THE NORTHERNMOST UNIVERSITY
of Technology in Scandinavia

3D-analysis of compaction in granular materials

X-ray microtomography and digital volume correlation combined with modelling

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Introduction / Motivation…

Increase fundamental knowledge regarding interaction processes during compaction of granular materials

Examples of applications:

- Powder metallurgy
- Ceramic forming
- Pharmaceuticals
- Explosives

Introduction / Motivation

Suitable compaction laws are required:

General:
•A homogeneous bed is usually desired. Regions of large relative motion (usually shear bands) will affect the mechanical integrity of the finished product.

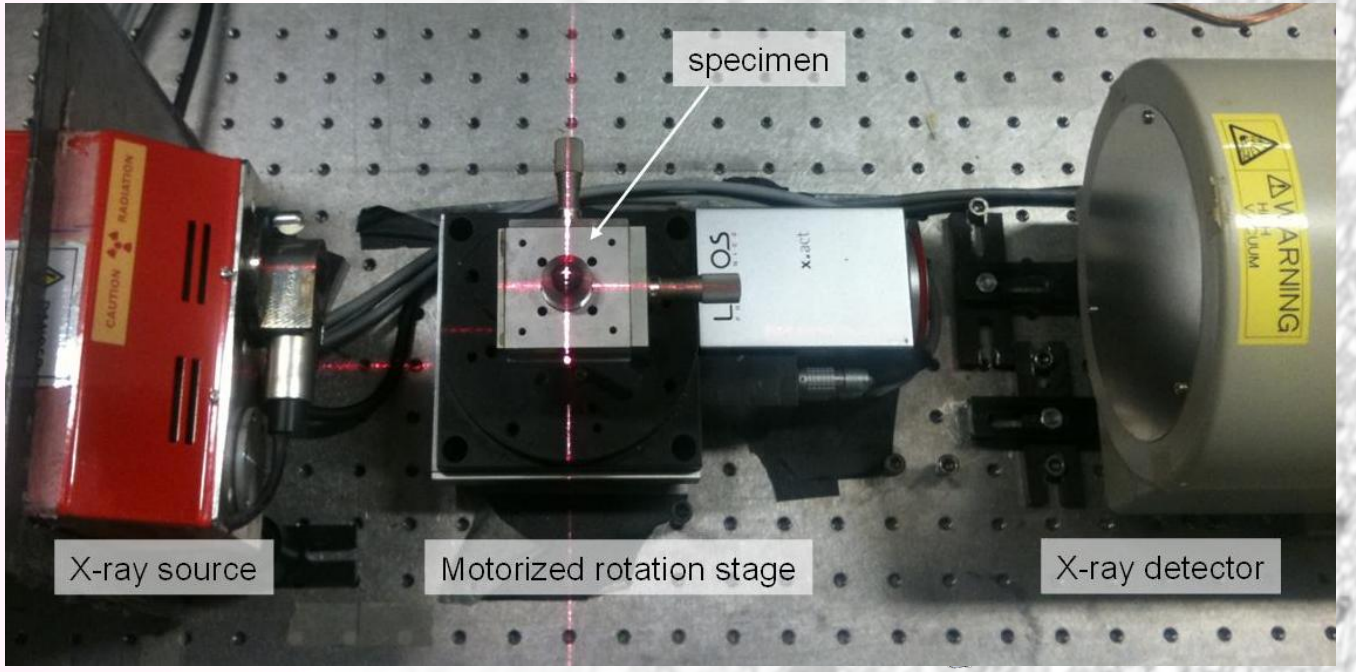
Pharmaceuticals:
•A homogeneous bed gives a better controlled concentration, solubility and absorption of the various substances.

Explosives safety:
•Shear bands act to dissipate mechanical work as heat in a localized region, which may have important (and fatal) consequences when dealing with explosives.

Brief description of experimental techniques and methods…

- X-ray microtomography (XMT)
  (Micro Computed Tomography, microCT)
- Digital Volume Correlation (DVC)

X-ray microtomography (XMT)

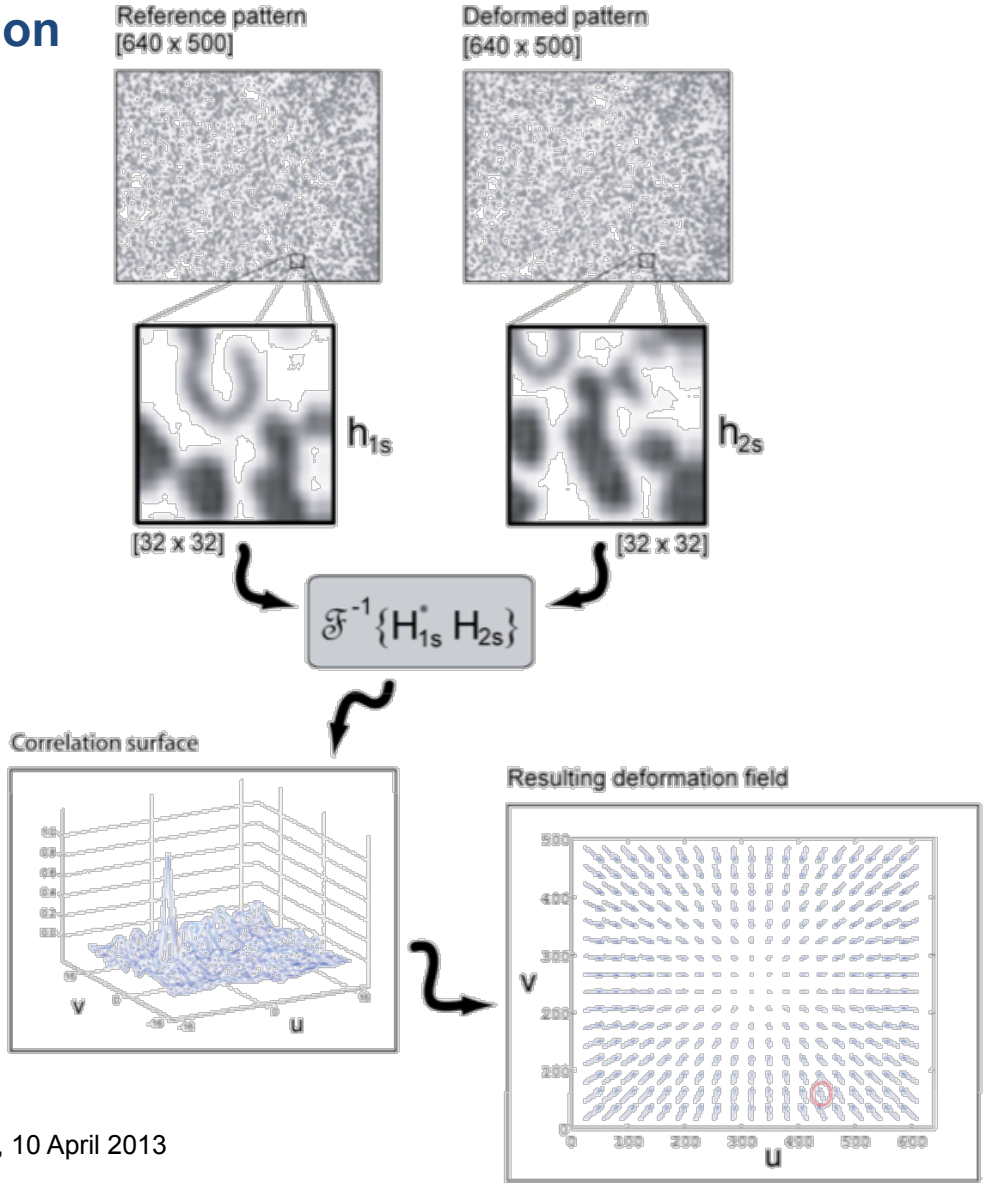


- **3D imaging** of microstructure, based on density
- **Non-destructive**, allows repeated imaging of the same sample

Digital Volume Correlation

Digital Volume Correlation

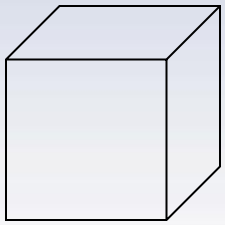
The principle / DIC



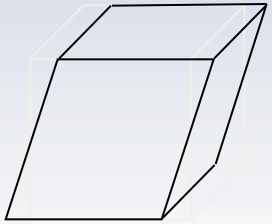
Digital Volume Correlation

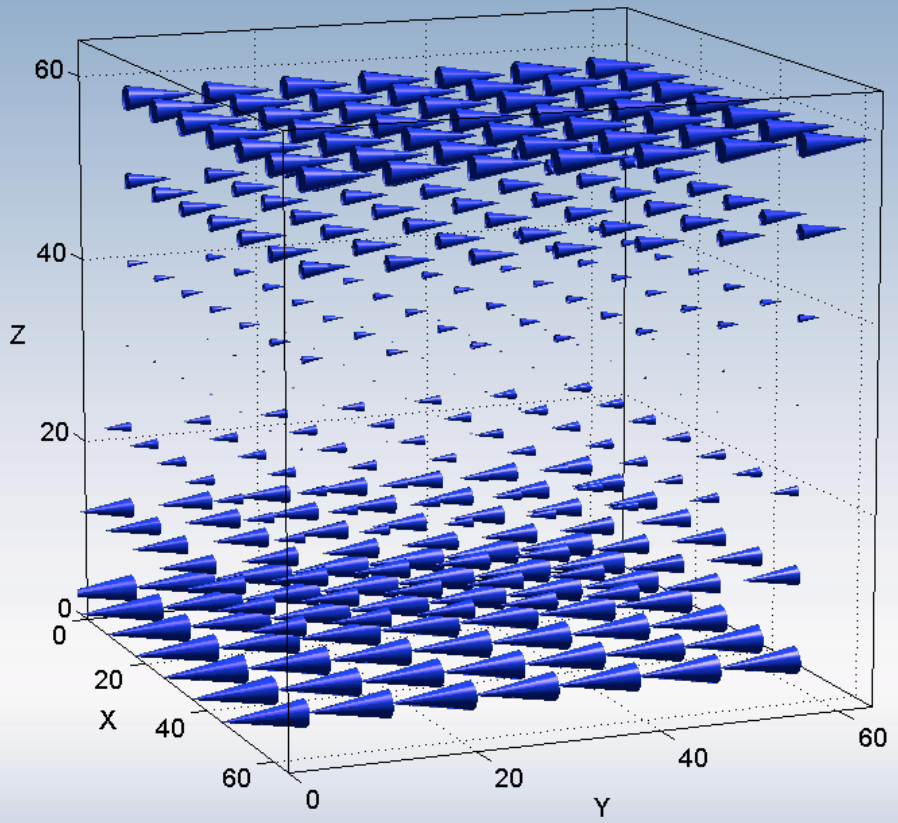
The principle

Reference volume



Deformed volume





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3D analysis of compaction in granular sugar

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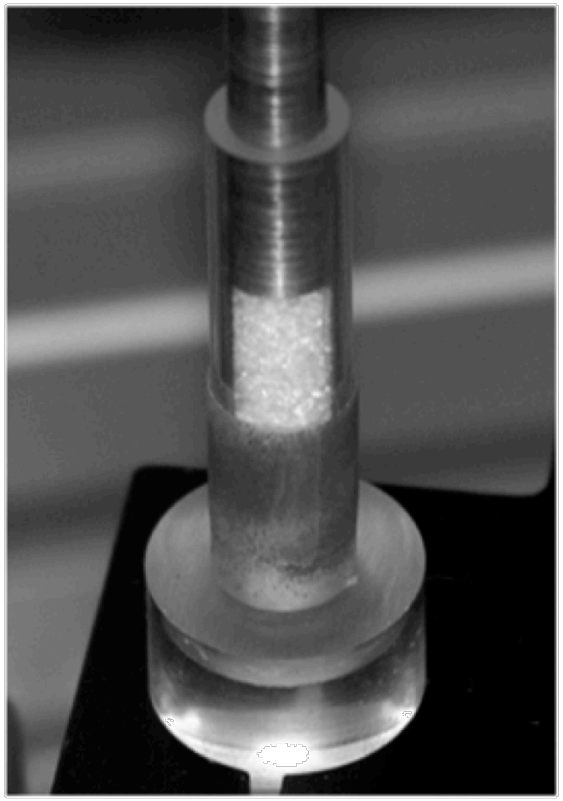
…first of all, why use sugar?

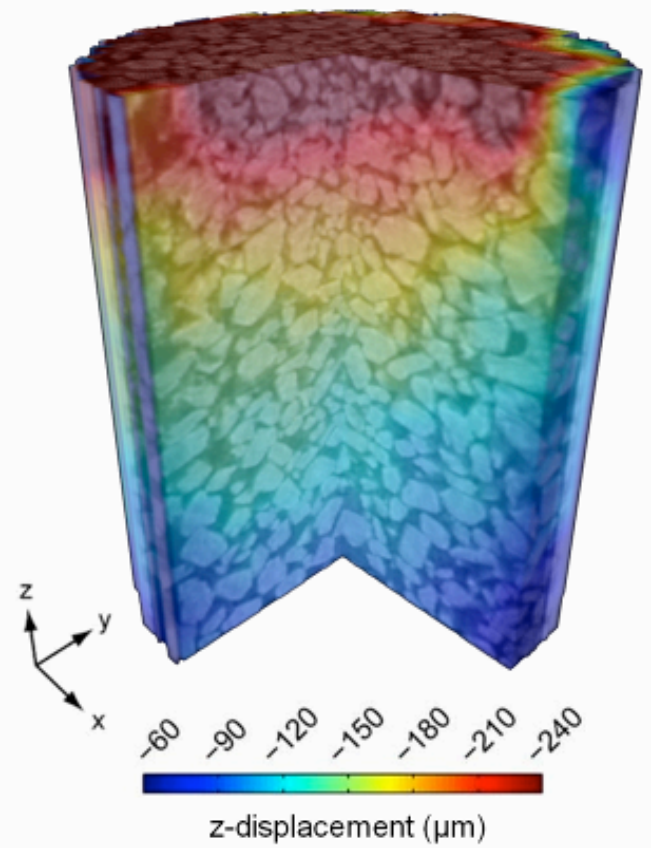
Granular sugar is commonly used as a simulant of explosive crystals in mechanical experiments.

It is safe to use and easy to access.

Granular compaction

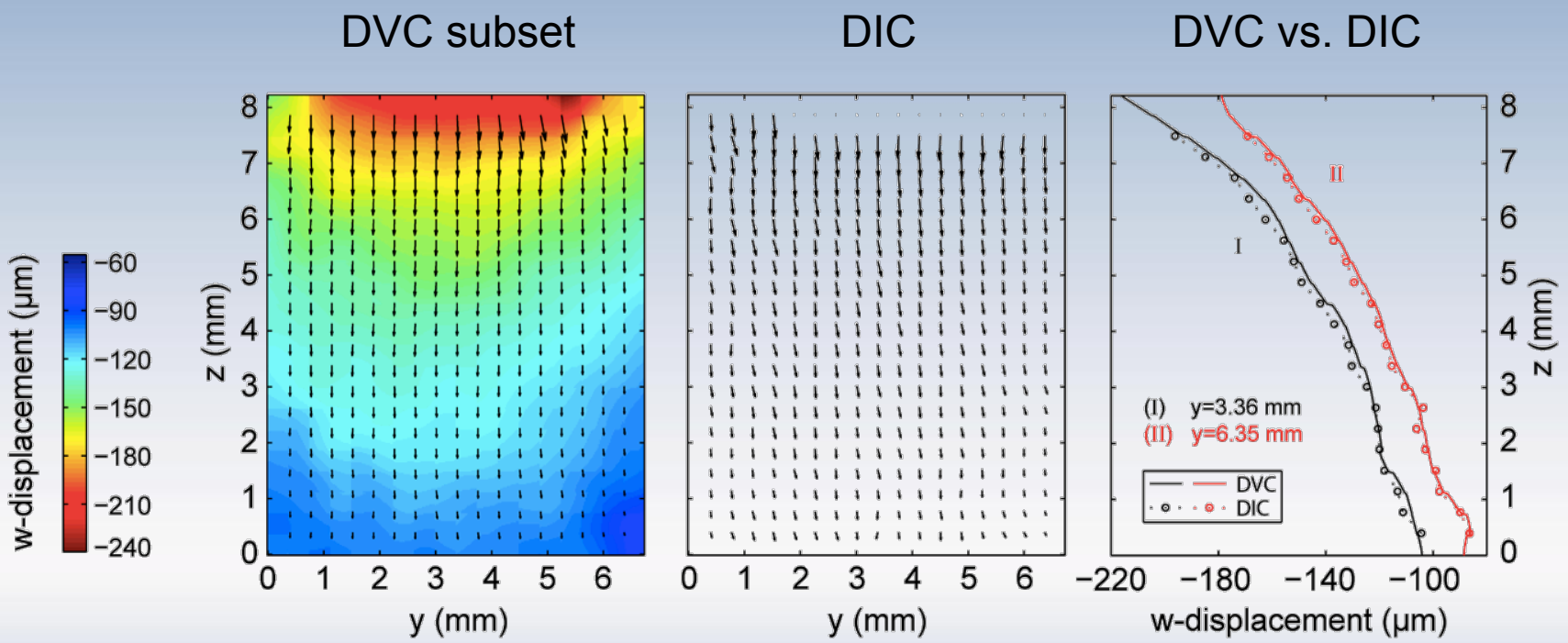
Previous study.





Granular compaction

Previous study. Comparison DVC and DIC

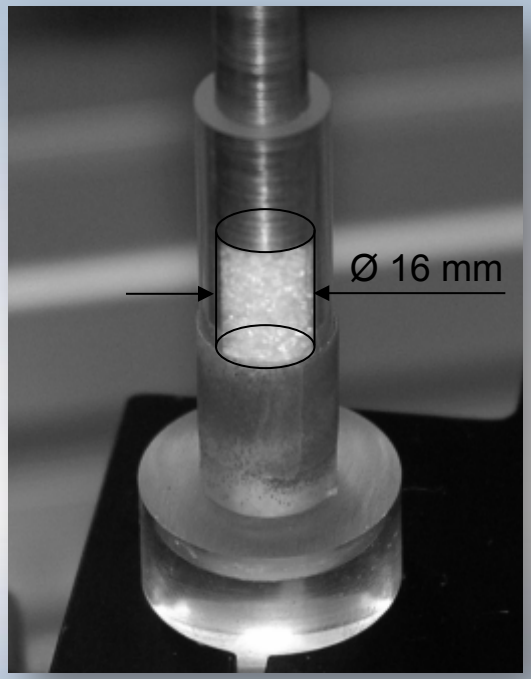


The current study…

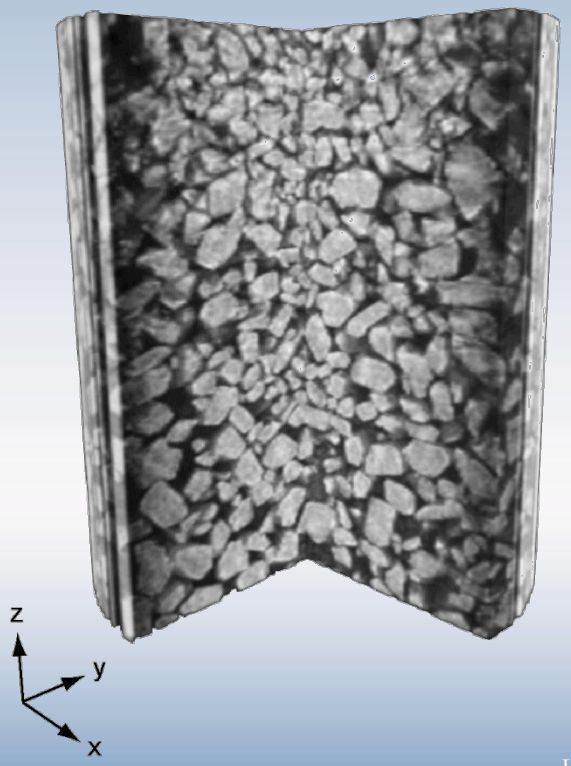
Granular compaction

The sample

A bed of granular sugar encapsulated in a hollow Perspex cylinder with inner diameter 16 mm. The initial height is 17 mm.



Reconstructed sugar structure

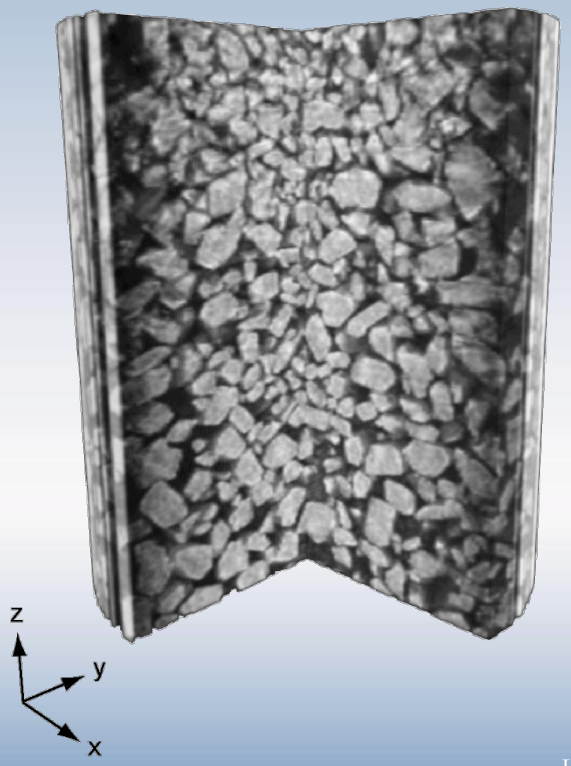


Granular compaction

The sample

The particle size of the sugar crystals range from 0.1 to1.0 mm, with mean at 0.5 mm.

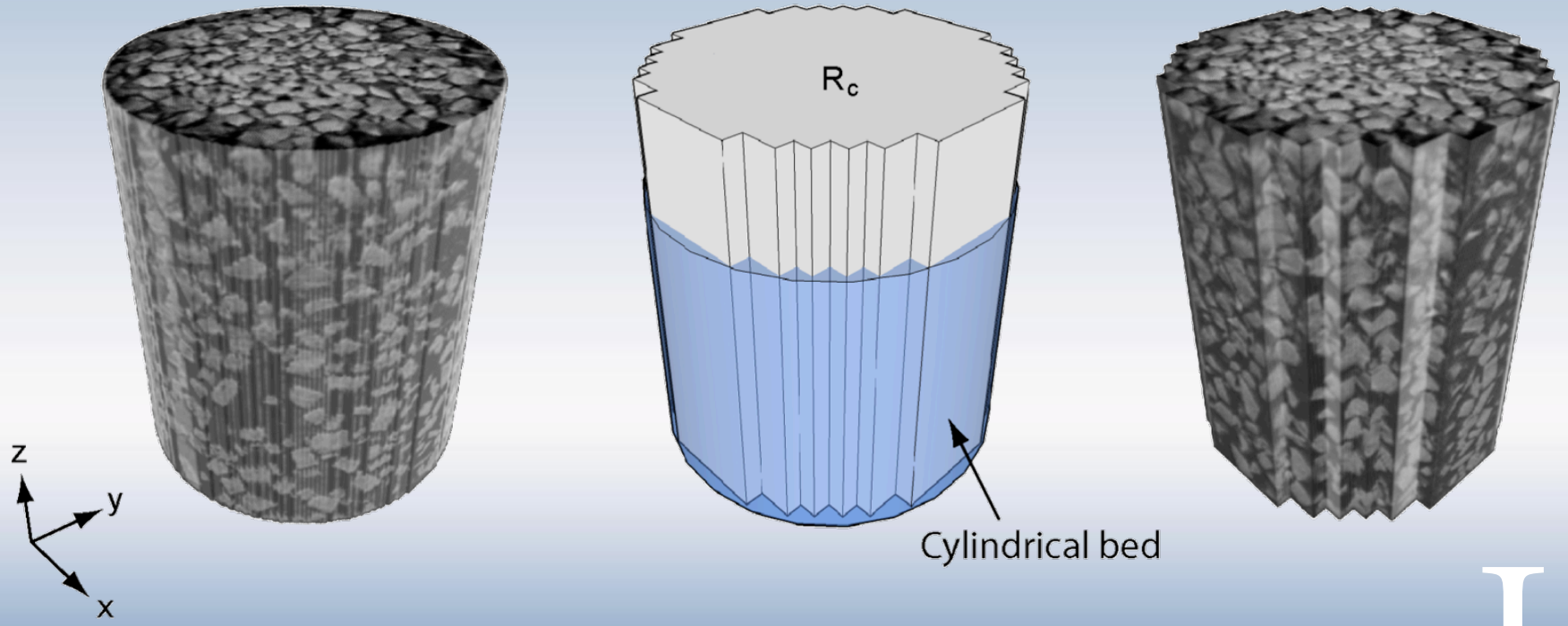
Reconstructed sugar structure



Granular compaction

The sample

Correlation analysis is carried out in region R_c with dimensions 14.7 x 14.7 x 15.9 mm^3 (384 x 384 x 416 voxels).



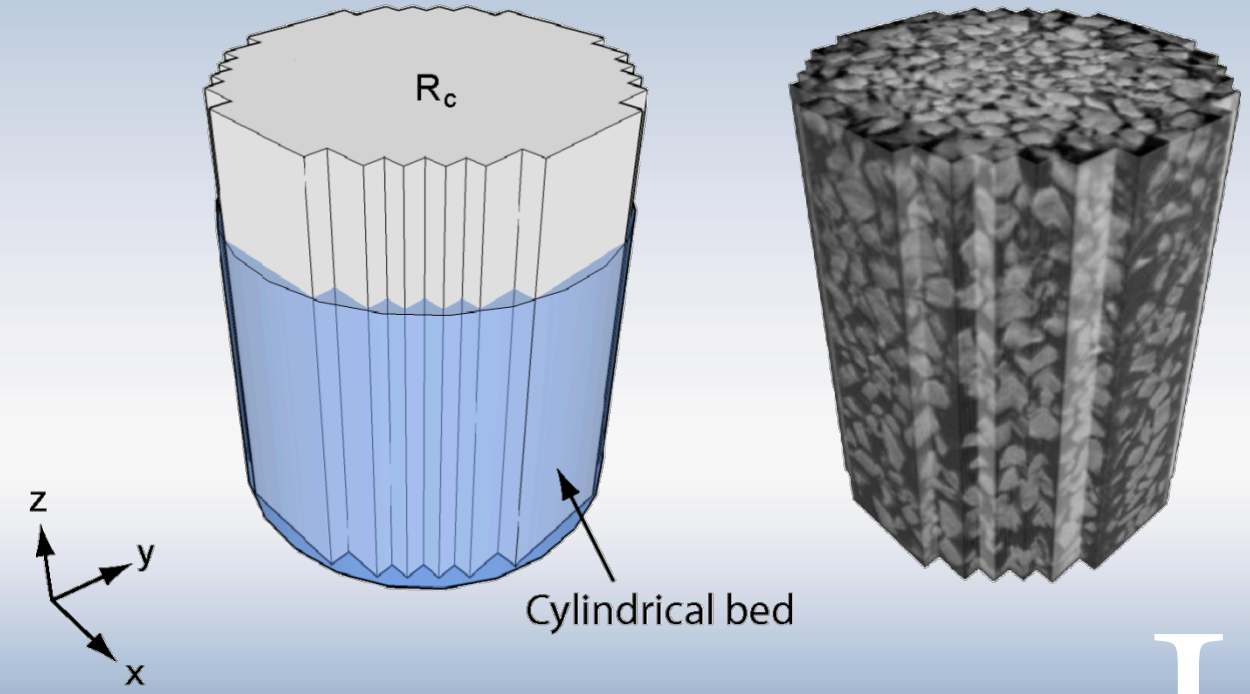
Granular compaction

The sample

Correlation analysis is carried out in region R_c with dimensions 14.7 x 14.7 x 15.9 mm^3 (384 x 384 x 416 voxels).

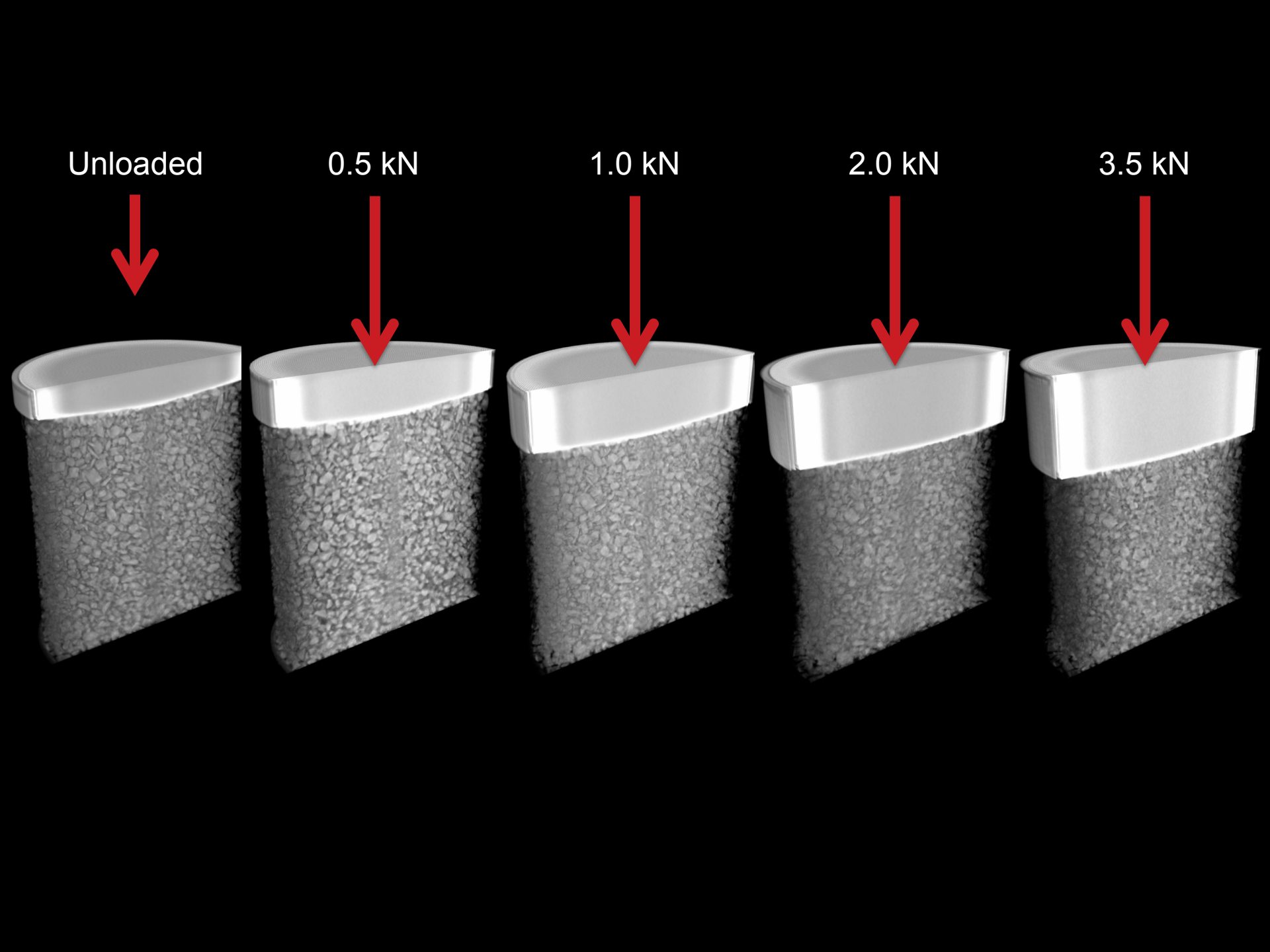
Subvolumes
Size: 64^3 voxels
2.45^3 mm^3

Pitch: 32 pixels
1.22 mm



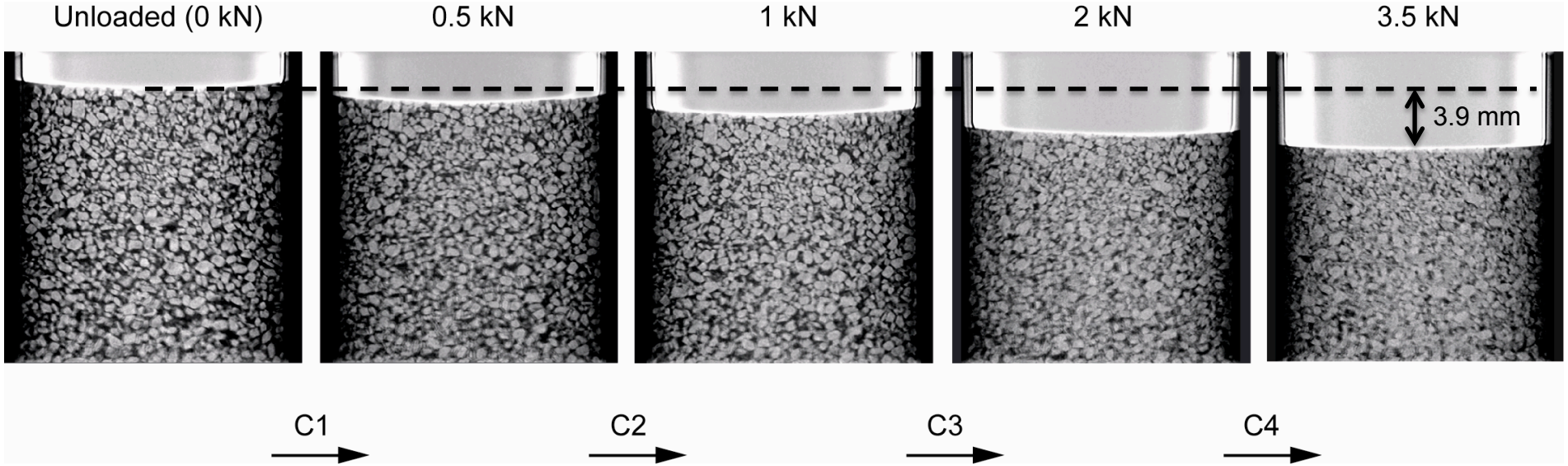
The granular bed was loaded in four steps:

0 ➔ 0.5 ➔ 1.0 ➔ 2.0 ➔ 3.5 kN

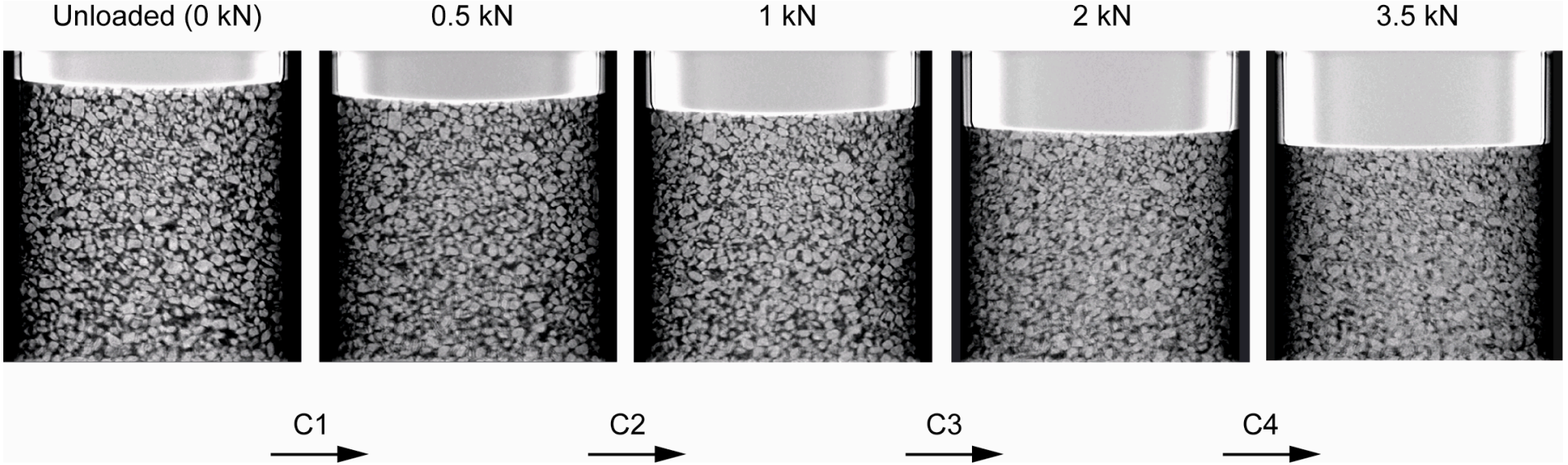

Unloaded
0.5 kN
1.0 kN
2.0 kN
3.5 kN

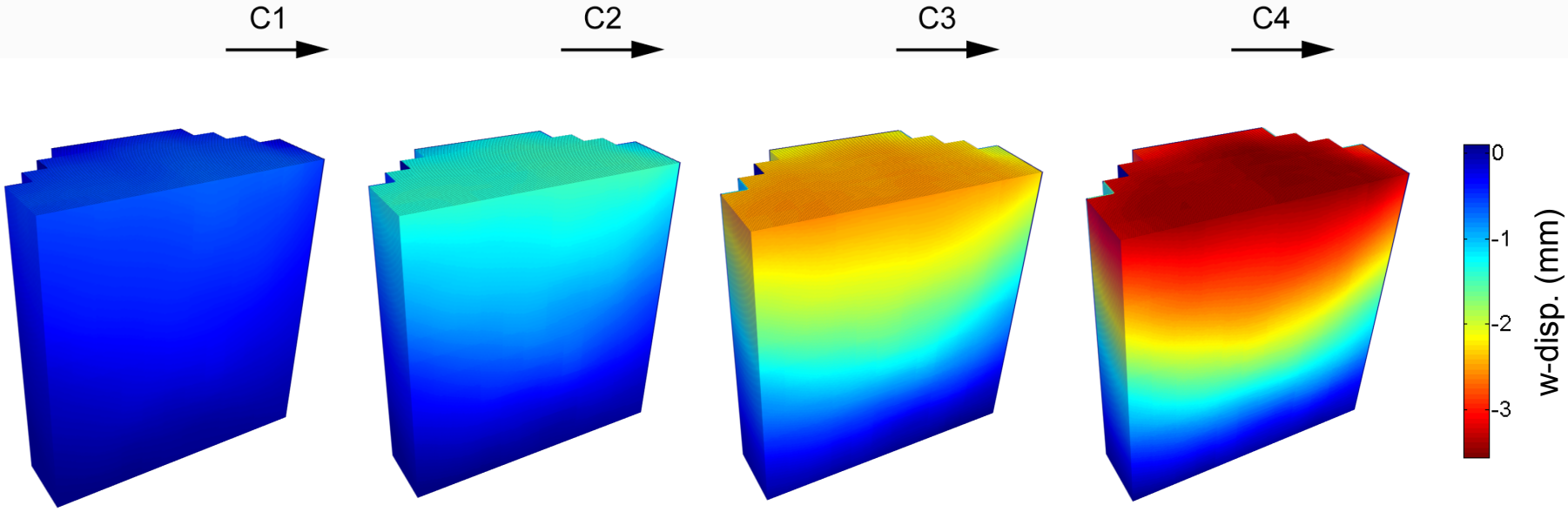
Granular compaction

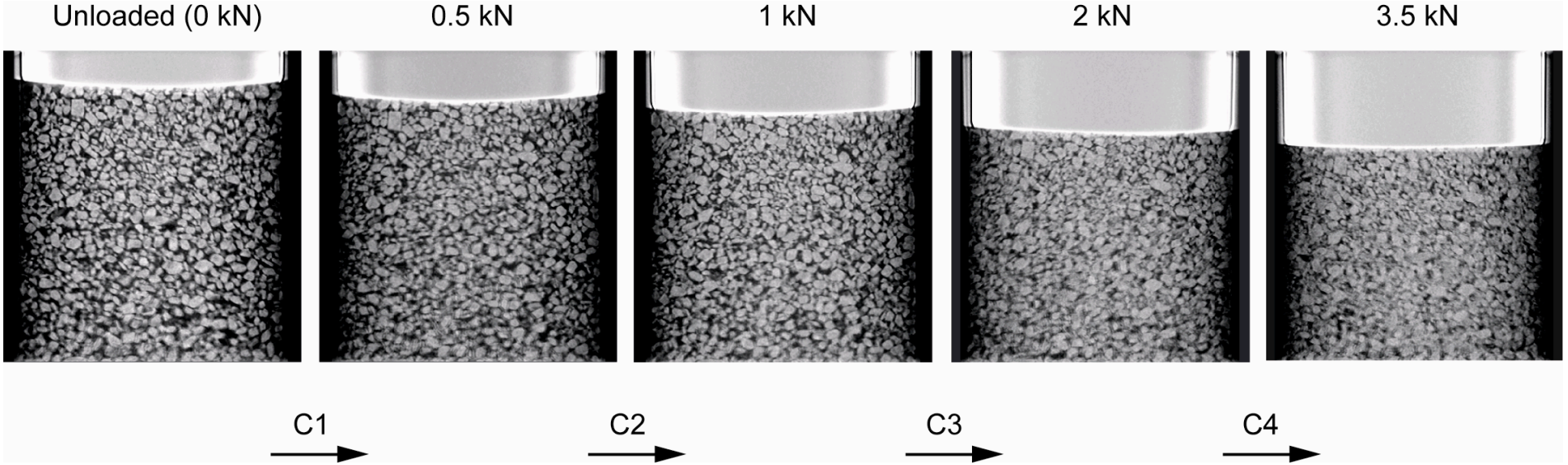
XMT results

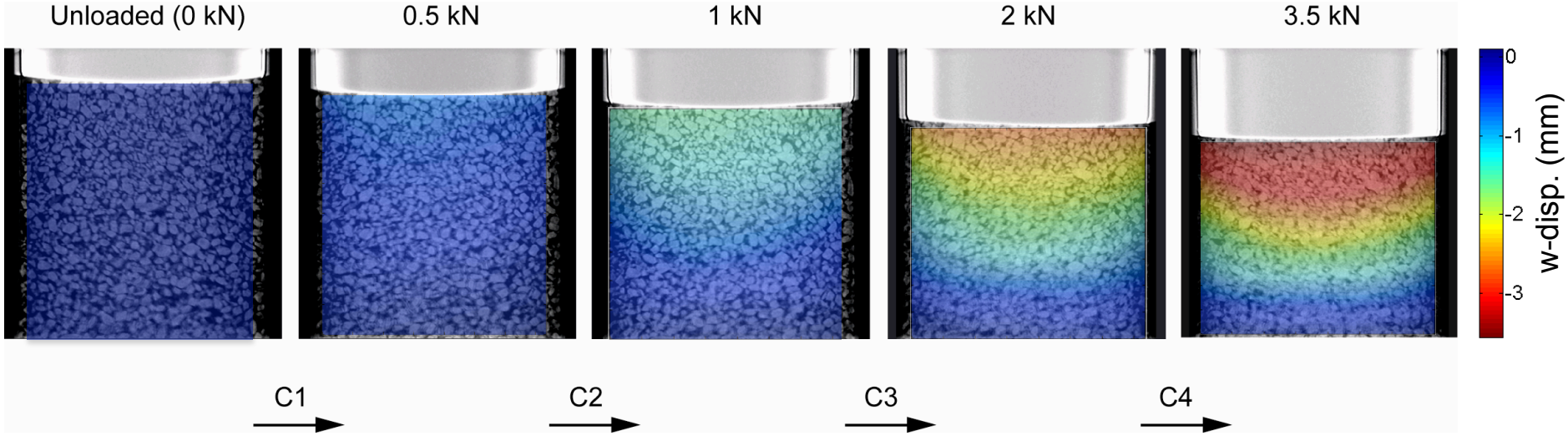


DVC results…

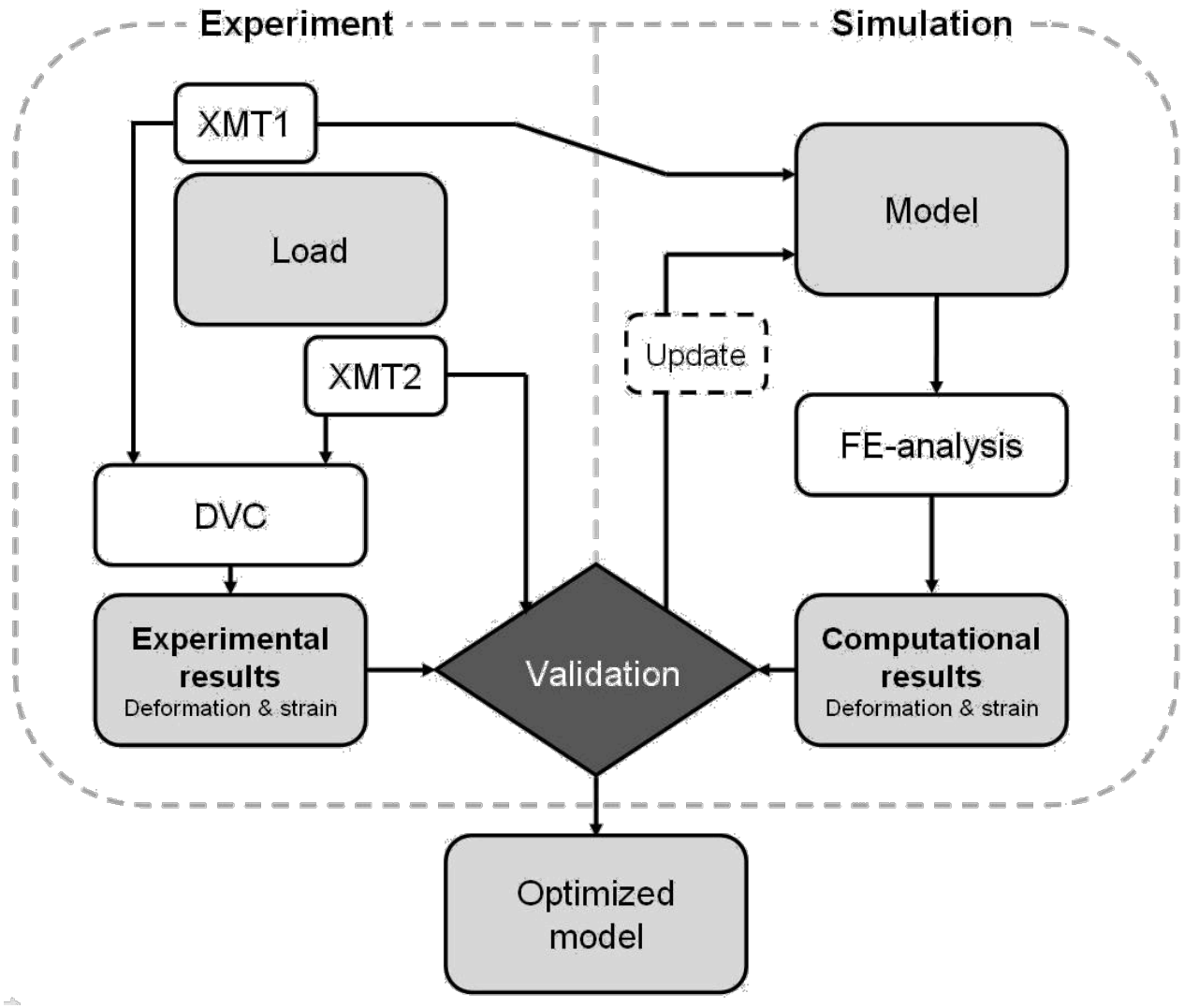

Unloaded (0 kN)
0.5 kN
1 kN
2 kN
3.5 kN


C1
C2
C3
C4
0
-1
-2
-3
w-disp. (mm)


Unloaded (0 kN)
0.5 kN
1 kN
2 kN
3.5 kN
C1
C2
C3
C4
z (mm)
x (mm)
w-disp. (mm)
0
-1
-2
-3


Unloaded (0 kN)
0.5 kN
1 kN
2 kN
3.5 kN
0
-1
-2
-3
w-disp. (mm)
C1
C2
C3
C4

Experiments and modelling…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XMT2
DVC
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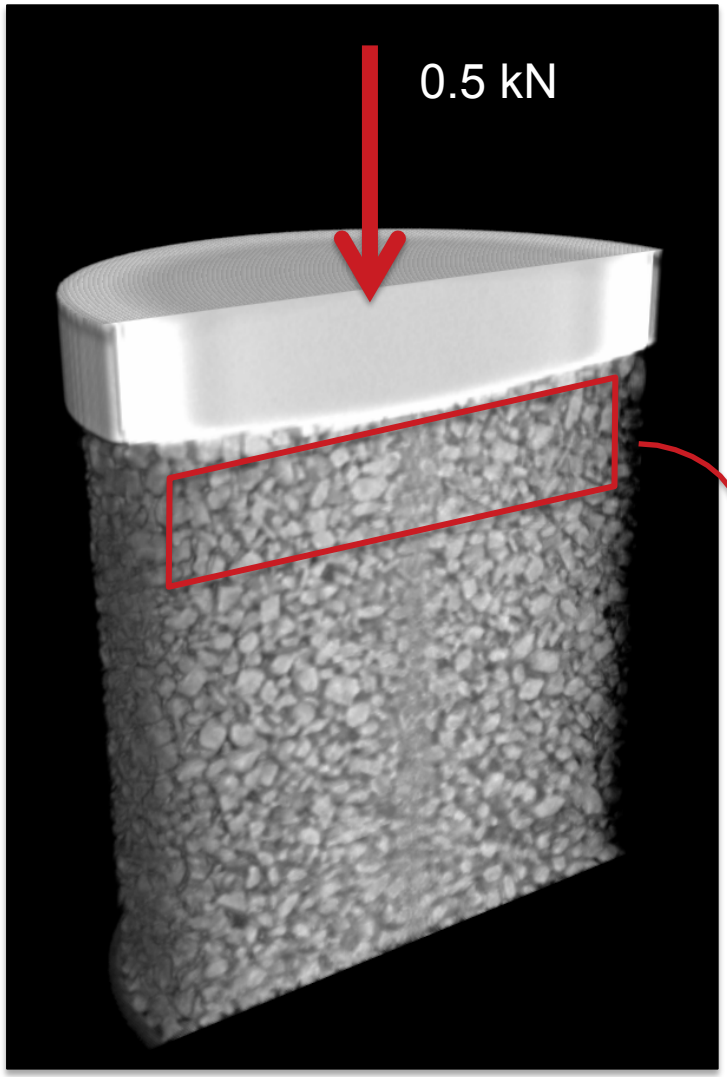
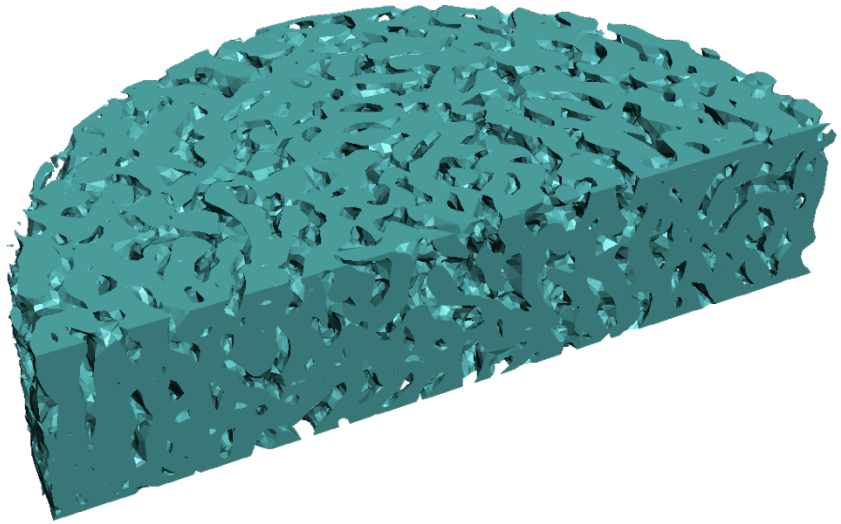
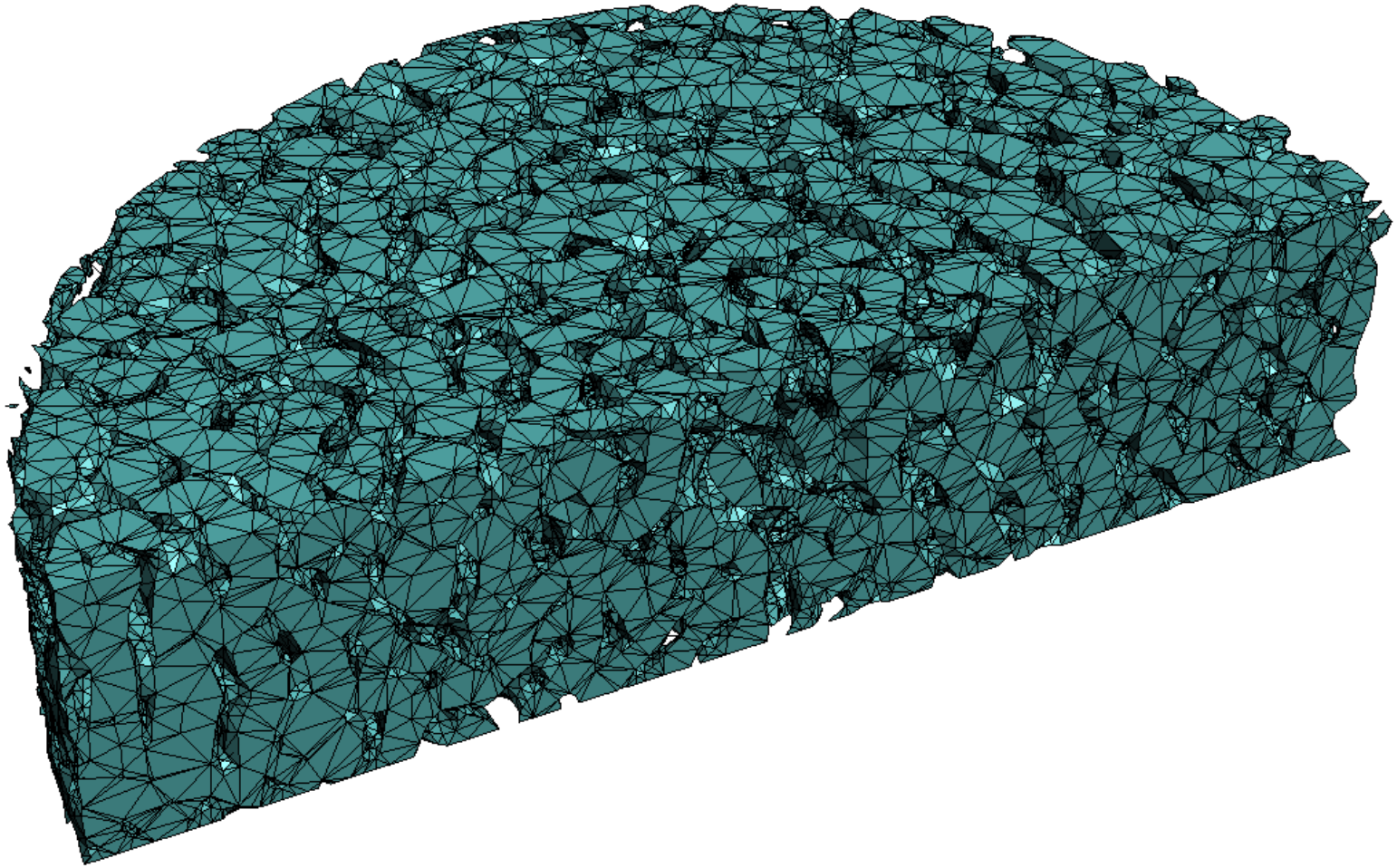
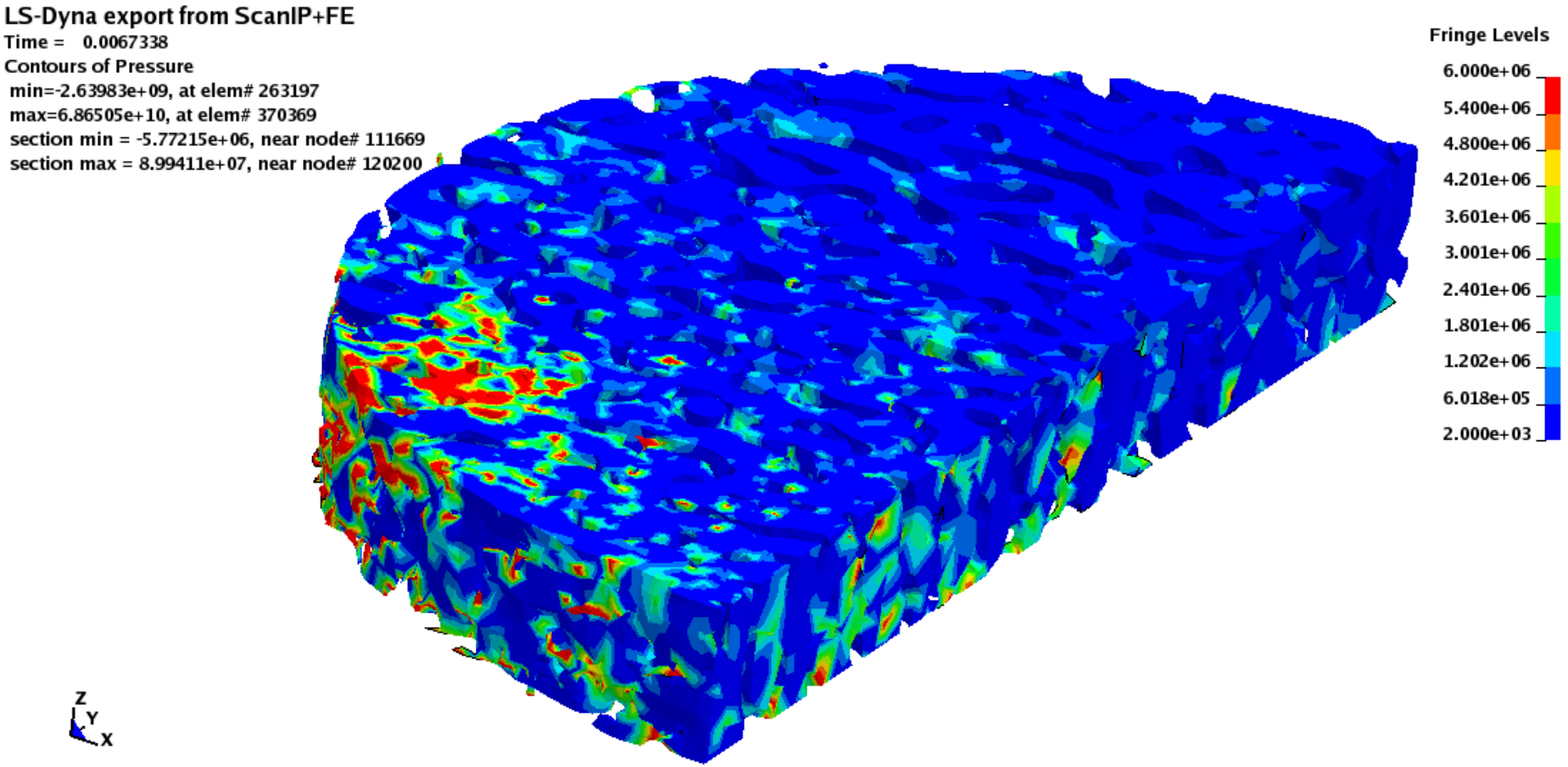
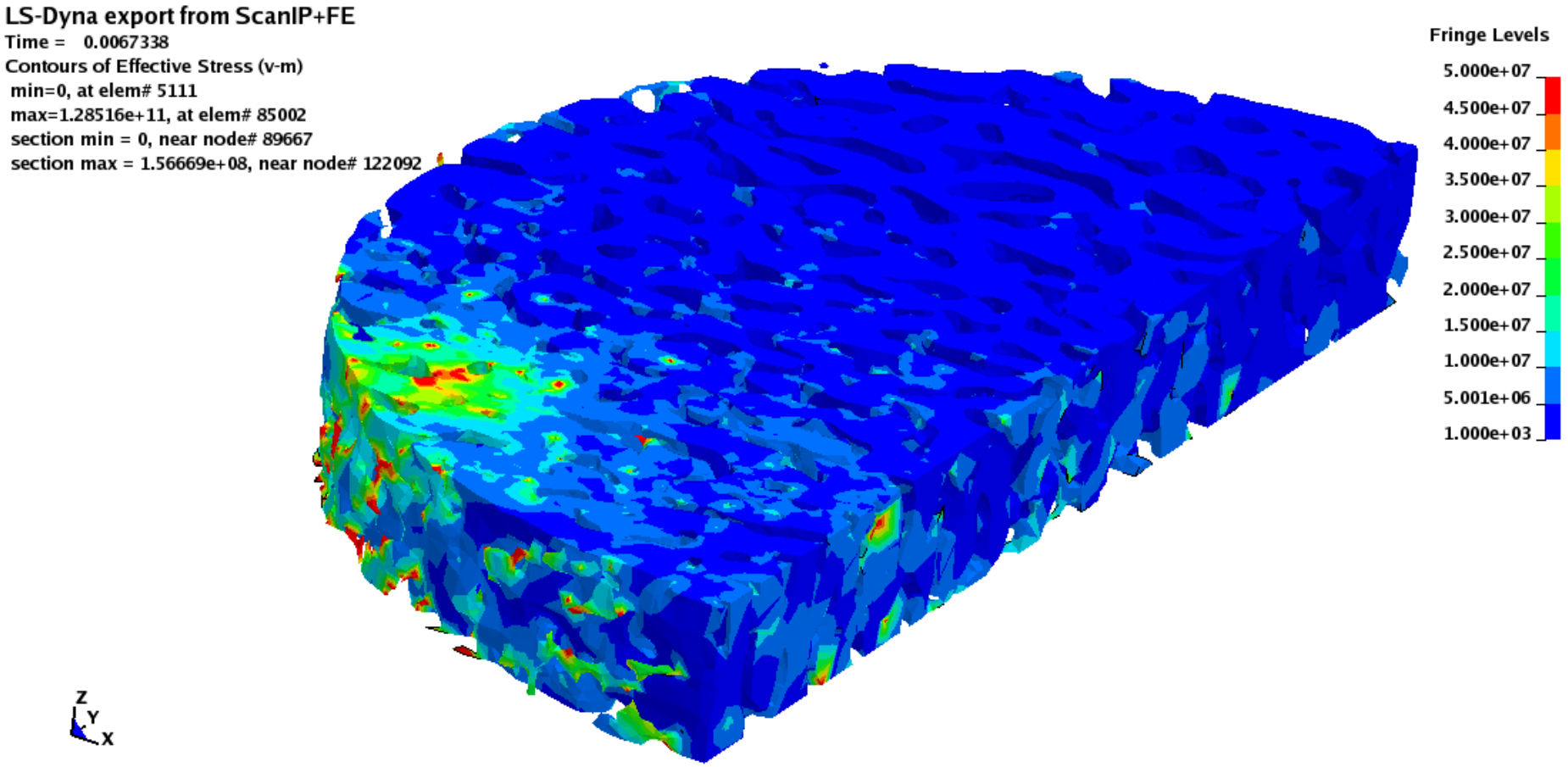
Deformation & strain
Validation
Update
Model
FE-analysis
Computational results
Deformation & strain
Optimized model

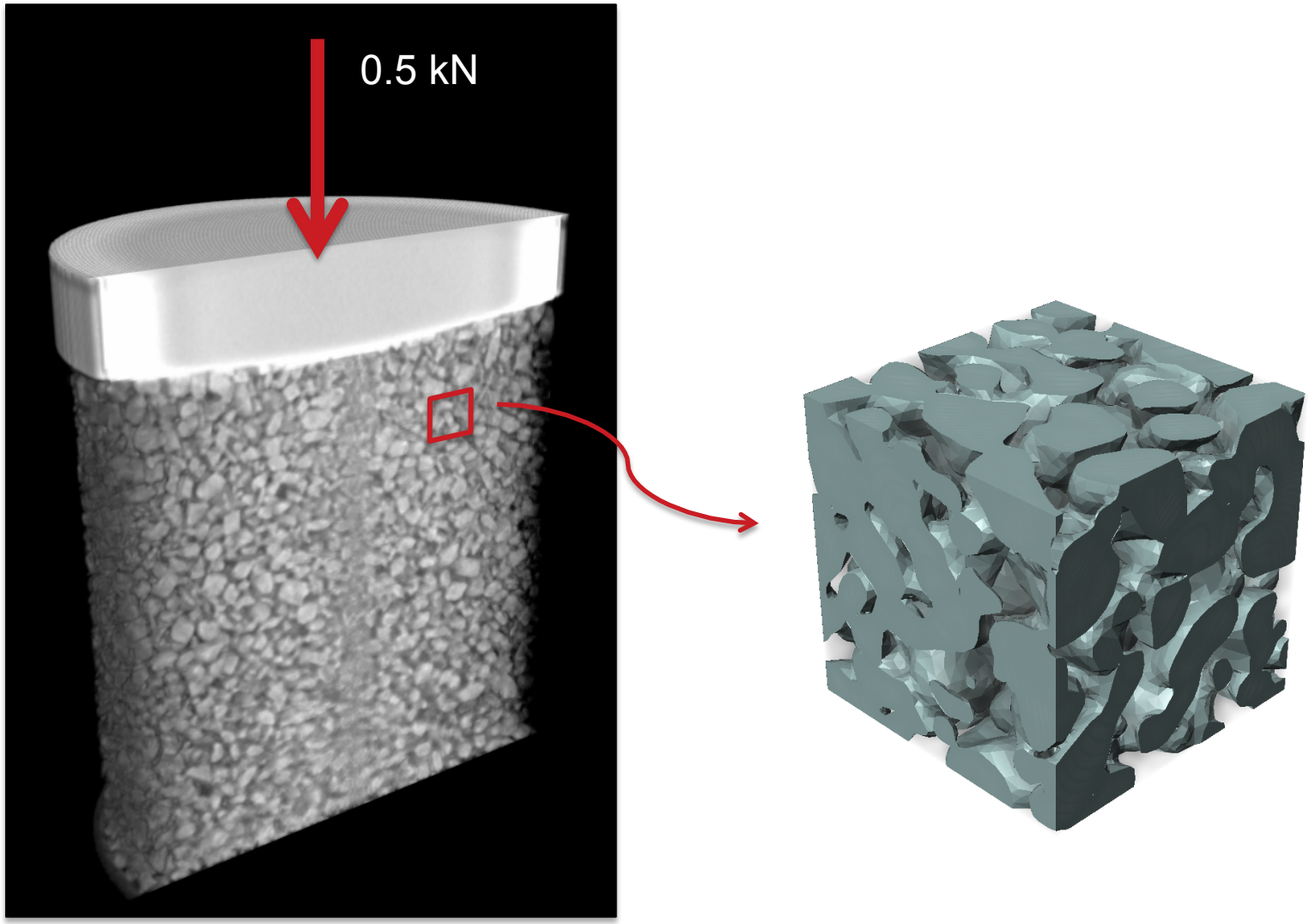

0.5 kN

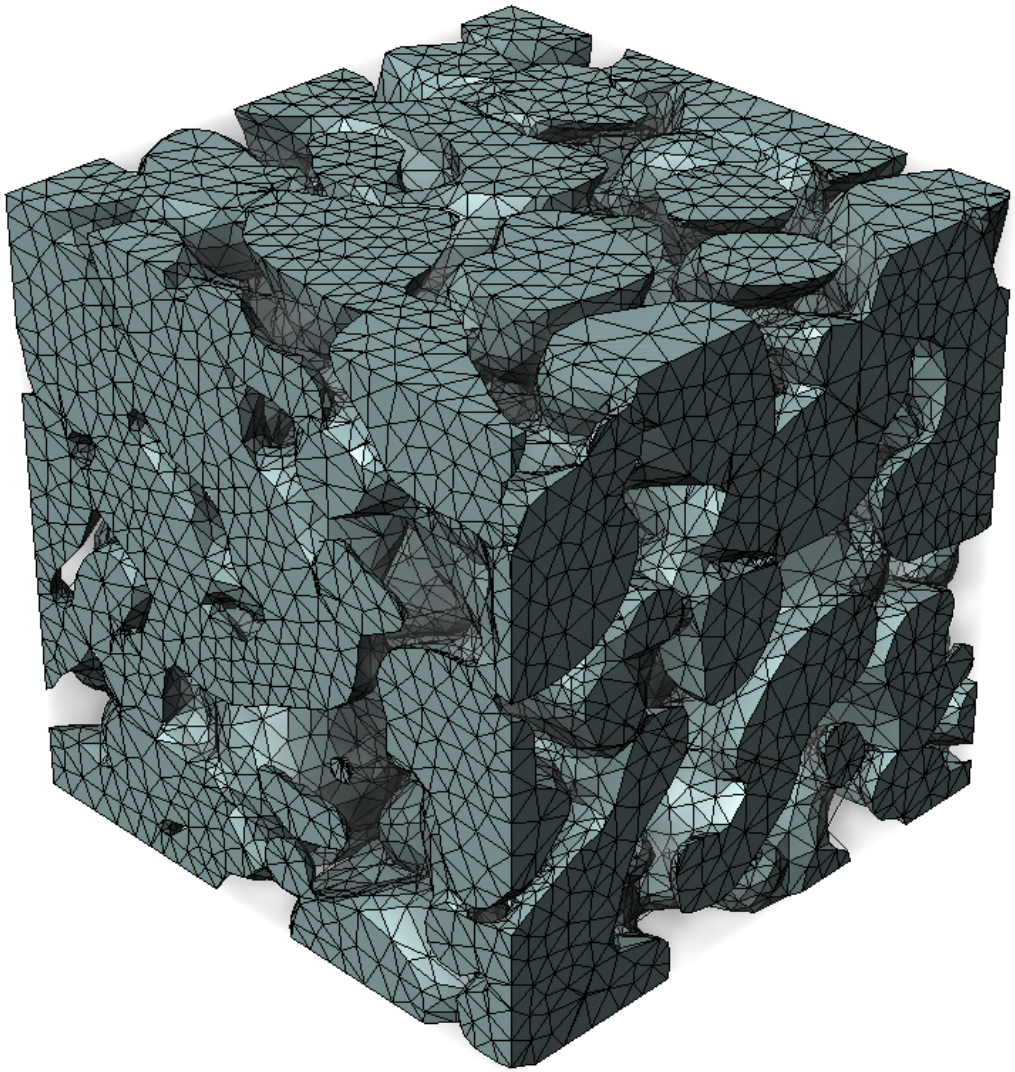


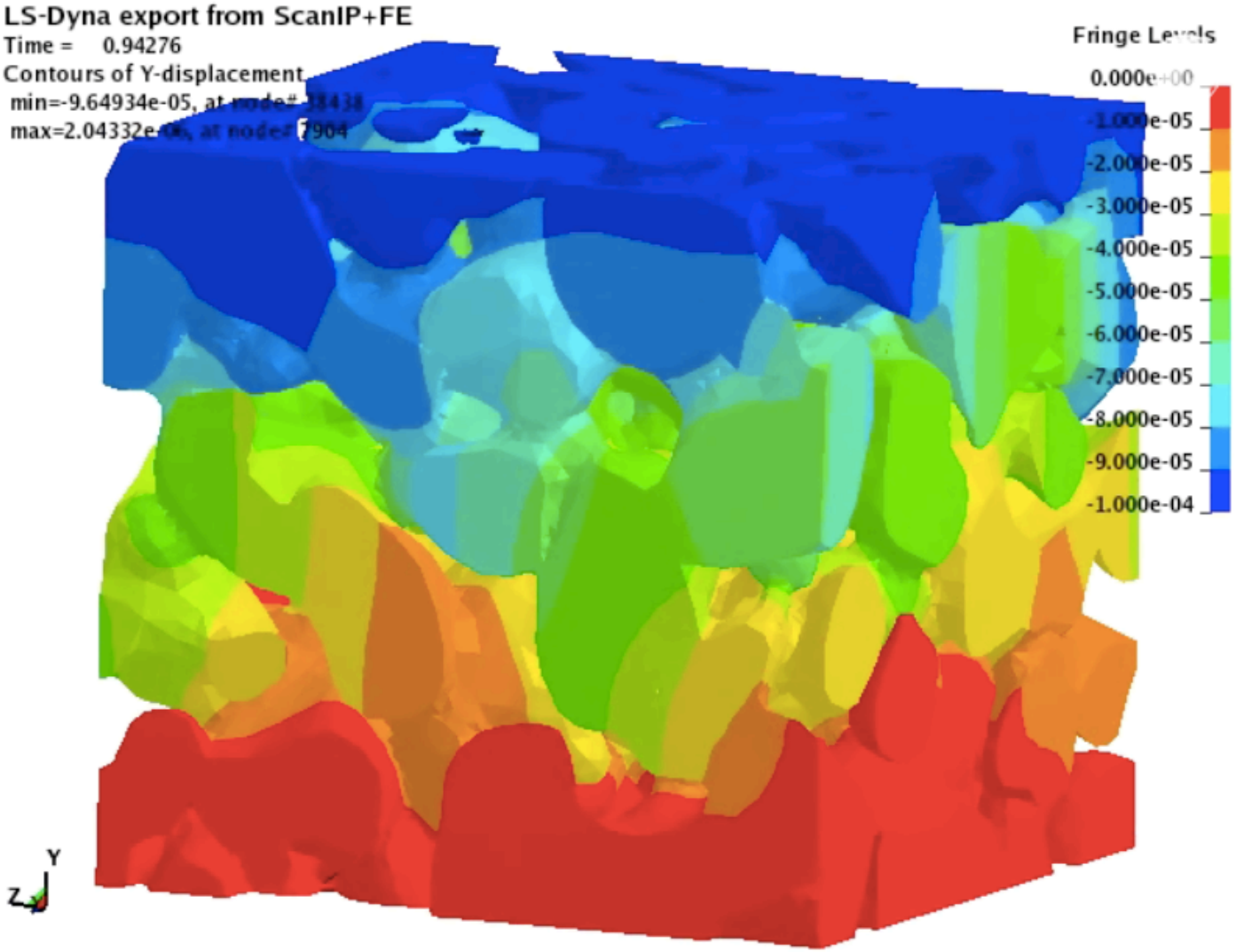


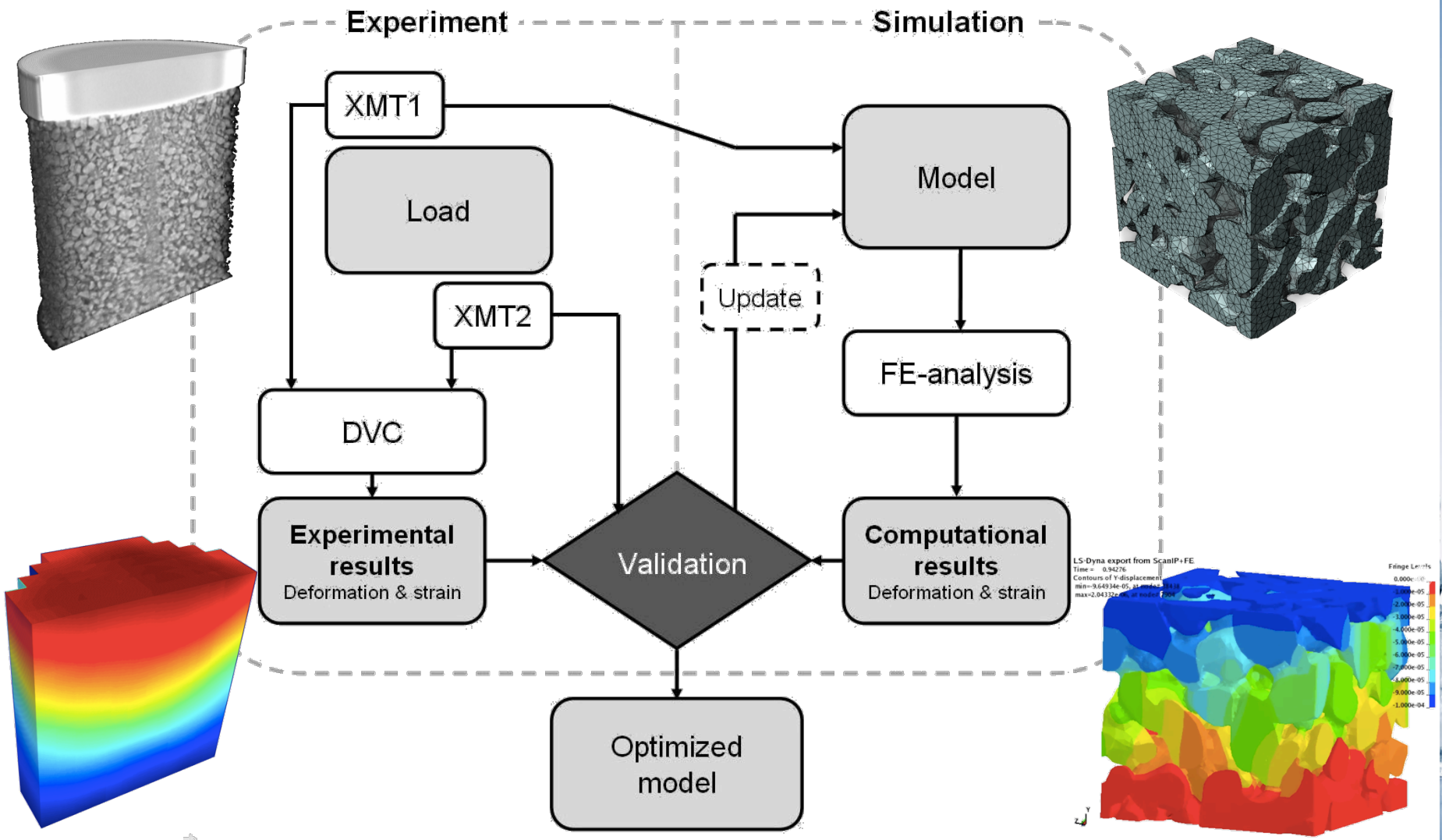

LS-Dyna export from ScanIP+FE
Time = 0.0067338
Contours of Pressure
min=-2.63983e+09, at elem# 263197
max=6.86505e+10, at elem# 370369
section min = -5.77215e+06, near node# 111669
section max = 8.99411e+07, near node# 120200
Fringe Levels
6.000e+06
5.400e+06
4.800e+06
4.201e+06
3.601e+06
3.001e+06
2.401e+06
1.801e+06
1.202e+06
6.018e+05
2.000e+03
Z
Y
X


LS-Dyna export from ScanIP+FE
Time = 0.0067338
Contours of Effective Stress (v-m)
min=0, at elem# 5111
max=1.28516e+11, at elem# 85002
section min = 0, near node# 89667
section max = 1.56669e+08, near node# 122092
Fringe Levels
5.000e+07
4.500e+07
4.000e+07
3.500e+07
3.000e+07
2.500e+07
2.000e+07
1.500e+07
1.000e+07
5.001e+06
1.000e+03
Z
Y
X


0.5 kN




LS-Dyna export from ScanIP+FE
Time = 0.94276
Contours of Y-displacement
min=-9.64934e-05, at node# 13431
max=2.04332e-05, at node# 7904
Fringe Levels
0.000e+00
-1.000e-05
-2.000e-05
-3.000e-05
-4.000e-05
-5.000e-05
-6.000e-05
-7.000e-05
-8.000e-05
-9.000e-05
-1.000e-04
Y
Z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Conclusions / Future work…

Conclusions / Future work

Experiments

X-ray microtomography and digital volume correlation allows us to study the compaction of granular materials in 3D.

The obtained displacement fields agree well with other measurements and observations.

Modelling

Modelling is carried out based on image data from the XMT scans.

Room for improvements:

- **XMT** Higher spatial resolution, Shorter scan time, In-situ loading
- **DVC** Handle discontinuities, Adaptivity…
- **Modelling** Grain interaction, Wall friction, Micro/Macro-consistency

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THE SWEDISH RESEARCH COUNCIL

Thank you!