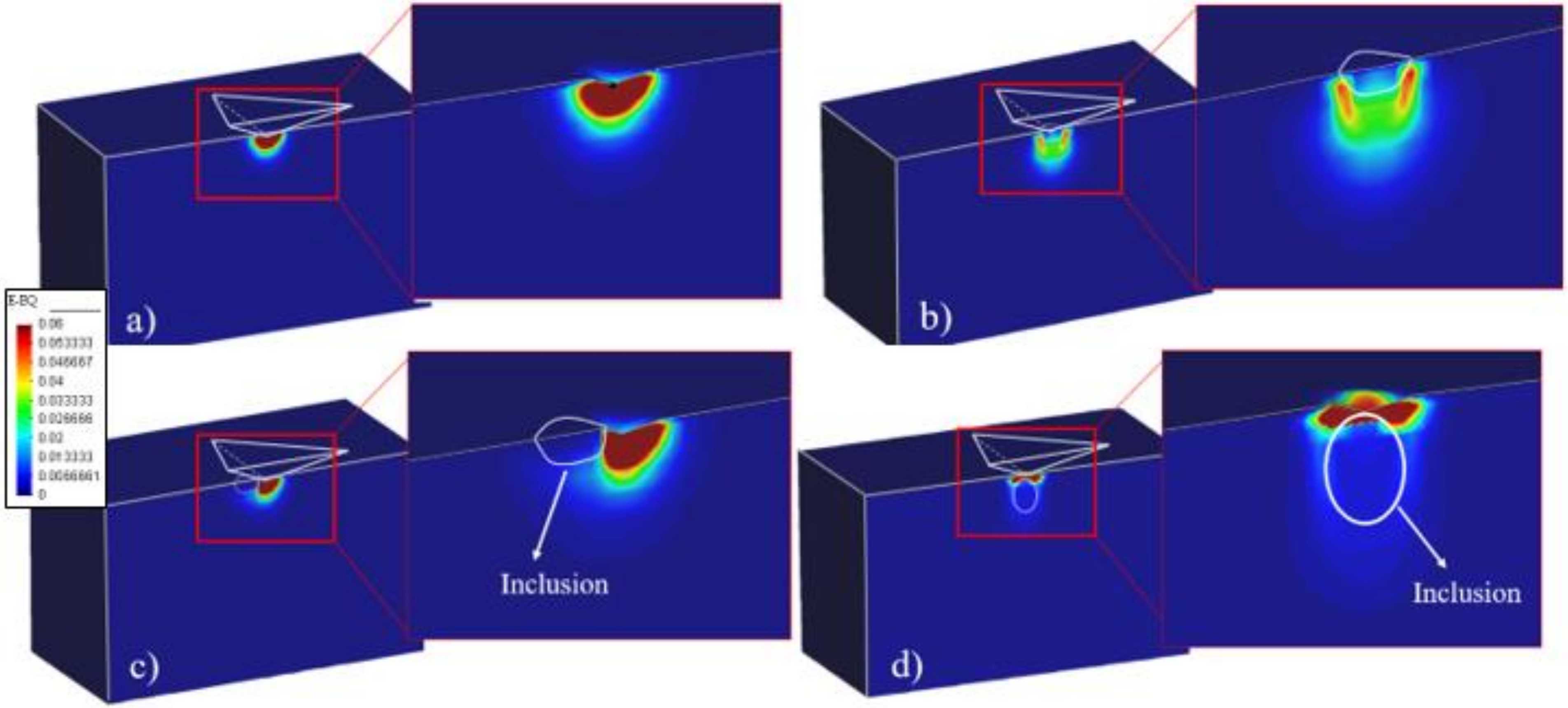
Displacement
U=100 nm,
$D_{inclusion}$=690nm



Representative Volume Element RVE - Phase properties

Strain stress field
Displacement
U=100 nm,
$D_{inclusion}$=690nm

¶



Representative Volume Element RVE - Phase properties 2

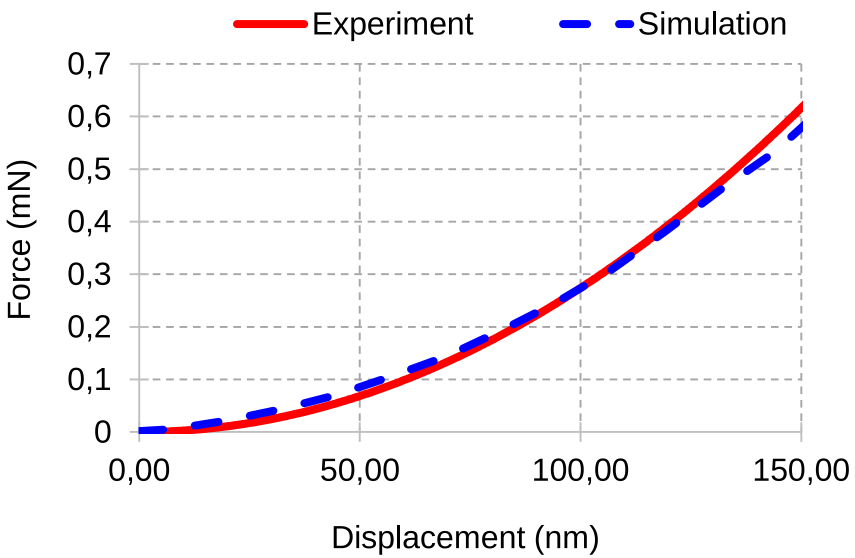
- Influence of individual inclusion on the indenter loading response
- A critical distance between the inclusion and indentation location annihilates the inclusion effect.

$$\frac{\sigma_Y matrix}{\sigma_Y inclusion} = 0.036$$ & Si size [100-690] nm Berkovich curve not affected if :

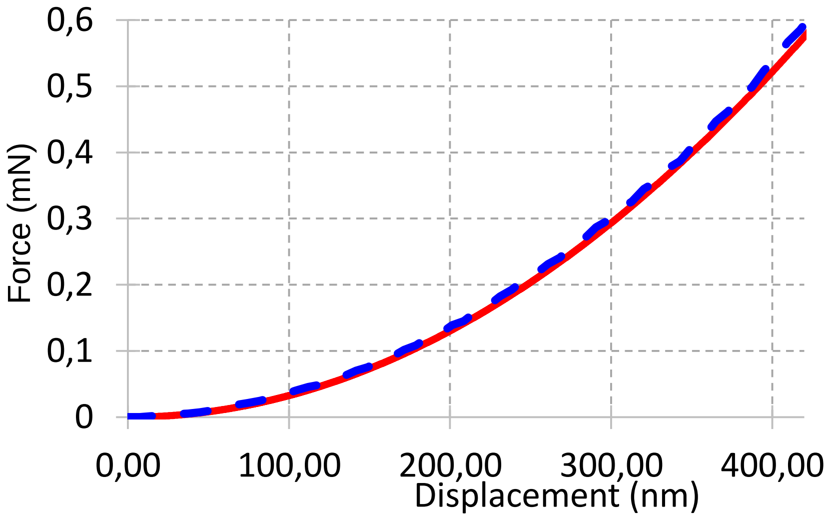
Si size < 200nm or distance from particule > 345 nm (proved for largest Si size)

→ Efficient tool for curve selection process and post treatment to identify the mechanical properties of matrix phase.

Berkovitch indenter



Cube Corner indenter = validation



Representative Volume Element RVE - Phase properties 3

Analytical Yield stress calculation from microstructure ?

Hall-Petch's law $= \sigma_0 + \frac{k}{\sqrt{d}}$

- NaMo model [1,2]:

$$\sigma_y = \sigma_0 + \sigma_{disl} + \sigma_{sol} + \sigma_{bp}$$

- σ_0 : Pure aluminium yield strength
- σ_{disl} : Dislocations contribution
- σ_{sol} : Solid solution contribution
- σ_{gb} : Grain boundaries contribution
- σ_{sh} : Sheared precipitates contribution
- σ_{bp} : By-passed precipitates contribution

- Quadratic model [3]:

$$\sigma_y = \sigma_0 + \sigma_{gb} + \sigma_{sol} + \sqrt{\sigma_{sh}^2 + \sigma_{bp}^2 + \sigma_{disl}^2}$$

For by-passed precipitates

$$\sigma_{bp} = \frac{M \cdot F_{bp}}{b \cdot l} = \frac{M}{br_p} \cdot \sqrt{\frac{3}{4\pi} \cdot \frac{f_p}{\alpha G b^2}} \cdot F^{\frac{3}{2}}$$

For sheared precipitates

$$\sigma_{sh} = \frac{M \cdot F_{sh}}{b \cdot l} = \frac{M F_{sh}^{3/2}}{b} \cdot \sqrt{\frac{N_a}{2T}}$$

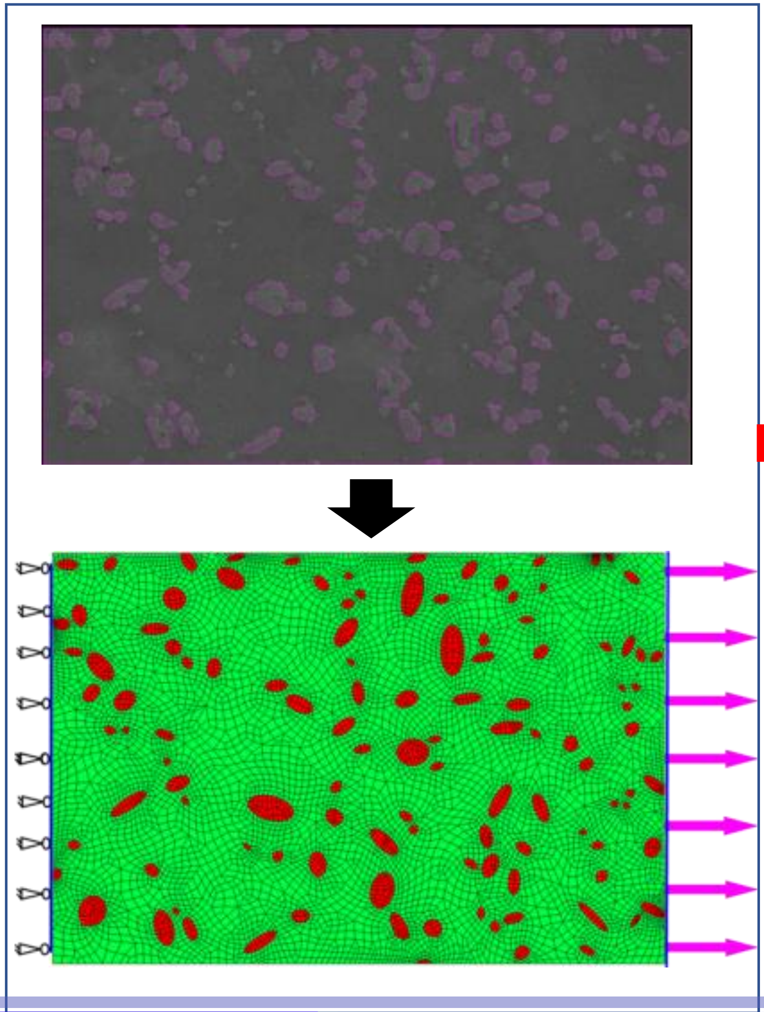
M → Taylor factor
k_B → Boltzmann constant
$\dot{\varepsilon}_0$ → Reference strain rate
$\dot{\varepsilon}$ → Nominal strain rate
τ_{y0} → Zero-temperature stress
ΔE_b → The energy barrier.

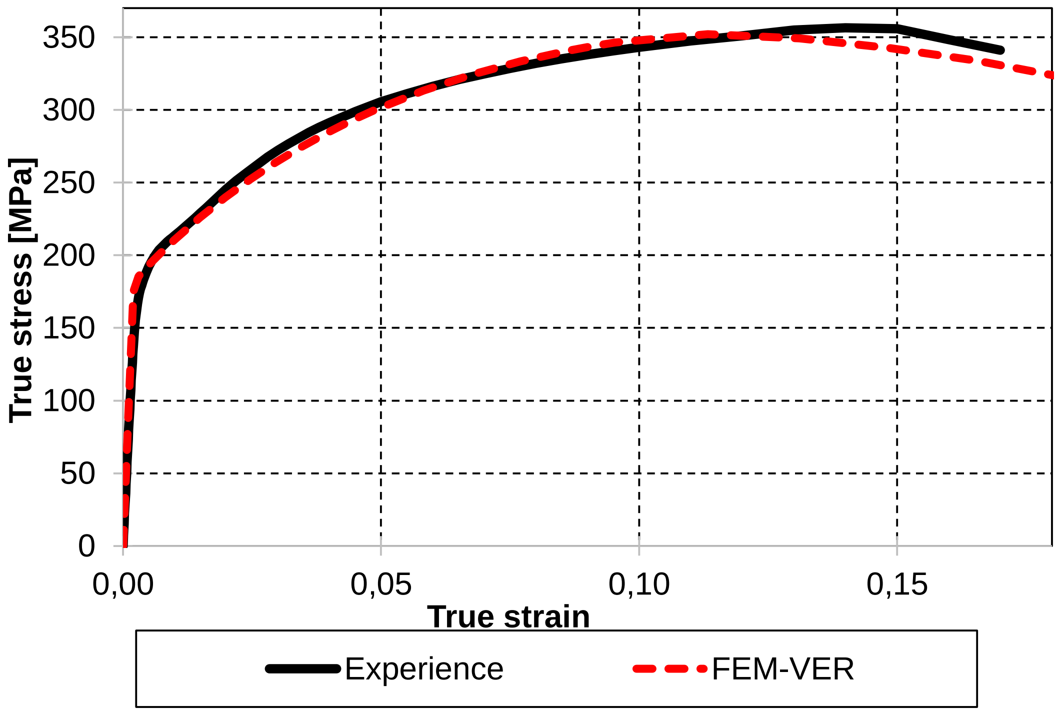
b → Burger's vector
G → shear modulus
α → geometric constant close to 0.5
r_p → particle mean radius
G → *shear modulus*
T → Line tension generated by a dislocation inked between two obstacles

N_a → Density of precipitates by surface unit
f_p → Volume fraction of the precipitates
l → Mean distance between precipitates
F_{bp}, F_{sh} → Force required to overcome the pining of the dislocation

[1] O. Engler et al., Materials Science & Engineering A, 2019
[2] J. Delahaye, PhD thesis, ULiège, 2022
[3] J. Taurines, PhD thesis, UDLyon, 2023

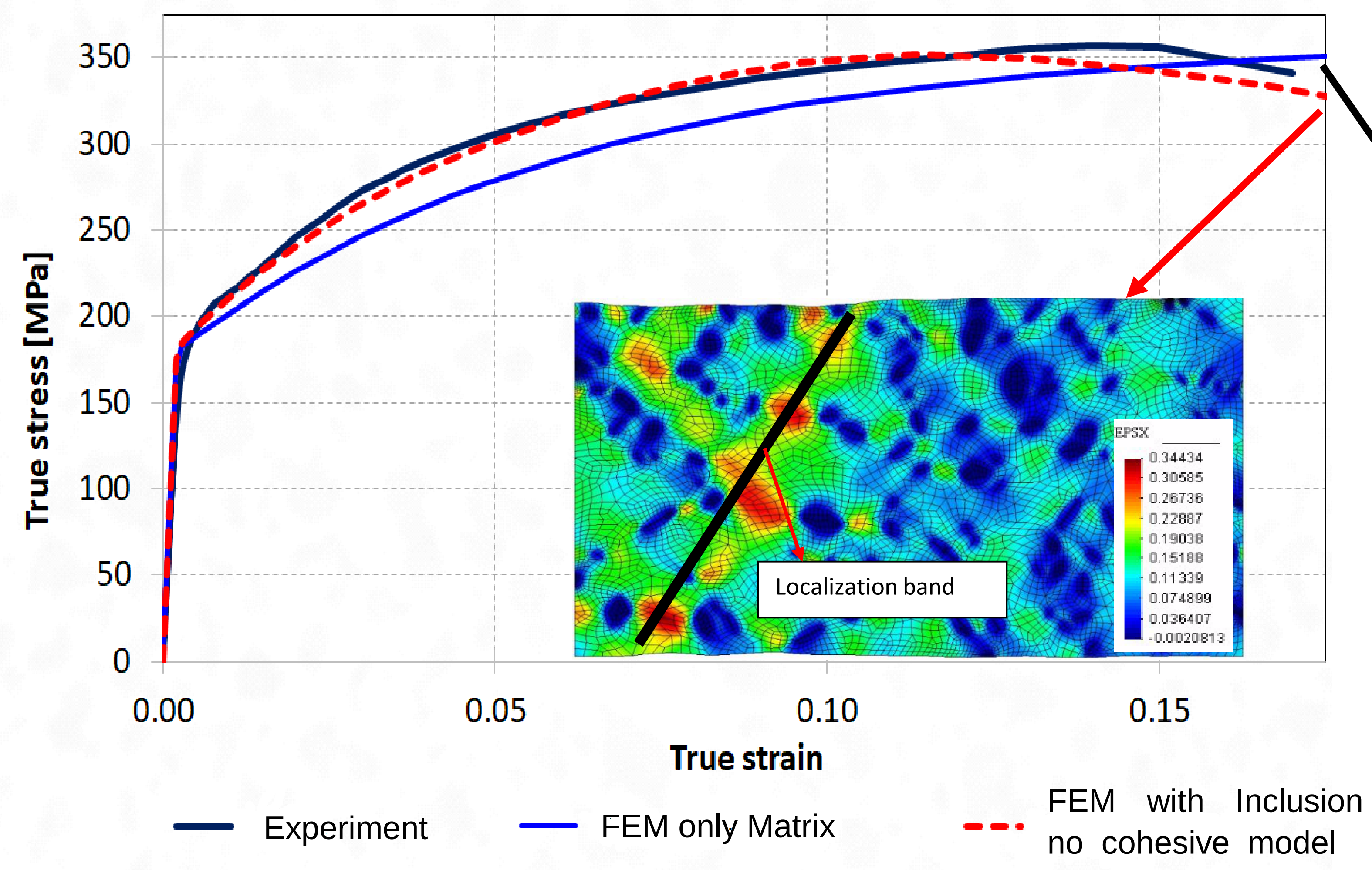
Representative Volume Element RVE - Application

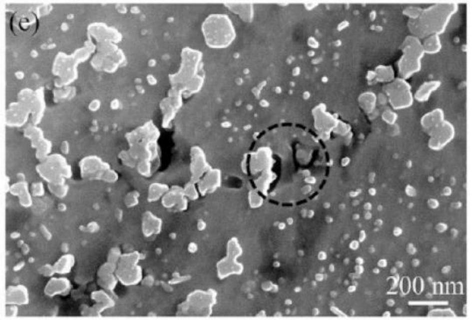




Validation of large VER by tensile test model

Large RVE Application - no cohesive element





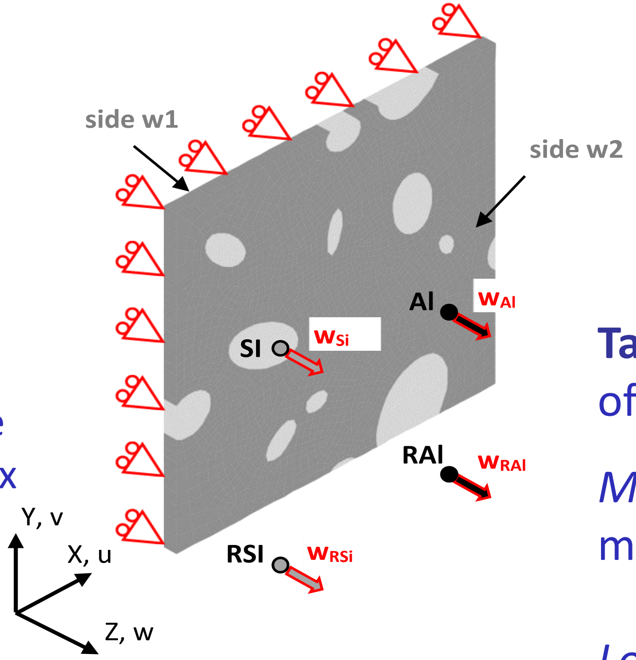
ductile failure with damage nucleation sites = mainly particle-matrix decohesion

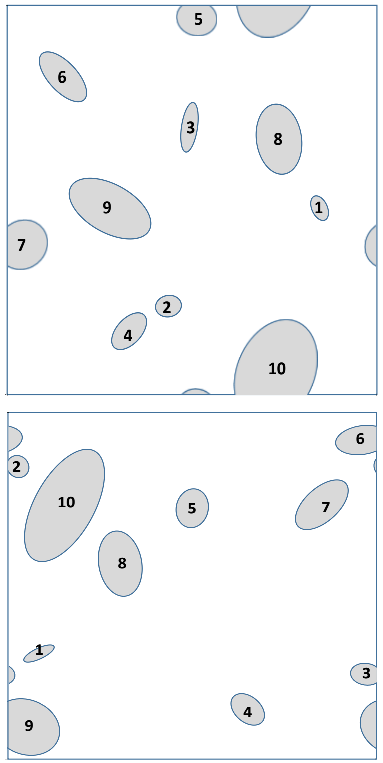
Comparison between the experiment and simulation of tensile test (big RVE no cohesive element)

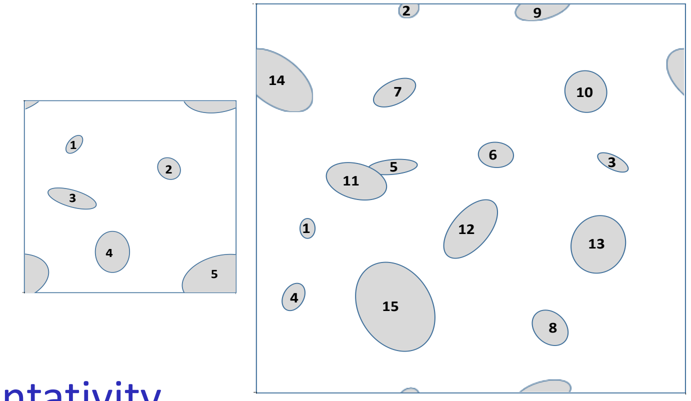
Smaller Representative Volume Element RVE

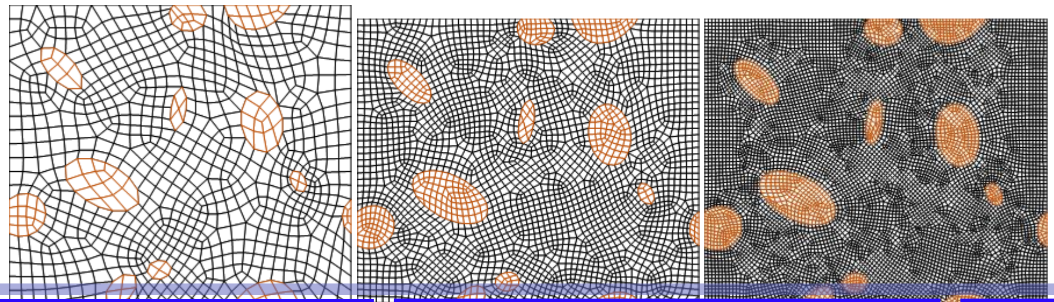
2D or 3D → 2.5D
Representative Size → 10 particles
Mesh density → medium

Strong strength ratio Si particle α-Al matrix









Target: representativity of a macro tensile test in Y dir.

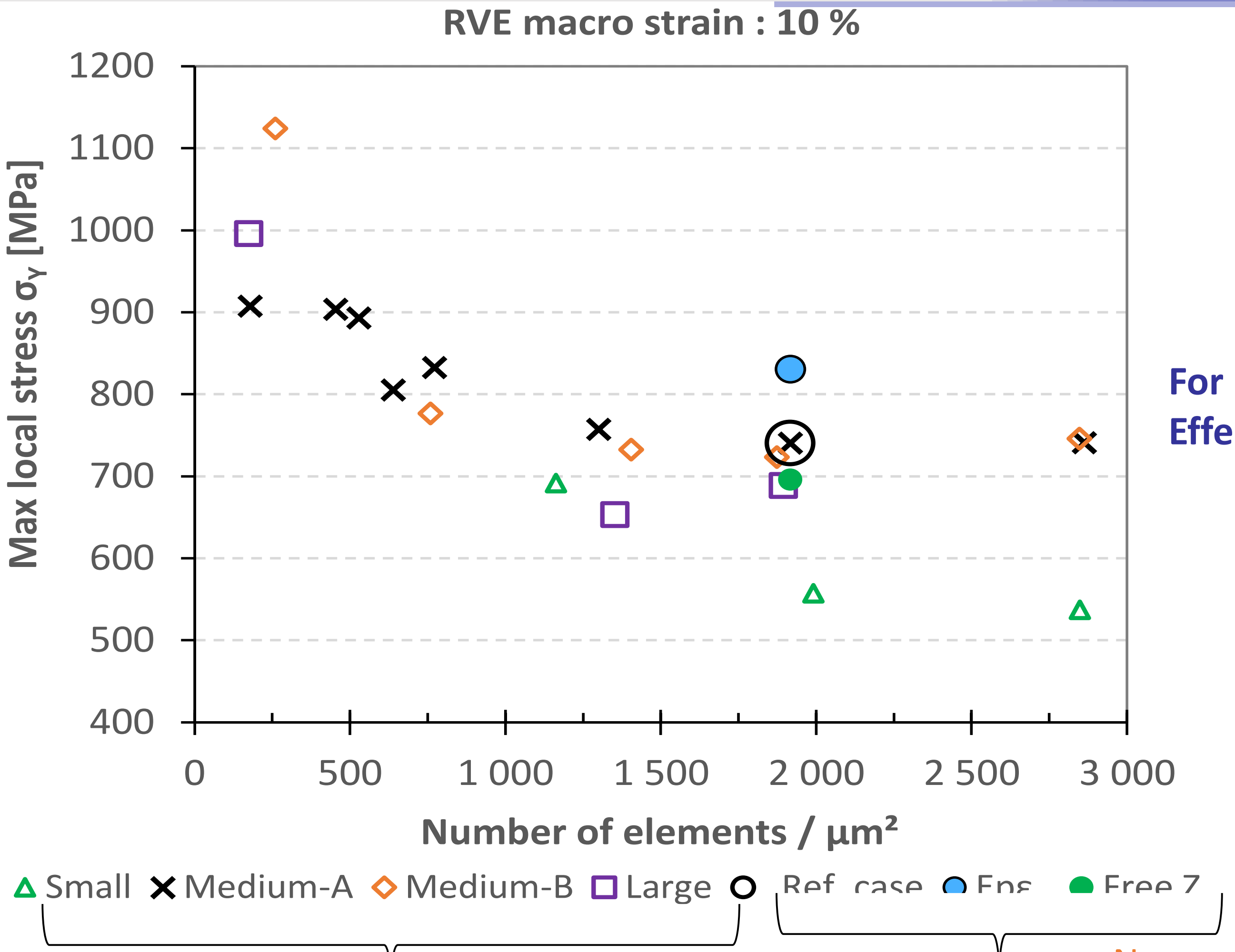
Macro level : $\varepsilon_X \approx \varepsilon_Z$ isotropic material

Local level: strength in z dir
Identical for all particles
Interface: Cohesive elements

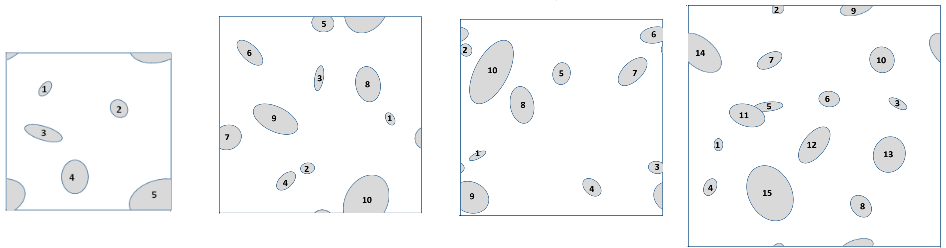
Bouffioux et al. ESAFORM 2022

Representative Volume Element RVE

With periodic boundary conditions



For Medium-A RVE
Effect of boundary condition

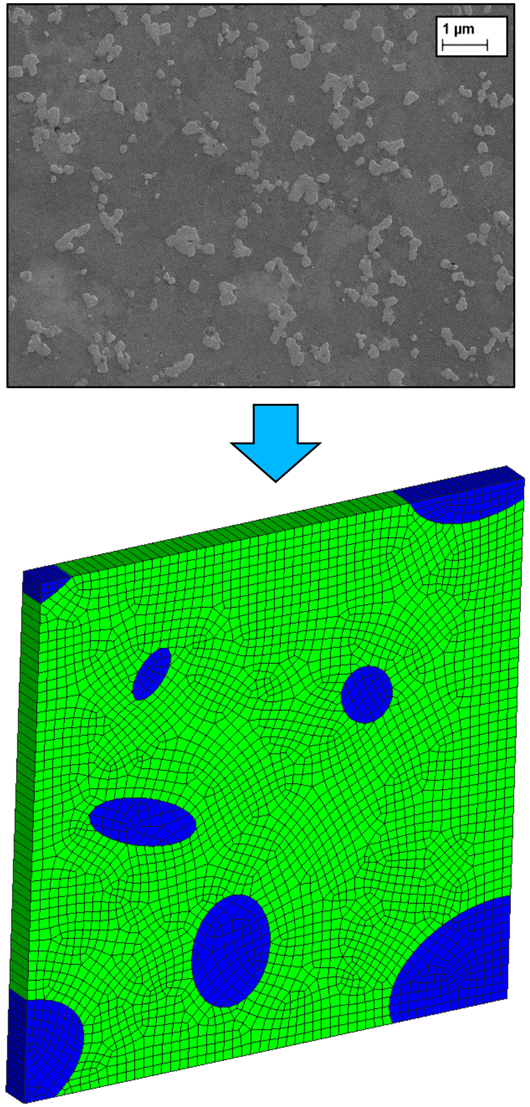


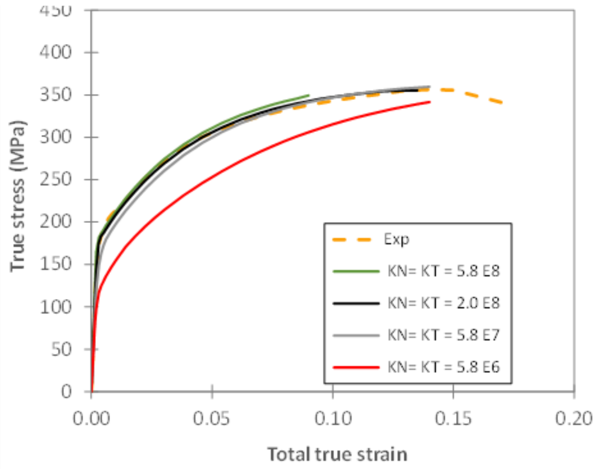
2.5D

Plane strain

No macro stress however effect of strength heterogeneity (3D law 1 element layer mesh)

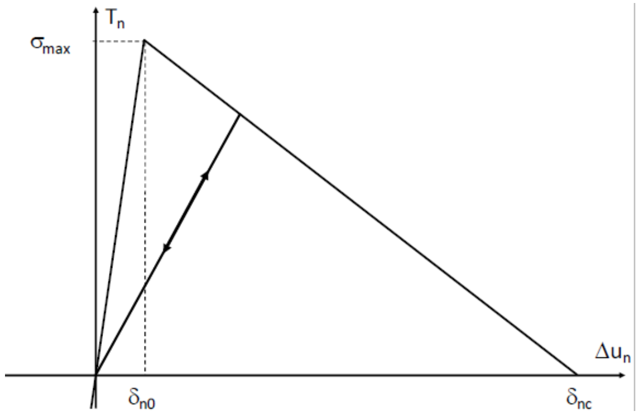
Small RVE Application with cohesive element

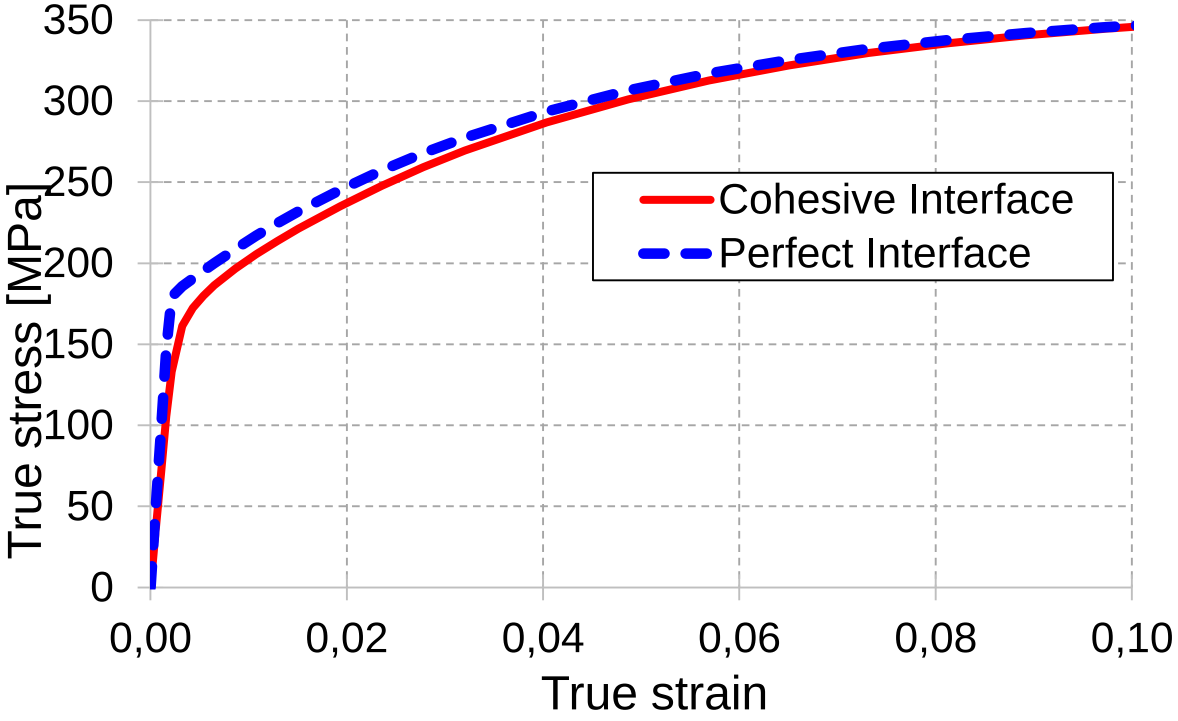




σ_{max}	δ_{n0}	δ_{nc}	τ_{max}	δ_{t0}	δ_{tc}
550	5.5E-6	6E-6	550.	5.5E-6	6E-6

KN= σ_{max} / δ_{N0} et KT= τ_{max} / δ_{T0}

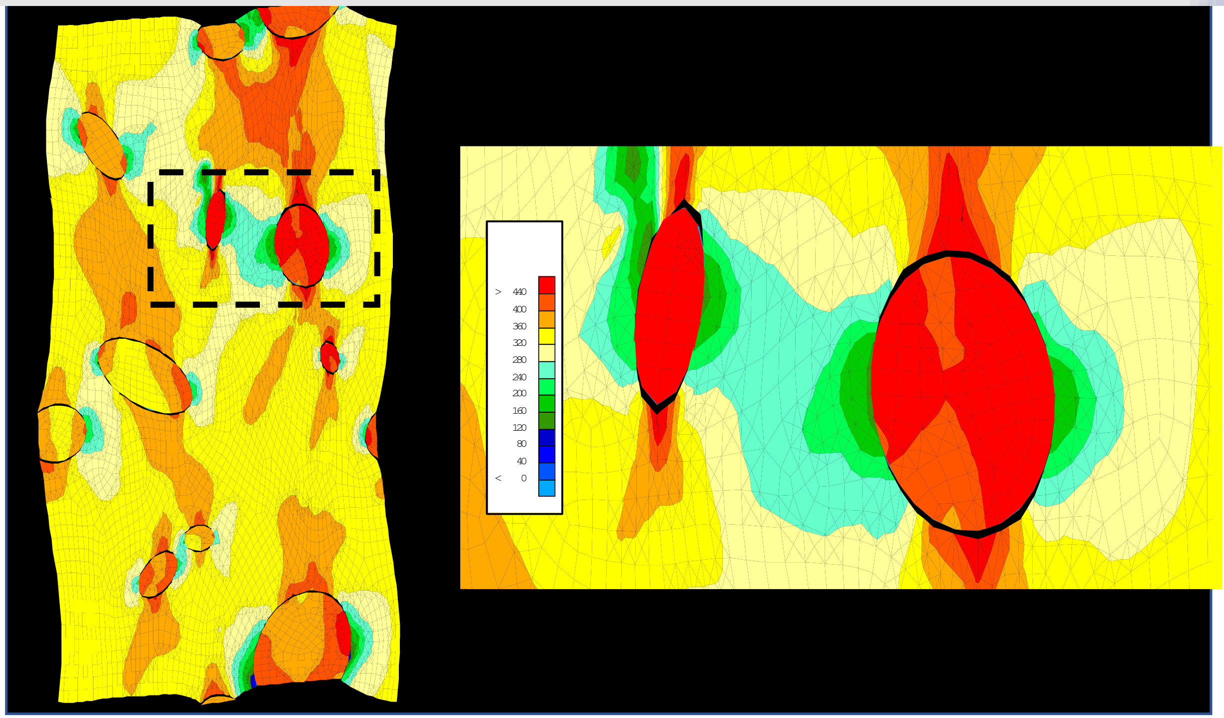


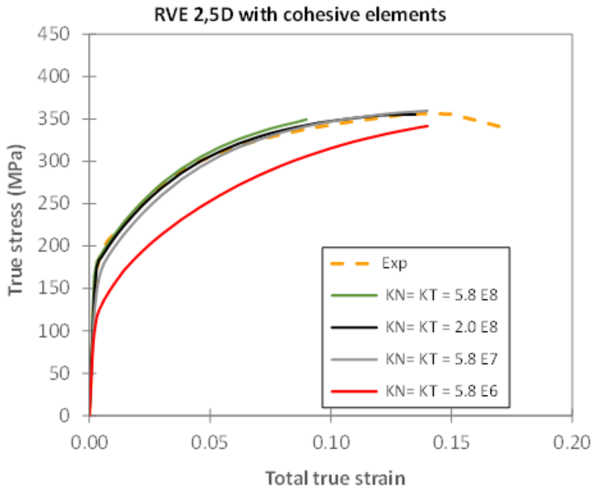


RVE Application – with cohesive element

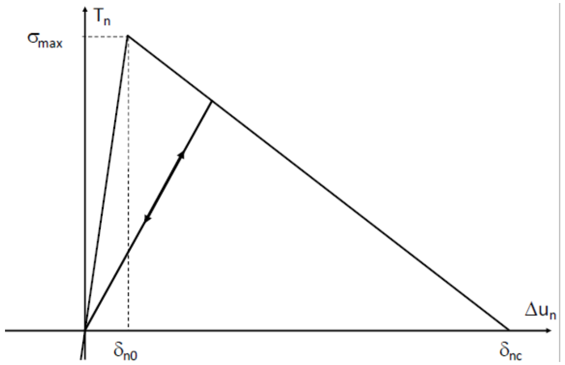
2.5D RVE (10 Si particles)
with in plane : periodic boundary conditions

2.5D behavior
// 3D RVE field





KN= σ_{max} / δ_{N0} et KT= τ_{max} / δ_{T0}



σ_{YY} stress in tensile direction [MPa] - a macro strain of 10 %. Displacement multiplied by 10 to enhance decohesion.

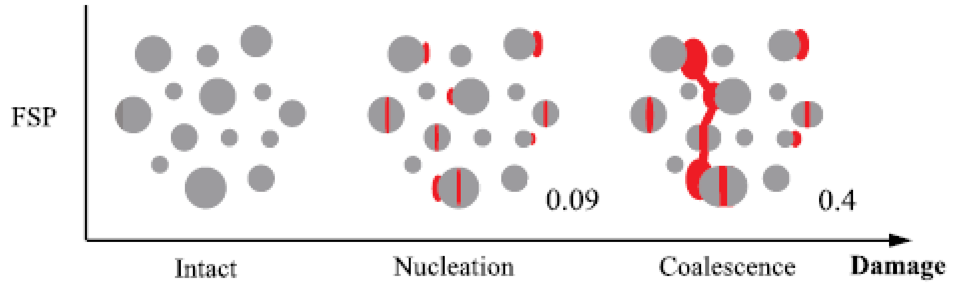
Cohesive element offers tensile and shear rupture

Indentified set of parameters

(same strength in tensile and shear) predicts tensile cracks happen first

Representative Volume Element RVE // Exp

Experiment analysis and RVE simulations gave the same rupture mechanism



Zhao et al. MSEA 2019

AlSi10MG processed by LPBF + FSP
Laser Powder Bed Fusion +
Friction Stir Processing

FSP – LPBF Al Si10Mg RVE → Fatigue ?

- Initial intention: fatigue Lemaitre & Chaboche parameters to α phase damage parameters in our cohesive law identified through cyclic tests on uniaxial and notched samples

→ to predict Wöhler curves with close but different microstructures, different notches…

→ use 2.5D RVE to be able to do multi-scale simulations FE^2 to compute different part behaviour

- Today : energy dedicated to generate sound large FSP samples more focused on understanding process upscaling…..

Contents

Conclusions - Perspectives

- Damage models can provide quantitative information but still requires **experimental campaigns** for reliable application:
- Remind in civil engineering **scaling factors** about damage parameters
- At smaller scale accurate identification of an RVE can take different approaches → **cross your experiences → multiply the validations**

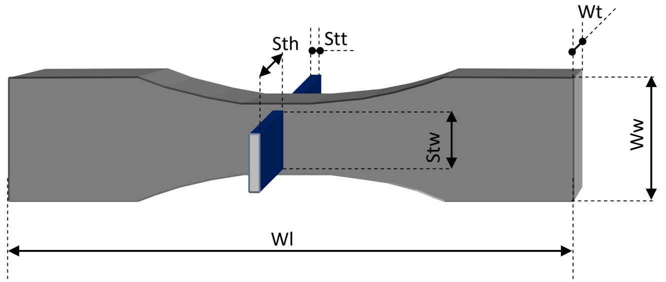
- Is RVE prediction correct for Baushinger effect?
- Is a coupled damage model essential or decoupled is OK ?
- Is my length scale = a tuning parameter or guided by microscopic approach?

for your attention

anne.habraken@uliege.be

WP 2: Fatigue study – Tests on small case specimen

			Web		Stiffeners			
Case	Test	Post treat.	Wt	Wm	Stt	Stw	Sth	
			Thick	Red. width	Thick	Length	Height	Effect
A	Fatigue	PIT	25	135	15	60	40	Ref. case, thick 25 mm, stiff 15 mm, welded, HFMI, edge distance. Effect of stress ratio
B	Fatigue	PIT	15	105	15	60	40	Smaller plate thickness // A
C	Fatigue	TIG	15	105	15	60	40	TIG remelting effect // B (PIT) on plate 15 mm
D	Fatigue	TIG	25	135	15	60	40	TIG rem. effect // A (PIT) on plate 25 mm
E	Fatigue	PIT	25	60	15	60	40	No distance to edges // A
F	Fatigue	TIG	25	115	15	40	40	TIG rem., decrease of the stiffeners length // D (TIG)
G	Fatigue	TIG	15	105	6	60	40	TIG rem., decrease of the stiffeners thickness // C (TIG)
H	Fatigue	PIT	40	60	15	60	40	Increase of the plate thickness // E
I	Fatigue	No	15	105	15	60	40	Fatigue behaviour of welding without post treatment
K (=A)	Static	PIT	25	135	15	60	40	To validate the simulation and the characterisation
L (=B)	Static	PIT	15	105	15	60	40	To validate the sensitivity to the sample sizes
BM	Fatigue		25	135				To study the fatigue behaviour on the base material alone



Effect of:

- plate thickness
- distance stiffener - edge
- stiffener length & thickness
- stress ratio
- post-treatment (PIT / TIG rem. / nothing)
- no welding, no post-treatment

+ static tests for characterisation validation

UCLouvain

Yield stress calculation

Alloys
- AlSi10Mg
- AlMg

- Hall-Petch's law

$$\sigma_{gb} = \sigma_{Al} = \sigma_0 + \frac{k}{\sqrt{d}}$$

➢ NaMo model $\sigma_y = \sigma_0 + \sigma_{disl} + \sigma_{sol} + \sigma_{bp}$

➢ Quadratic model

$$\sigma_y = \sigma_0 + \sigma_{gb} + \sigma_{sol} + \sqrt{\sigma_{sh}^2 + \sigma_{bp}^2 + \sigma_{disl}^2}$$

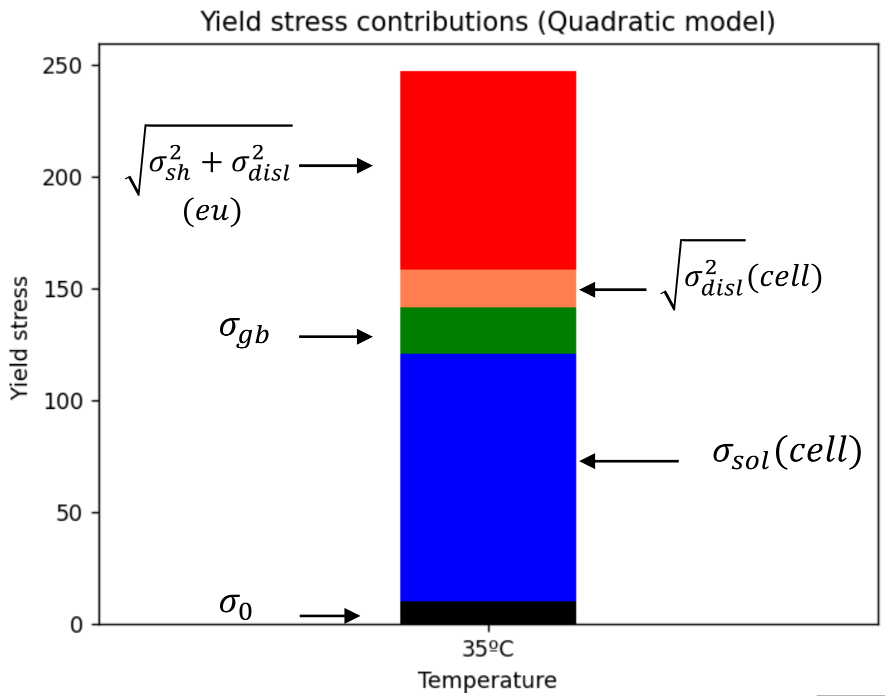
$$\sigma_{disl} = M\alpha Gb\sqrt{\rho}$$

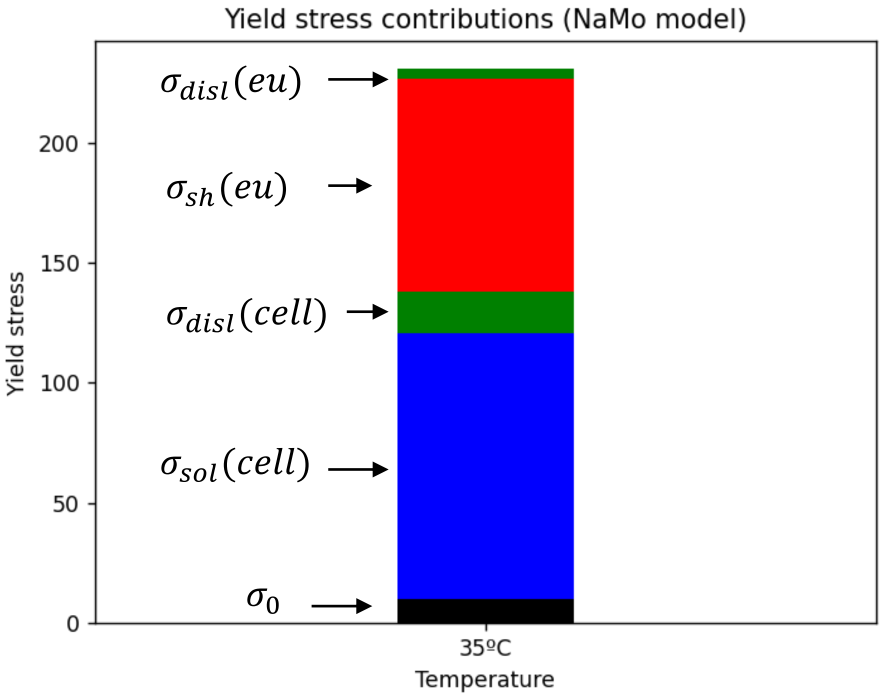
b → Burger's vector
G → shear modulus
α → geometric constant close to 0.5
M → Taylor factor

$$\sigma_{sol}(T) = M \cdot \tau_{y0} \cdot exp\left(-\frac{1}{0.55}\frac{k_B T}{\Delta E_b}\ln\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right)$$

M → Taylor factor
k_B → Boltzmann constant
$\dot{\varepsilon}_0$ → Reference strain rate
$\dot{\varepsilon}$ → Nominal strain rate
τ_{y0} → Zero-temperature stress
ΔE_b → The energy barrier.

Results (sample 35°C)





σ_0 : Pure aluminium yield strength
σ_{disl} : Dislocations contribution
σ_{sol} : Solid solution contribution
σ_{gb} : Grain boundaries contribution
σ_{sh} : Sheared precipitates contribution
σ_{bp} : By-passed precipitates contribution

Comparison of results:

Yield stress calculation		
Experimental	NaMo model	Quadratic model
$244 \pm 12\ [MPa]$	$231.0\ [MPa]$	$252.3\ [MPa]$