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Finite Element Model Levelling for Material Model Calibration using Digital Image Correlation

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Background and Motivation

Background:

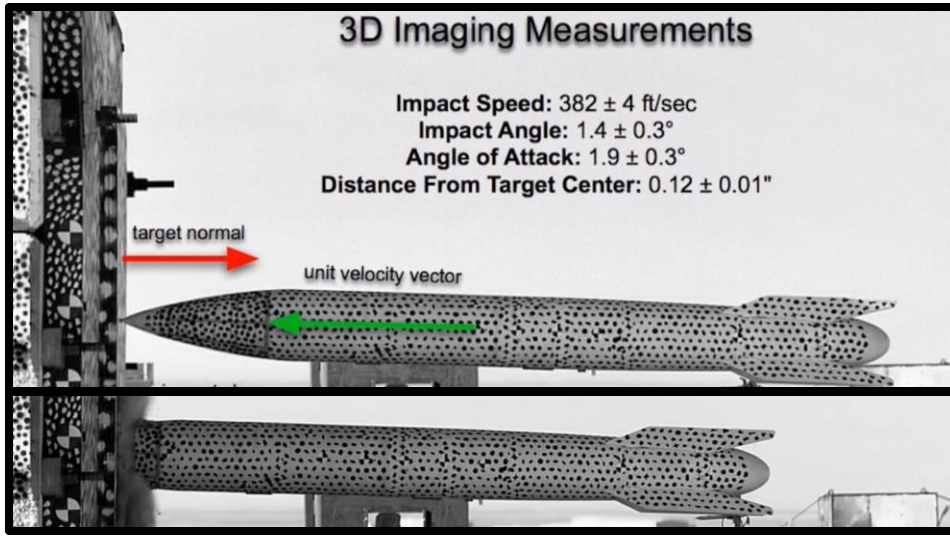
- Computational simulation to reduce expensive experimentation.
- Simulation accuracy is crucial, requiring robust calibration.
- Accuracy is enabled by robust measurements via digital image correlation (DIC) and inverse parameter identification techniques such as finite element model updating (FEMU).

Problem:

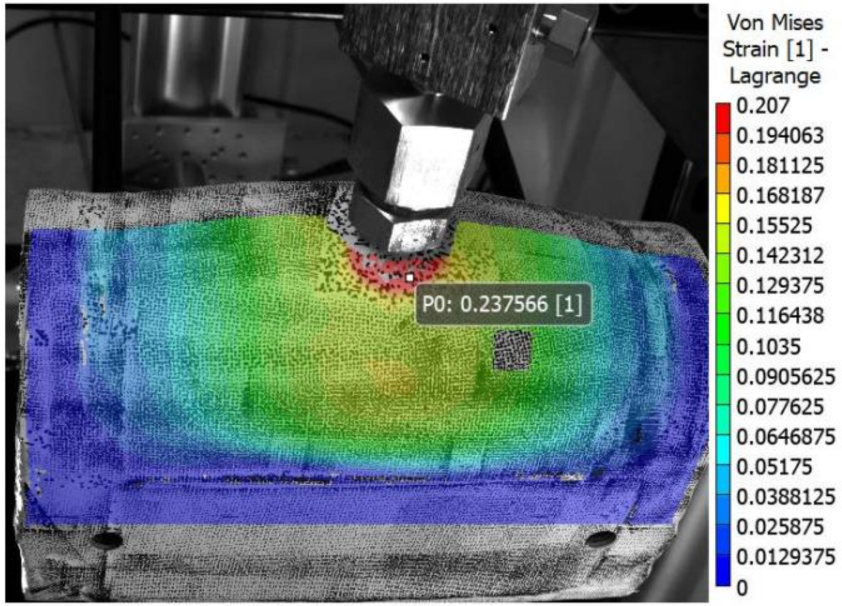
- DIC-measured strains suffer from a filtering bias caused by estimating the average strain across an area called a virtual strain gage (VSG).

Goal:

- We seek to account for the mismatch between the strains calculated through FEA and measured via DIC for the purpose of material model calibration.

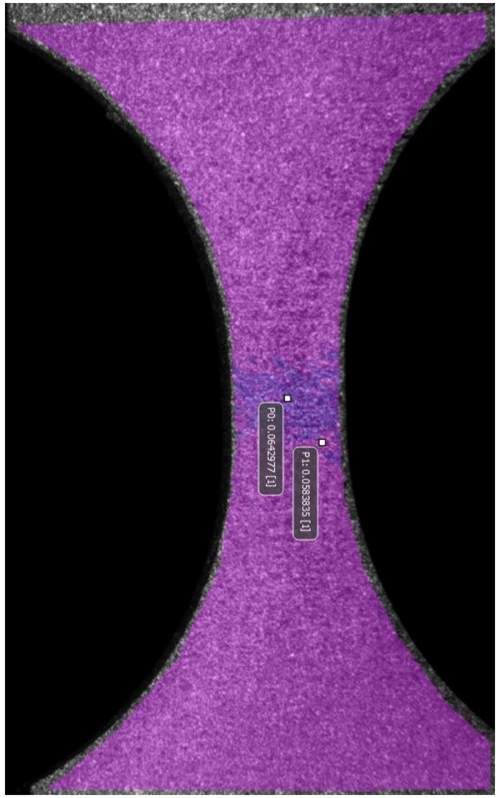


Sandia National Labs Ballistic Rocket Sled Test (December 2015)

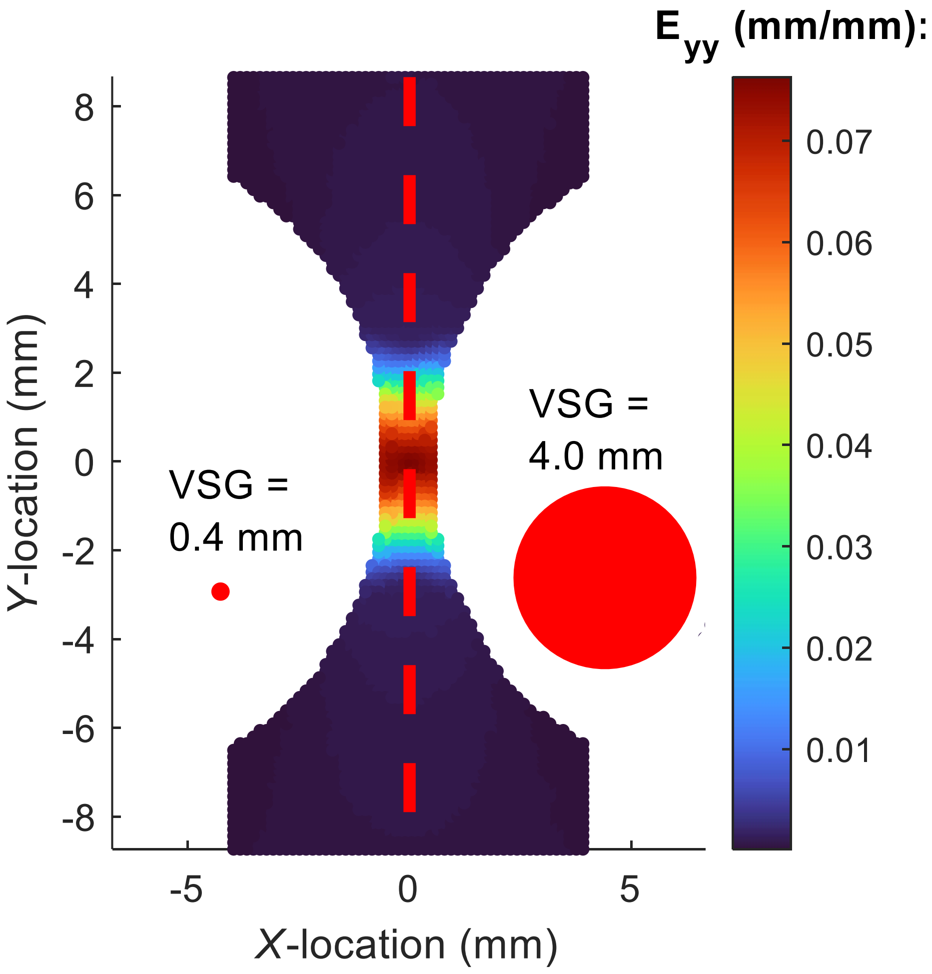


Lance, BW, & Carlson, MD. "Compact Heat Exchanger Semi-Circular Header Burst Pressure and Strain Validation." Proceedings of the ASME Turbo Expo 2019

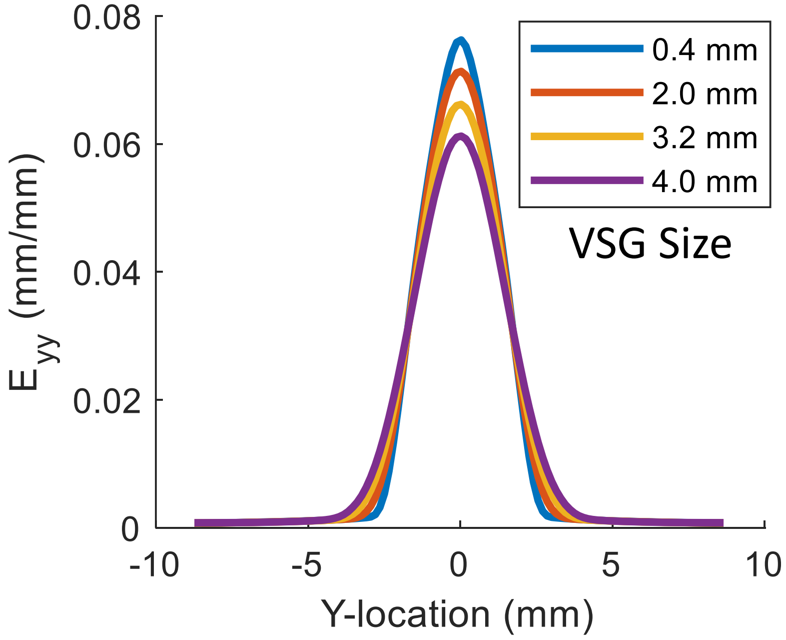
DIC experiences length-scale dependent filtering biases



304L hourglass specimen subjected to uniaxial tension

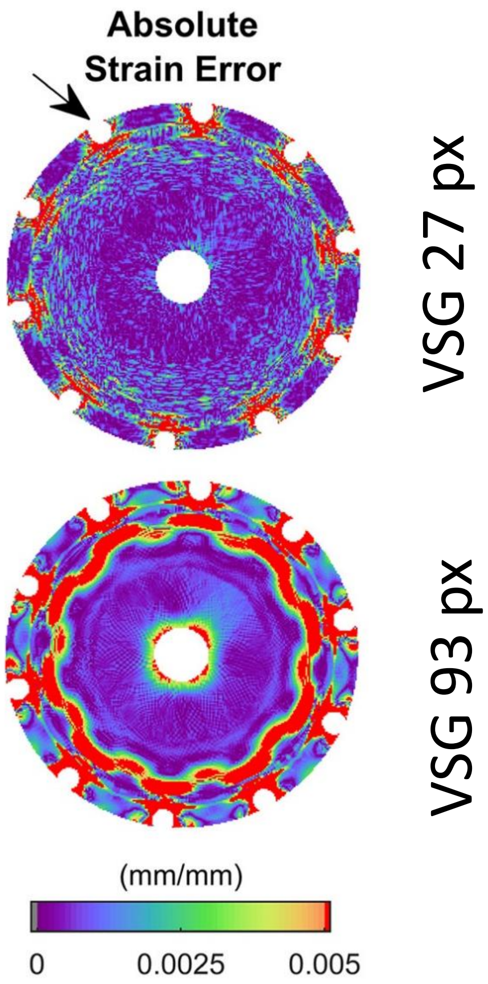


DIC results for a synthetic experiment.



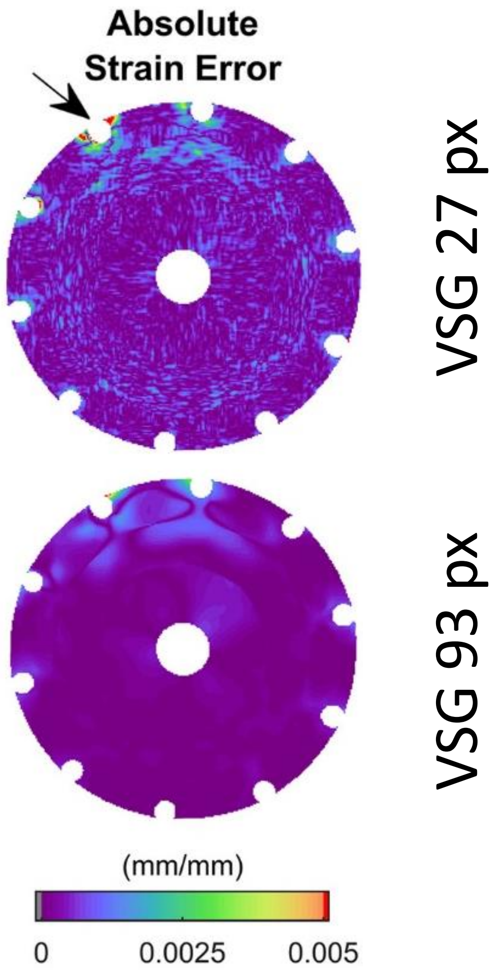
Sampled linecuts of the y-strain. Larger VSG sizes correspond to strain attenuation

The filtering causes a mismatch between FEA and DIC



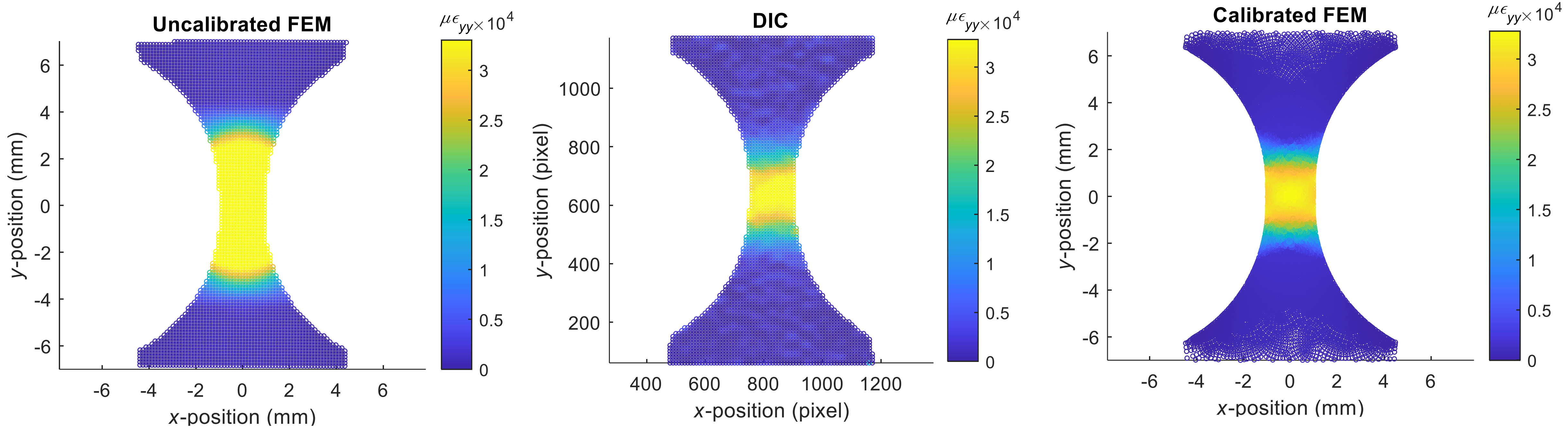
Discrepancy caused by mismatch of resolution between FEA and DIC

Comparison of strains after processing the FEA through a DIC simulator.



Lava P, Jones EMC, Wittevrongel L, Pierron F, (2020) Validation of finite-element models using full-field experimental data: Levelling finite-element analysis data through a digital image correlation engine. Strain 56(4): e12350. https://doi.org/10.1111/str.12350

Finite Element Model Updating (FEMU)



FEMU Objective Function

$$\chi_u^2(\{\boldsymbol{p}\}) = \frac{1}{N_\epsilon}\Sigma_{i=1}^{N_\epsilon}(\{\boldsymbol{\epsilon_m}\} - \{\boldsymbol{\epsilon_c}\})^2$$

$$\min_{\boldsymbol{p}} \chi_u^2(\{\boldsymbol{p}\})$$

Newton-Raphson Optimization

$$\delta\boldsymbol{p} = [\boldsymbol{H}^{i-1}]^{-1}[\boldsymbol{S}]^t\left(\{\boldsymbol{\epsilon}_m\} - \boldsymbol{\epsilon}_c\left(\boldsymbol{x},\{\boldsymbol{p}^{i-1}\}\right)\right)$$

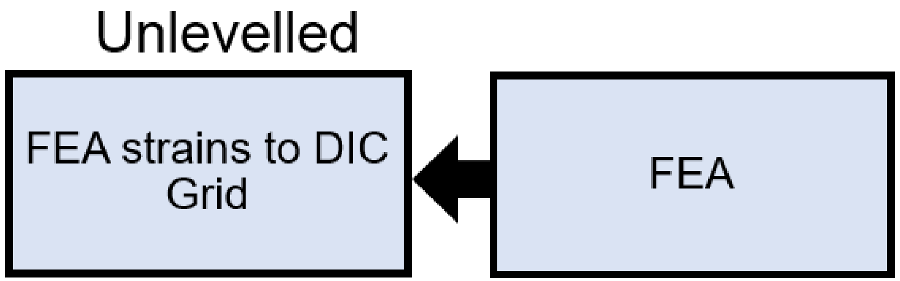
$\boldsymbol{\epsilon}_m$: the DIC measured strain
$\boldsymbol{\epsilon}_c$: the FEM calculated strain
N_ϵ: the number of strain measurements

$[\boldsymbol{H}]$: the Hessian matrix $[\boldsymbol{H}^i] = [\boldsymbol{S}^i]^{\mathrm{t}}[\boldsymbol{S}^i]$

$[\boldsymbol{S}]$: the sensitivity matrix $[\boldsymbol{S}] = \frac{\partial(\boldsymbol{\epsilon}_{FEM}^i)}{\partial p_j}$

Mathieu, F., Leclerc, H., Hild, F. et al. Estimation of Elastoplastic Parameters via Weighted FEMU and Integrated-DIC. Exp Mech 55, 105–119 (2015). https://doi.org/10.1007/s11340-014-9888-9

Direct of interpolation of FEA strain (ie unlevelled) for comparison is ill-advised

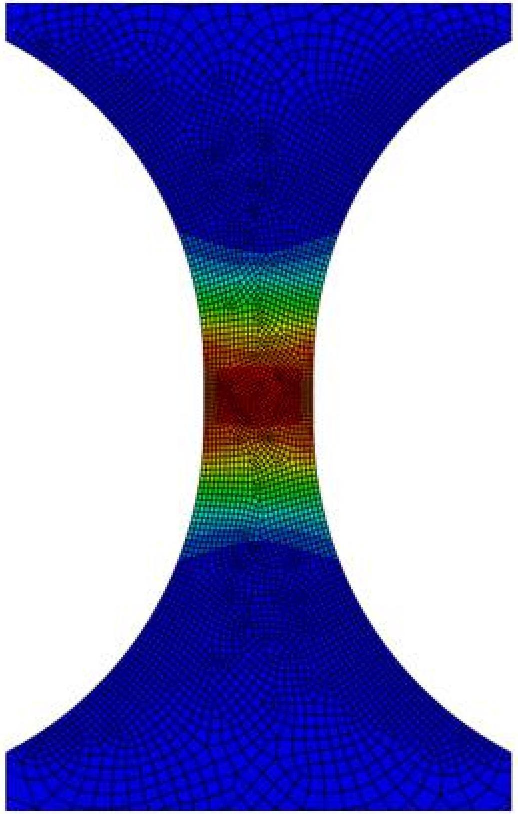


Strains computed using different:
- Calculation method
- Spatial resolution
- Tensor!

Logarithmic Strain (ABAQUS)

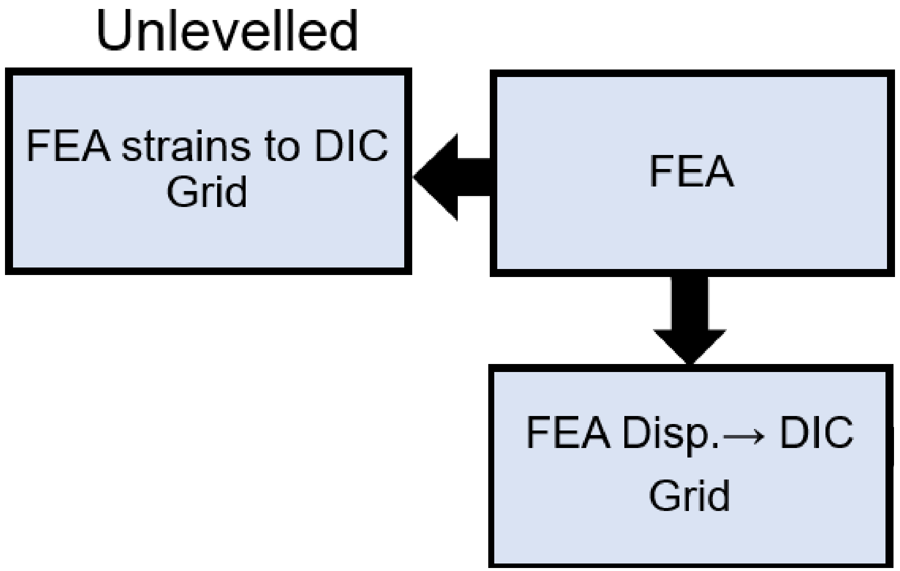
$$\boldsymbol{\varepsilon} = \ln(\sqrt{\mathbf{B}}) = \ln(\sqrt{\mathbf{F} \cdot \mathbf{F}^{\mathrm{T}}})$$

ABAQUS Logarithmic Y-Strain



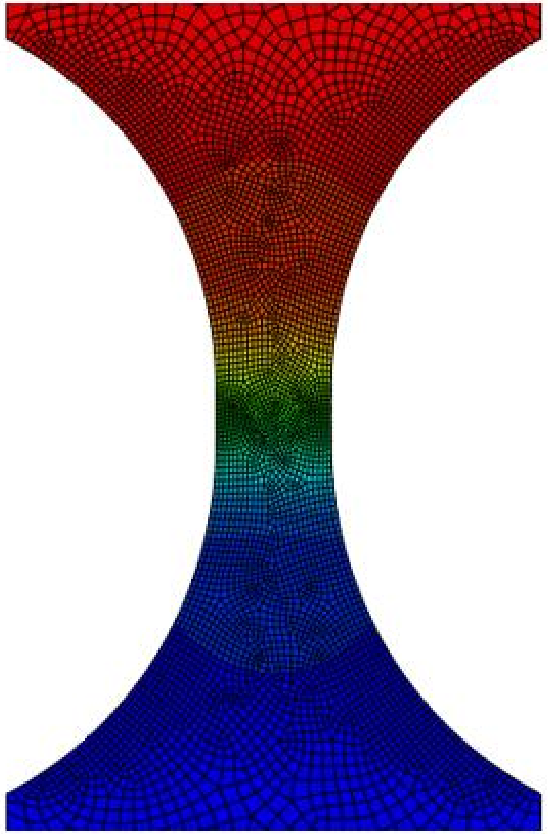
DIC Step Size

Direct interpolation of displacement is better



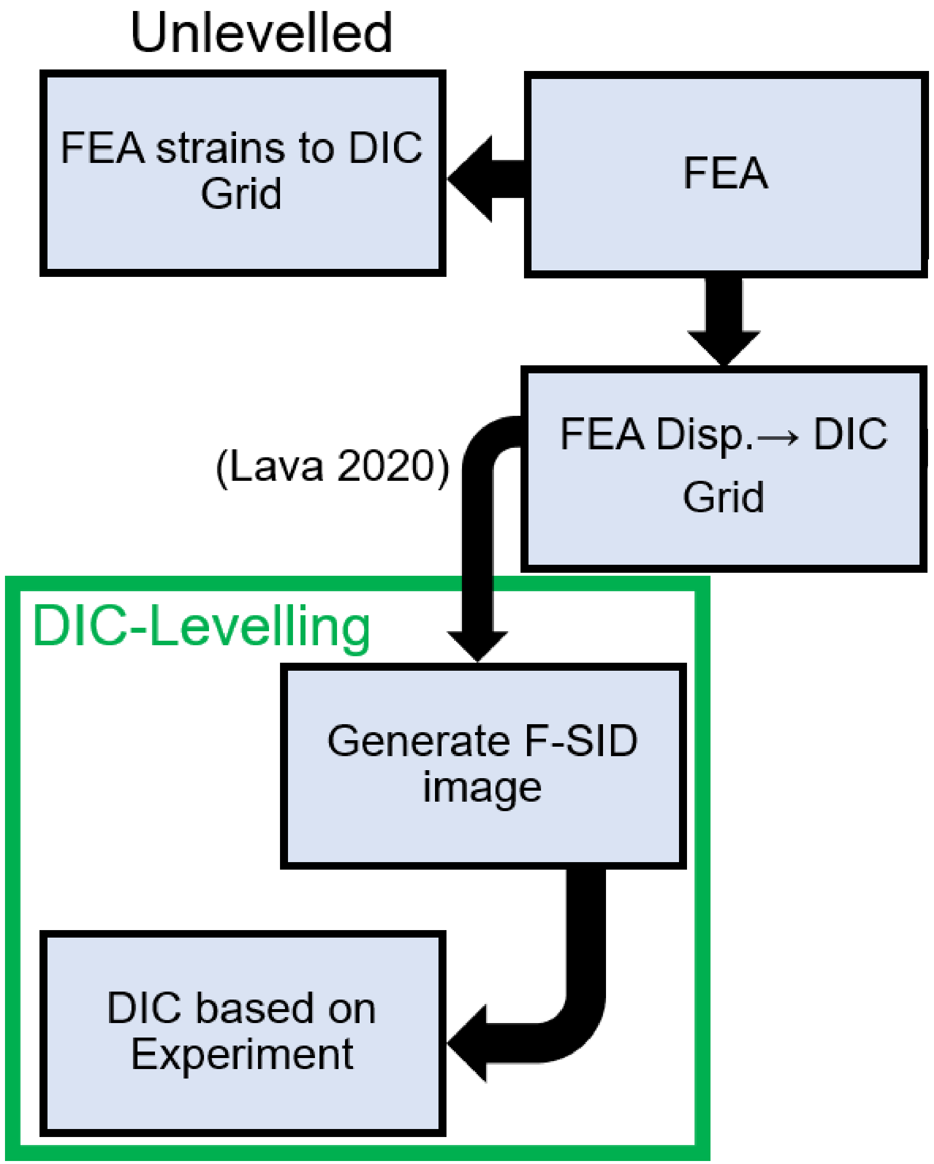
The FEM data is uncorrupted with only small errors due to registering to DIC grid.

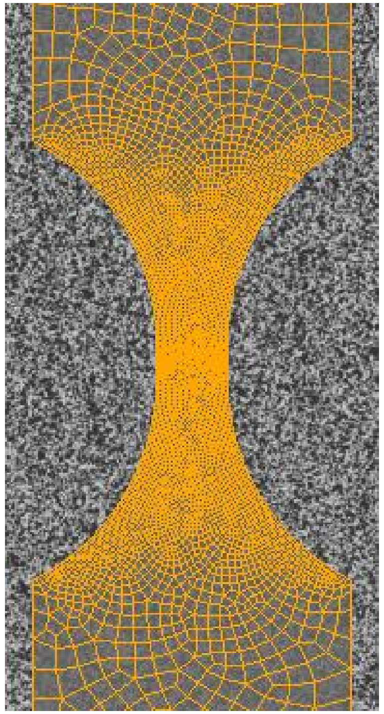
ABAQUS V-Displacement



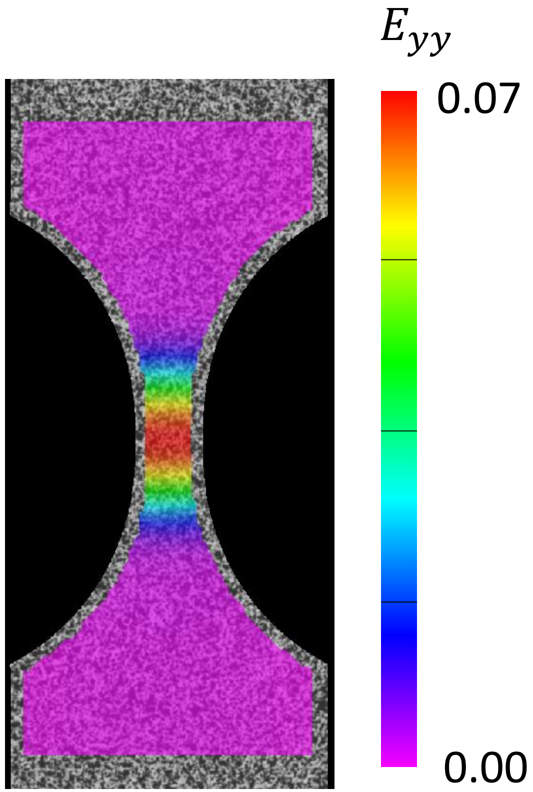
DIC Step Size

DIC-Levelling corrects for DIC errors





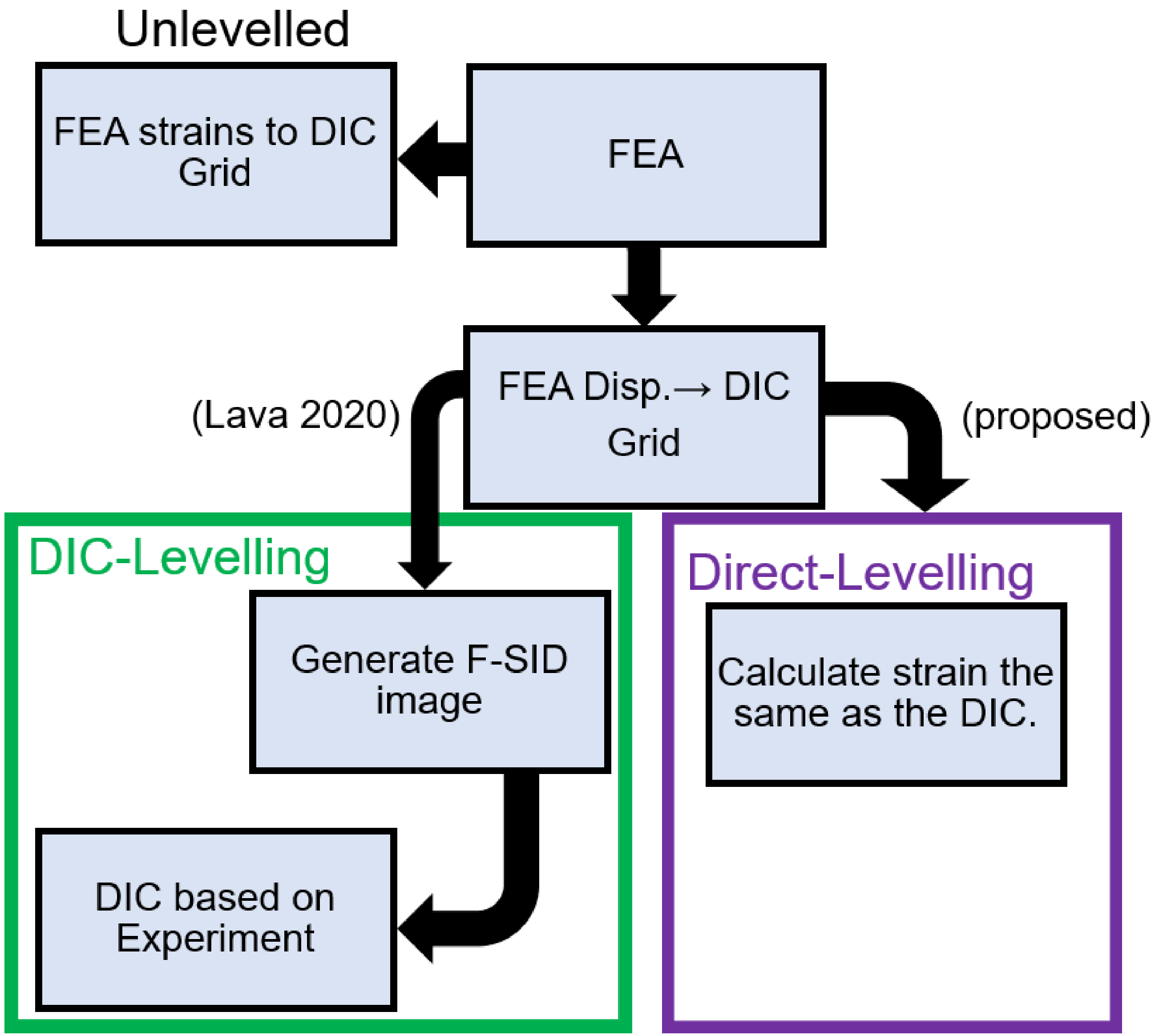
Mesh to pattern alignment



DIC Analysis of F-SID image

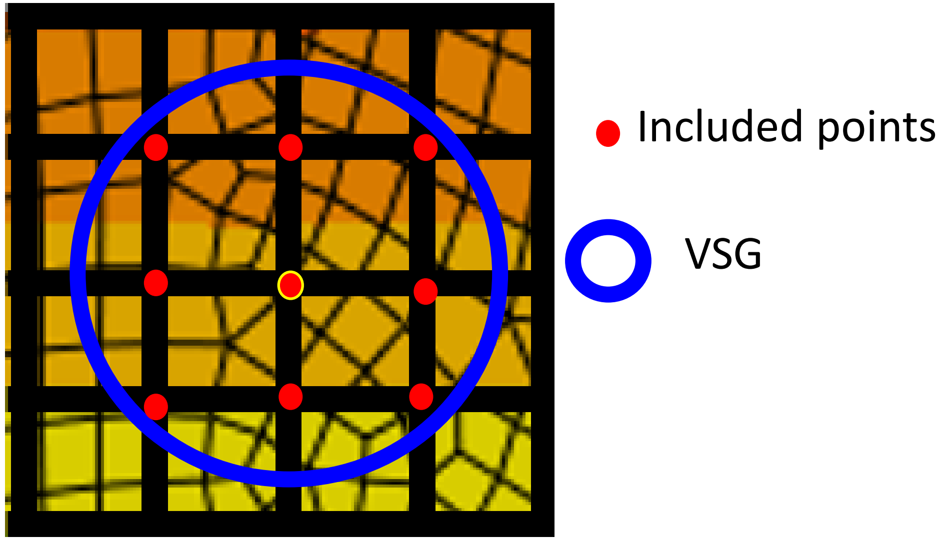
Rectifies issues with strain calculation, spatial resolution, and image based errors such as interpolation bias, image discretization, PIB. Does not account for image noise.

Direct-levelling the FEA output as a simple solution



Calculate the Green-Lagrange Strain Tensor via the polynomial shape function method

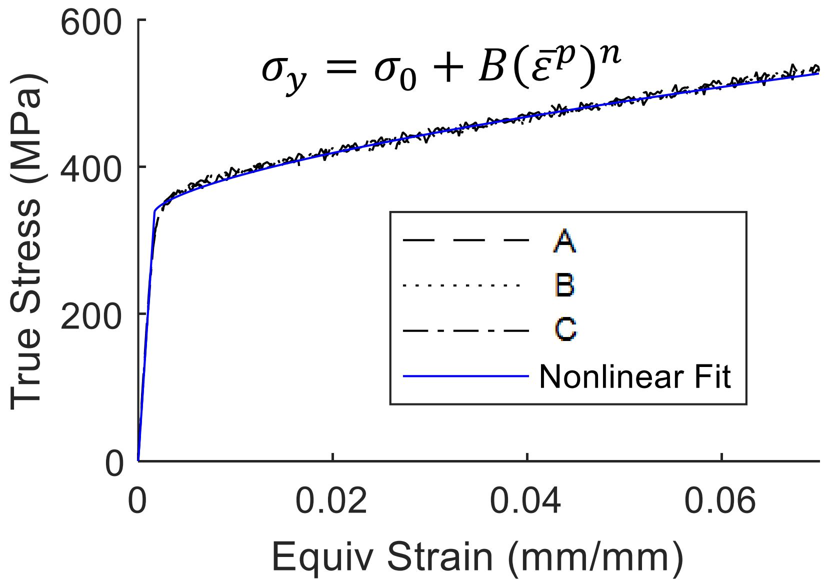
$$E_{KL} = \frac{1}{2}\left(\frac{\partial x_j}{\partial X_K}\frac{\partial x_j}{\partial X_L} - \delta_{KL}\right)$$



Material Model for FE Model

304L stainless steel tensile specimens

Material hardening is given by the power law:



Material model parameters

E = 200 GPa

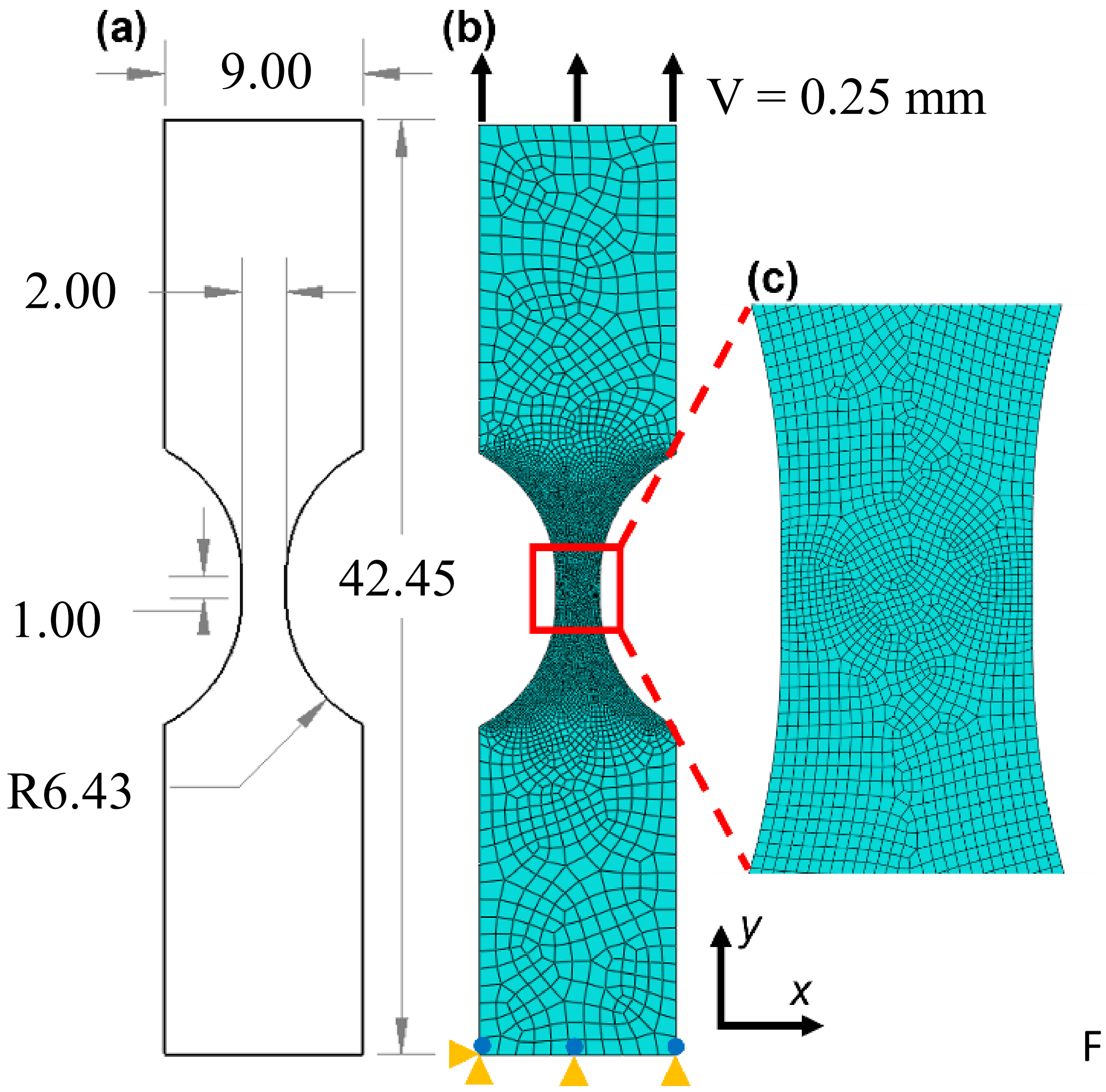
ν = 0.29

σ_0 = 339 MPa

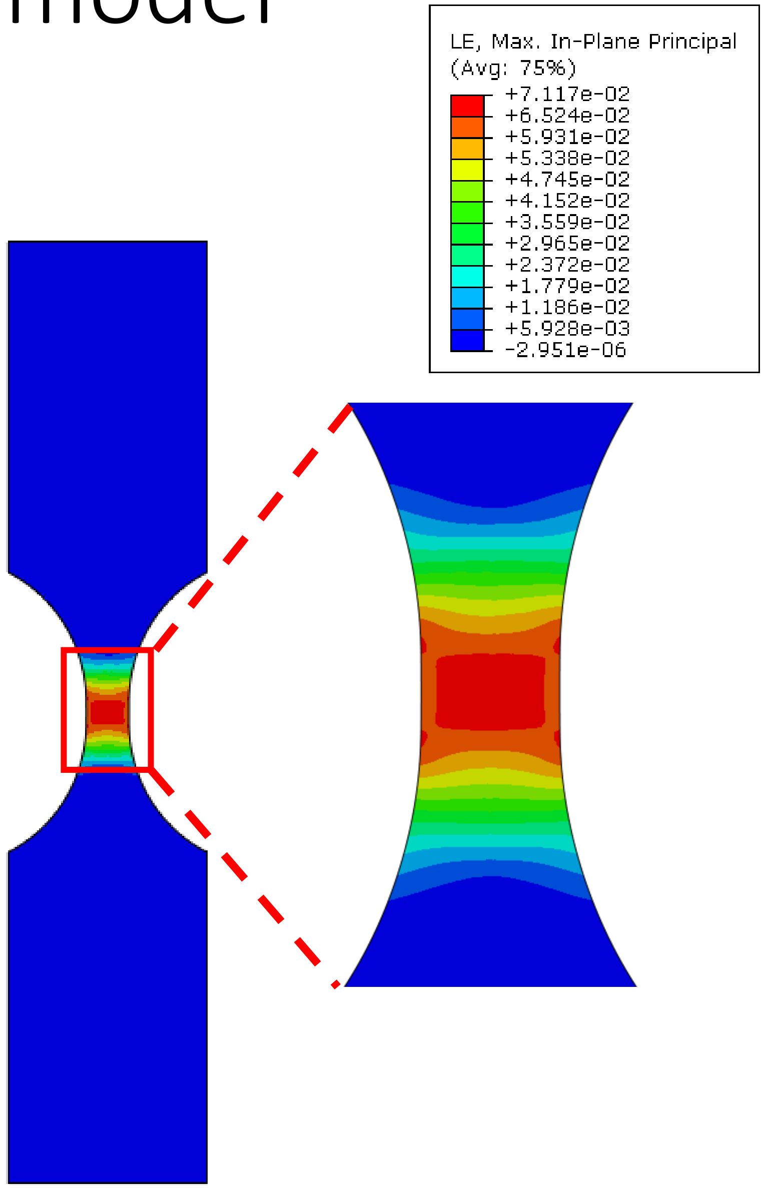
B = 1.07 GPa

n = 0.645

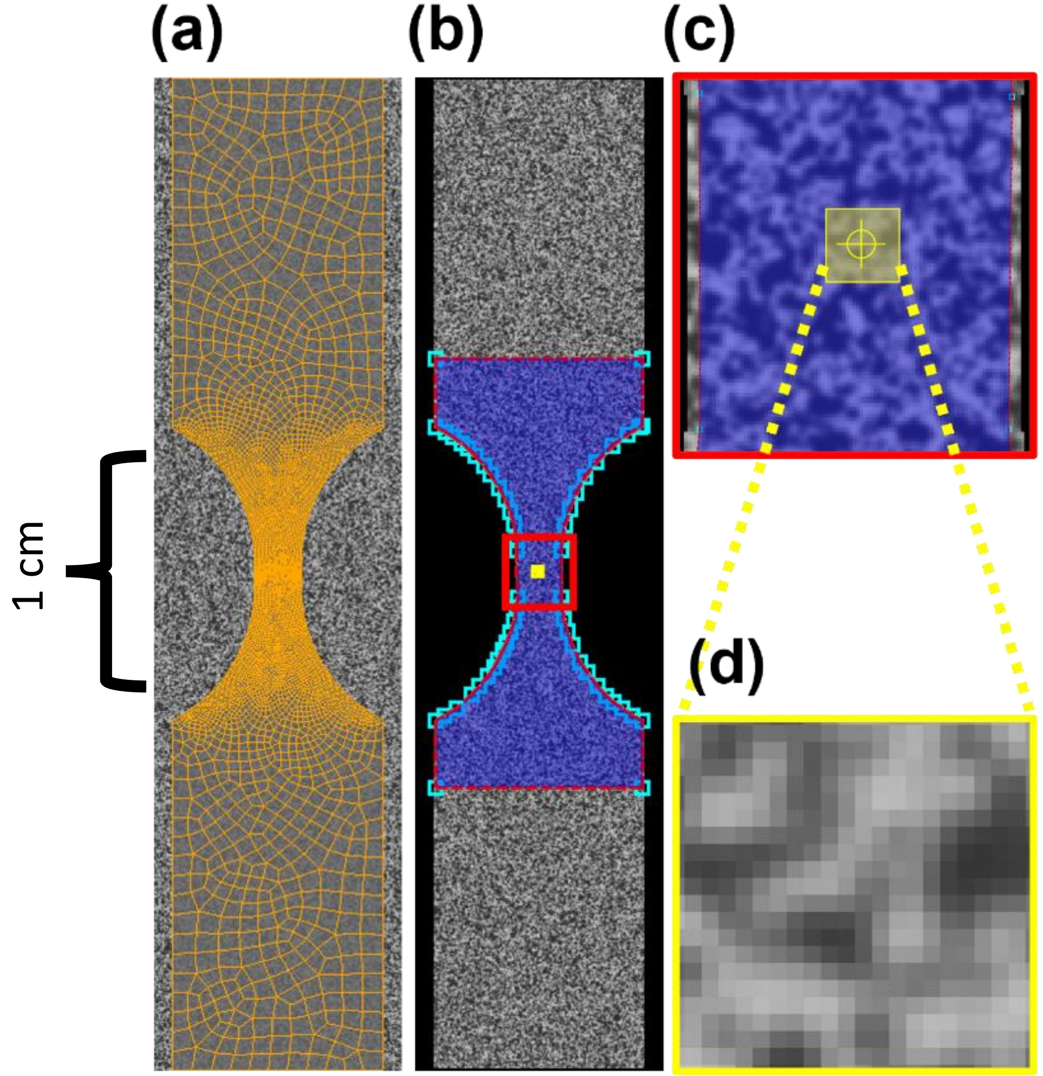
FEMU Calibration via direct-levelling: FE model



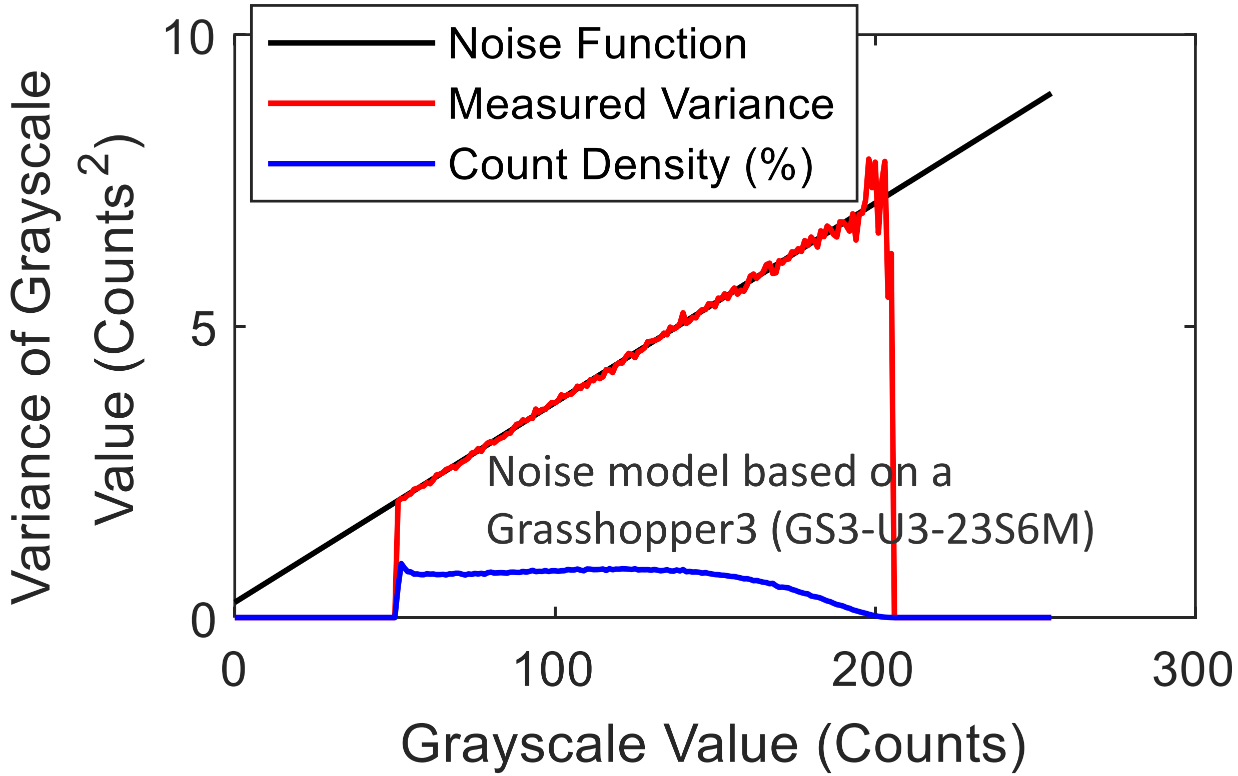
FE



Generation of Synthetic Images as “experimental” data



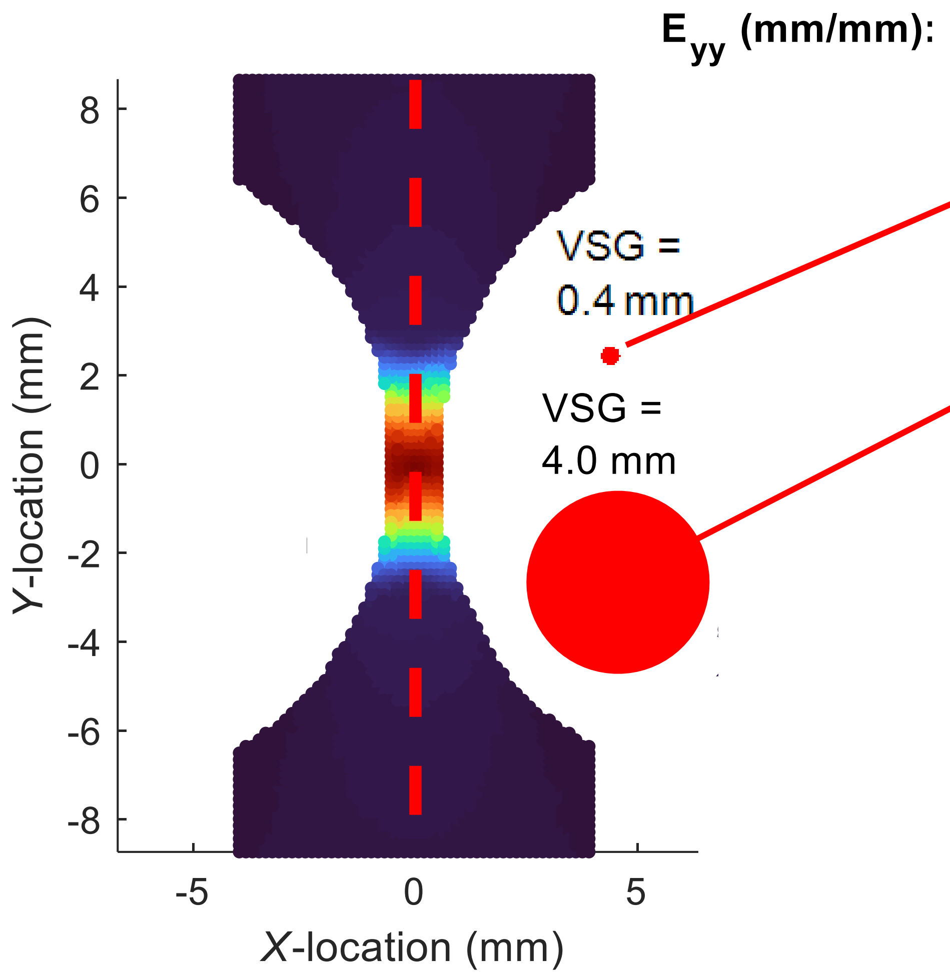
Deformation done by MatchID FEDEF module

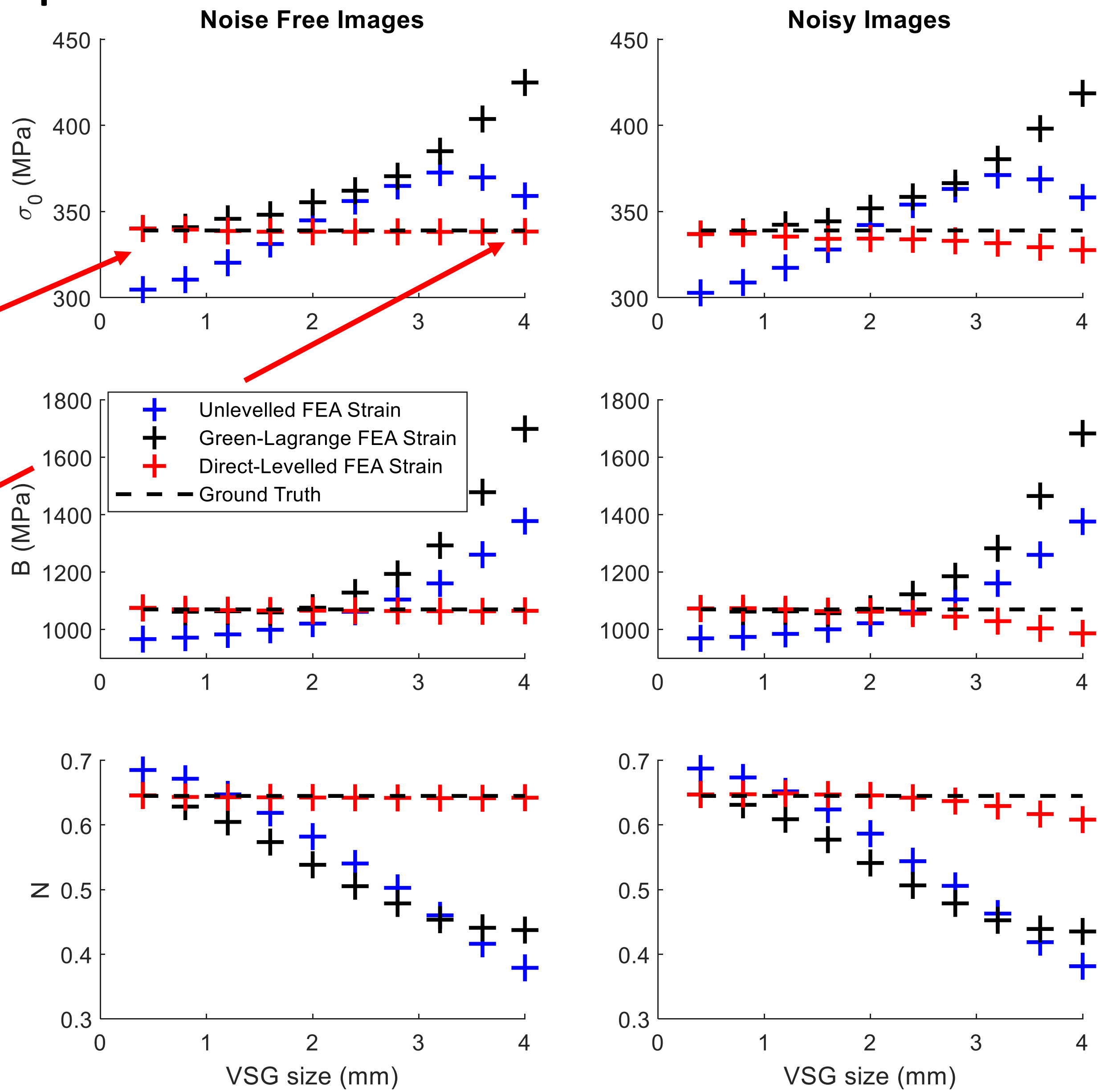


DIC Settings

Subset Size	Step Size	Shape Function	Criterion	Image Interpolant
21 px	7 px	Quadratic	ANSSD	Bicubic Spl.

Effect of direct-levelling on parameter identification





Conclusions and Future Work

Summary

- The errors due to the filtering effect of DIC can cause false errors when comparing DIC to FEA
- Properly levelling the FEM to the DIC results is important for an accurate calibration.
- Direct-levelling as opposed to full DIC-levelling is sufficient to obtain an accurate FEMU identification

Limitations

This method does not account for image-induced errors which we show is small compared to the filtering effects of DIC.

Identification errors using a DIC VSG of 0.8 mm

Levelling		Unlevelled	Direct-Levelled
σ_0	Noise Free	8.42%	-0.15%
B	Noise Free	9.19%	-0.03%
n	Noise Free	-4.12%	0.26%
σ_0	Noisy	8.92%	0.55%
B	Noisy	8.96%	-0.39%
n	Noisy	-4.43%	-0.40%

Identification errors have been reduced more than **10X** for the identification results using noisy images

Supplemental Slides: Identification Errors

DIC Shape Fun.		Quadratic	Quadratic	Quadratic	Affine	Affine	Quadratic
DIC Step Size (pixels)		7	7	7	7	7	2
Levelling		UL	TL	SL	SL	SSL & SL	SL
σ_0	Noise Free	8.42%	-0.56%	-0.15%	0.76%	0.16%	0.04%
B	Noise Free	9.19%	0.76%	-0.03%	1.20%	0.40%	0.11%
n	Noise Free	-4.12%	2.56%	0.26%	2.03%	0.37%	0.21%
σ_0	Noisy	8.92%	0.24%	0.55%	1.28%	0.68%	0.40%
B	Noisy	8.96%	0.70%	-0.39%	0.58%	-0.31%	-0.36%
n	Noisy	-4.43%	2.13%	-0.40%	1.16%	-0.54%	-0.25%