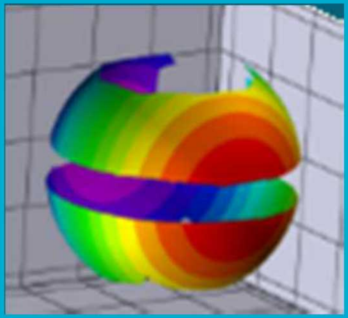
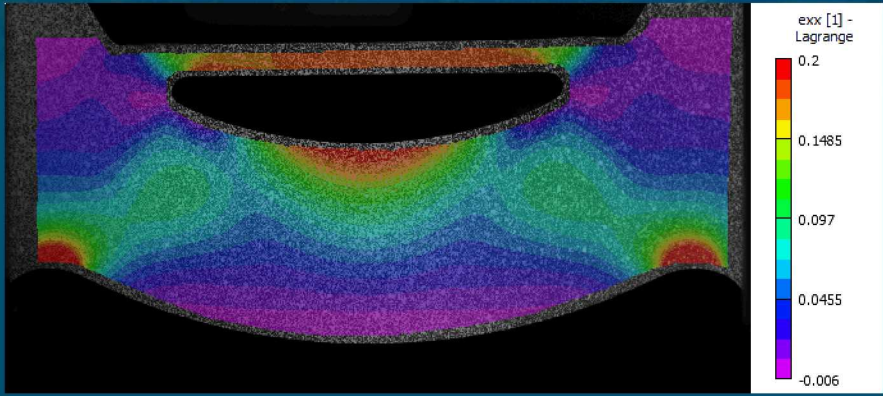
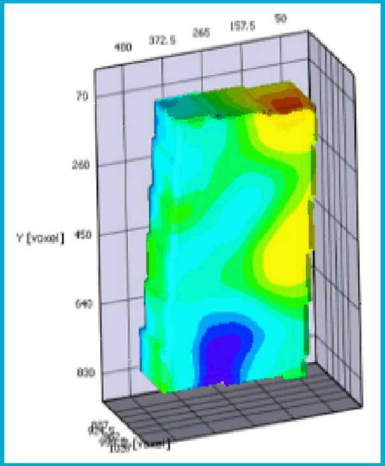
SAND2018-3244PE

Digital Image Correlation (DIC): A revolution in engineering measurements

Full-field quantitative data from micrometers to meters and hertz to megahertz – the DIC journey from university curiosity towards an industrially accepted technique







PRESENTED BY

Phillip Reu

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

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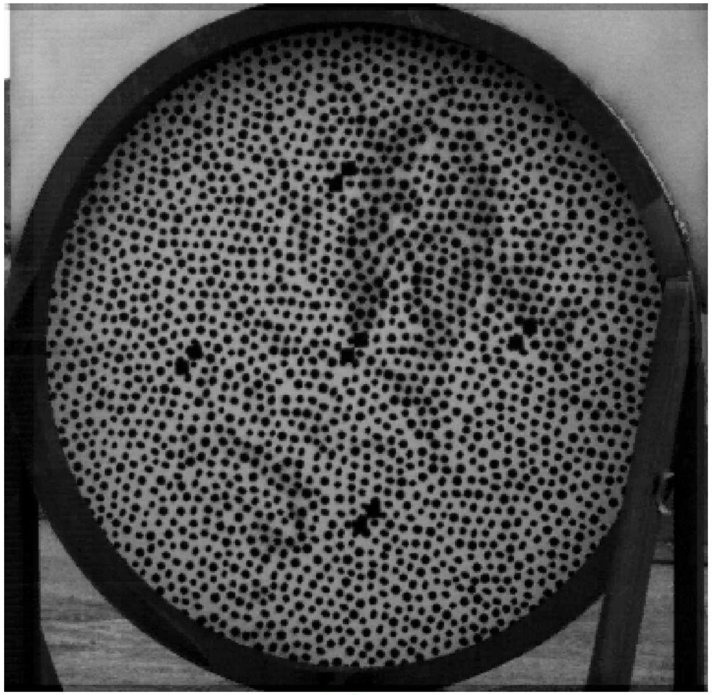
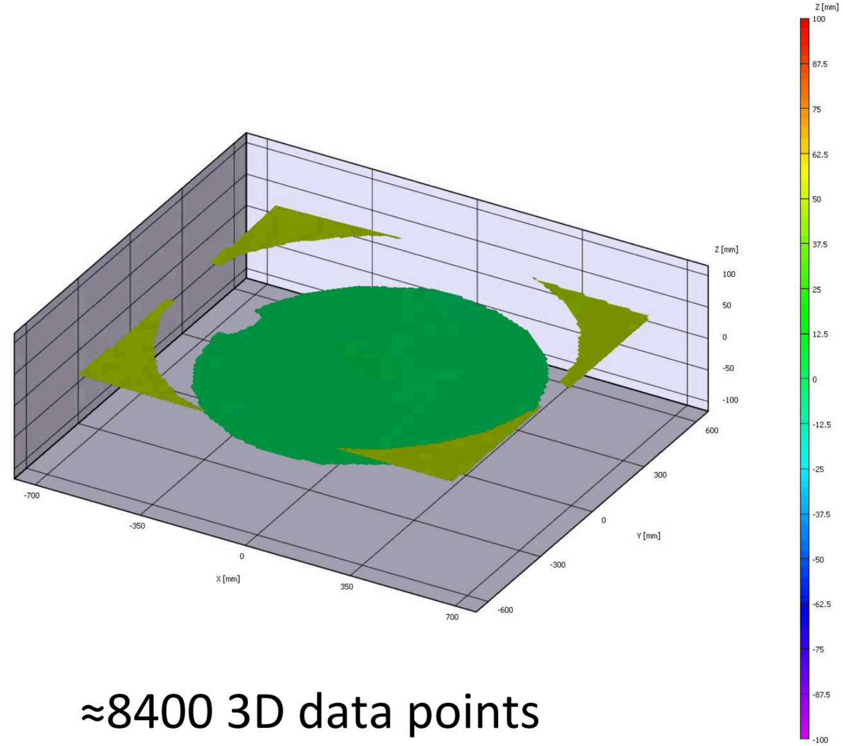
What is Digital Image Correlation (DIC)? It is a full-field image based shape, deformation and strain measurement technique.

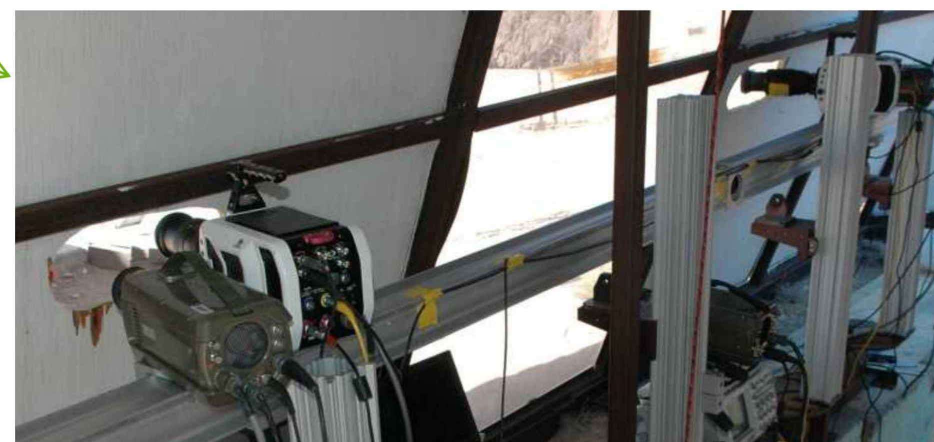


≈1.2 m

≈7.6 m



≈8400 3D data points



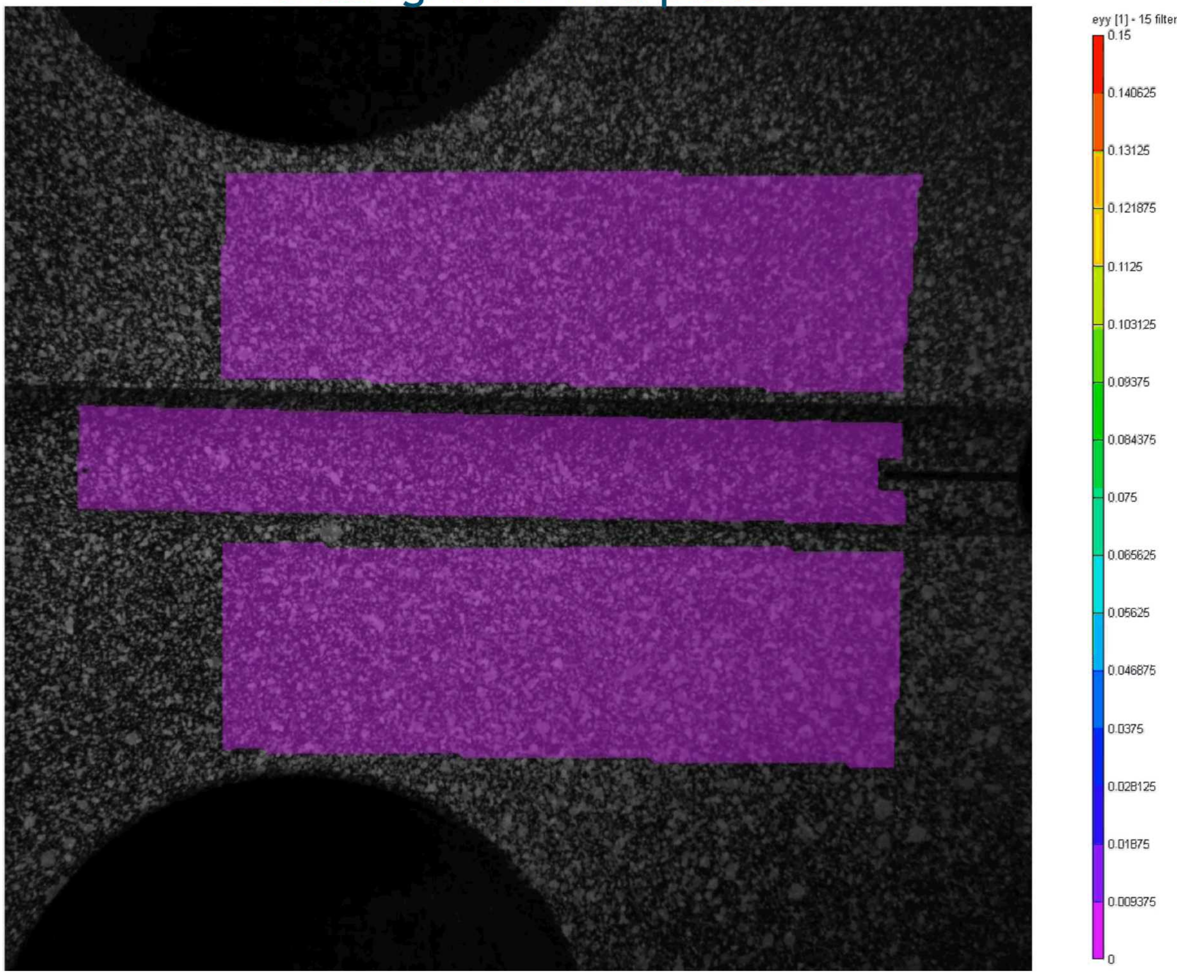
37,000 fps 368×360 Wide View

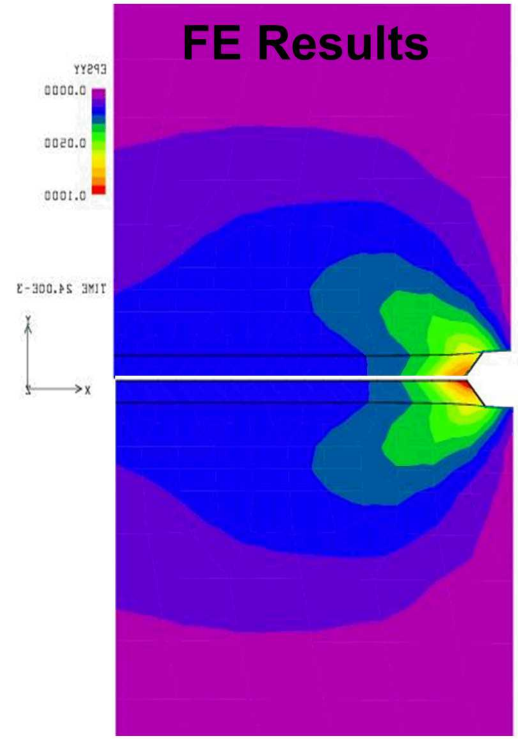
Talk about

1. What is Digital Image Correlation (DIC)?
2. How can we use DIC in engineering?
3. What support do we have for DIC training, standards, and certification.

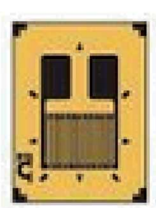
Full-field means you don't need to know exactly where the failure will occur!

Crack growth in a plate



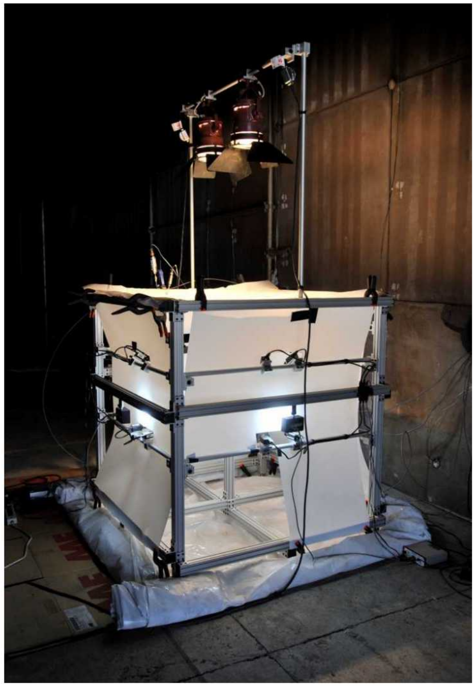


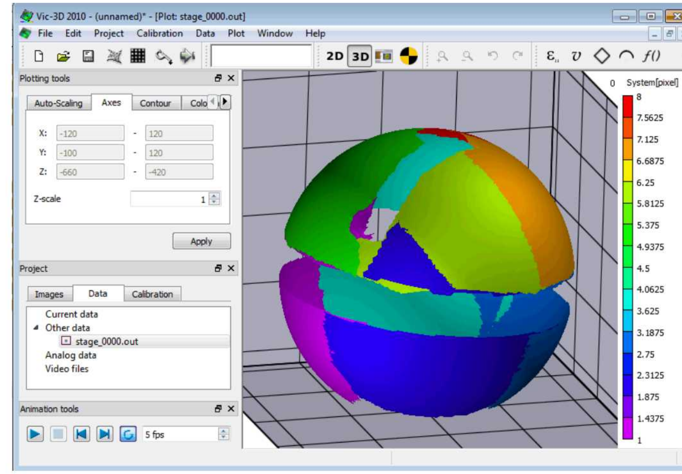
- With DIC you have a strain gauge everywhere and at all times.
- 100's με strain resolution
- Extremely high strain measurements possible
- Shape of the object simultaneously measured



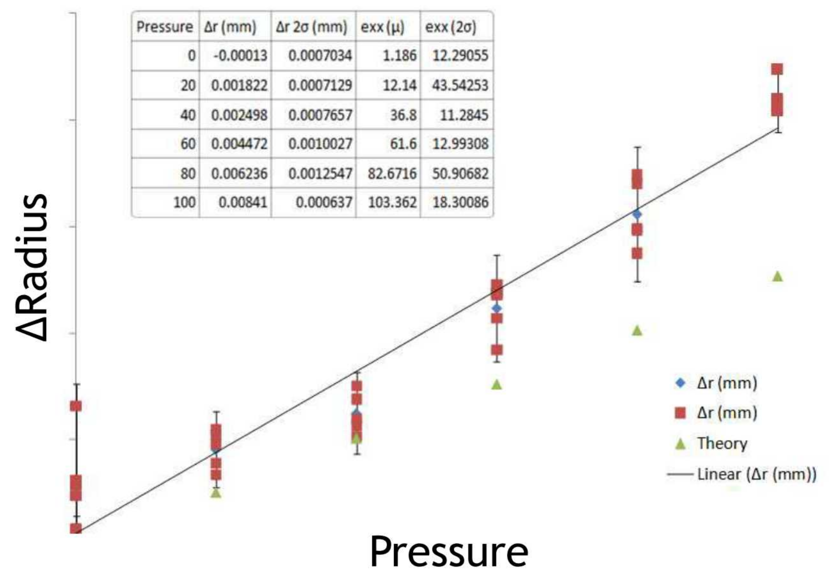
Where do you put the strain gauge?

Complex geometries can be measured with multi-camera systems.



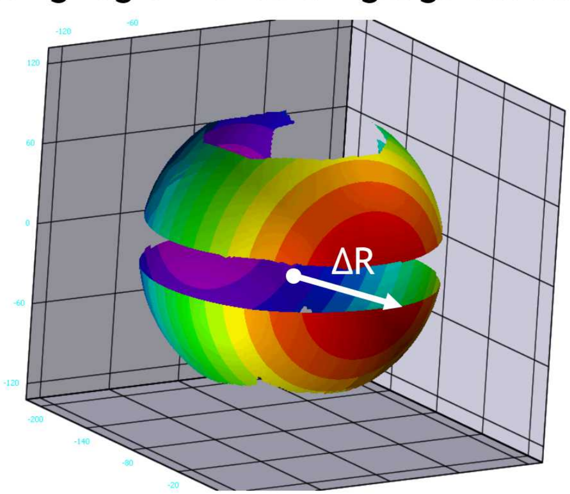


Change in radius noise floor of < 1.2 μm



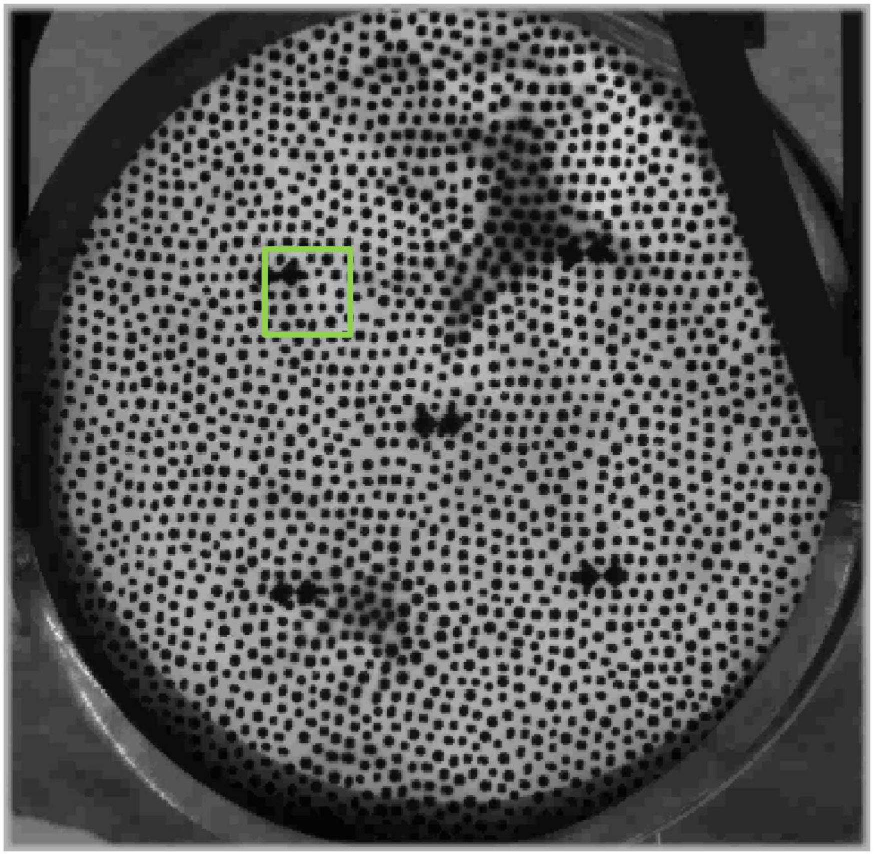
Pressure	Δr (mm)	Δr 2σ (mm)	exx (μ)	exx (2σ)
0	-0.00013	0.0007034	1.186	12.29055
20	0.001822	0.0007129	12.14	43.54253
40	0.002498	0.0007657	36.8	11.2845
60	0.004472	0.0010027	61.6	12.99308
80	0.006236	0.0012547	82.6716	50.90682
100	0.00841	0.000637	103.362	18.30086

Missing region for strain gauge validation



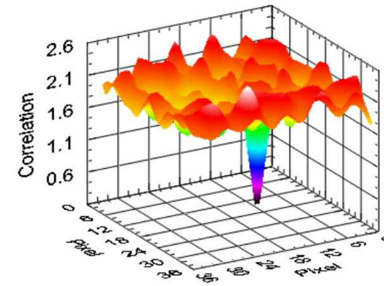
Key: Complex shapes can be measured.

DIC: Keep the dots in the box†

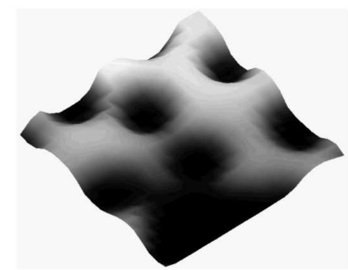


3 Hidden components of DIC‡

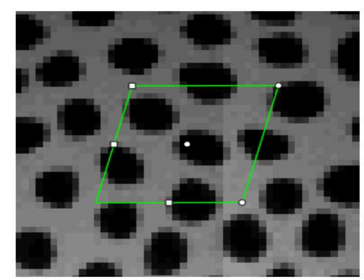
Matching



Interpolation



Shape Function



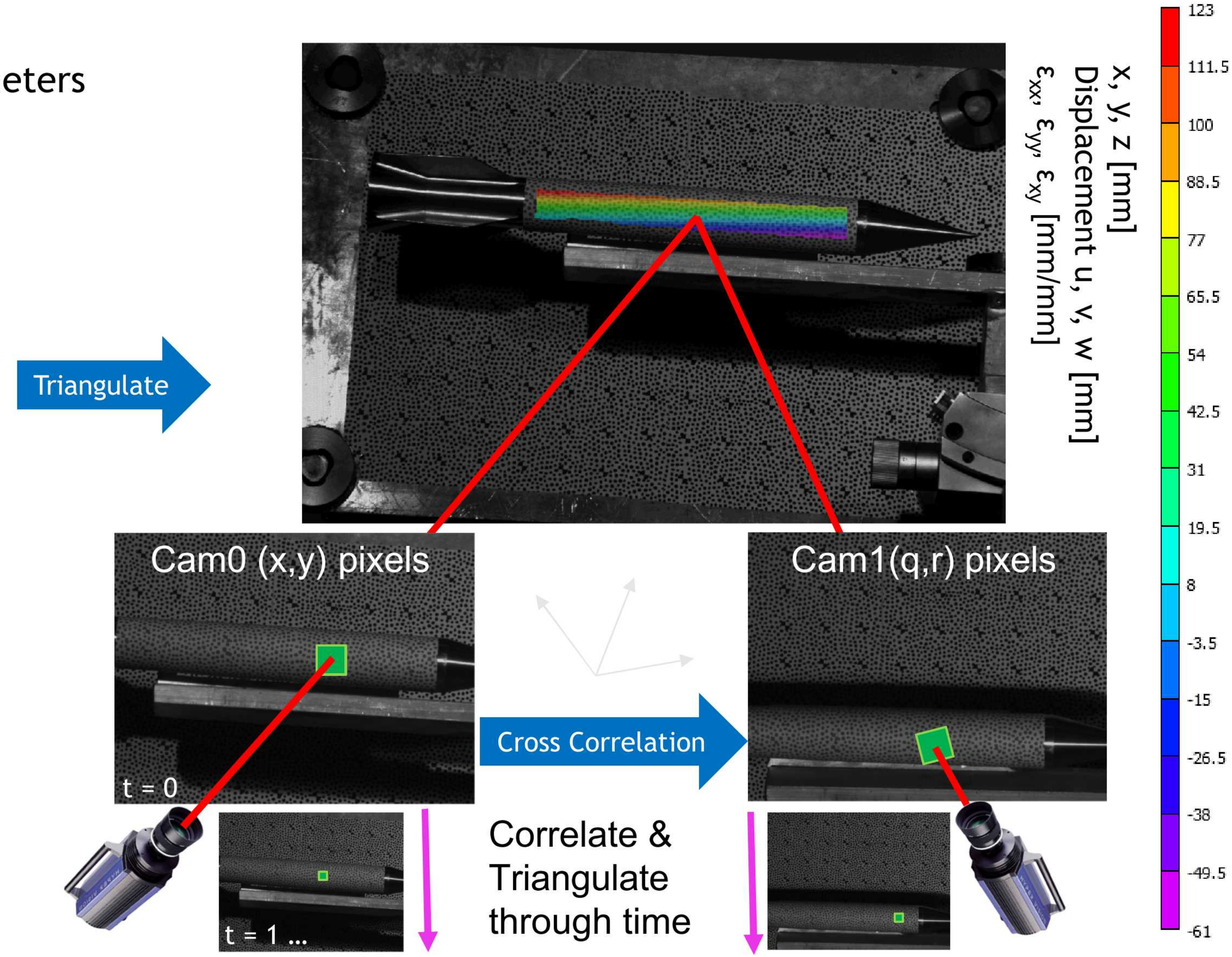
†Samantha Daly

‡Phillip Reu – Experimental Techniques "Art and Application of DIC"

Triangulation uses the calibration and the matched pixel locations in two images to find the 3D point in space

Calibration Parameters

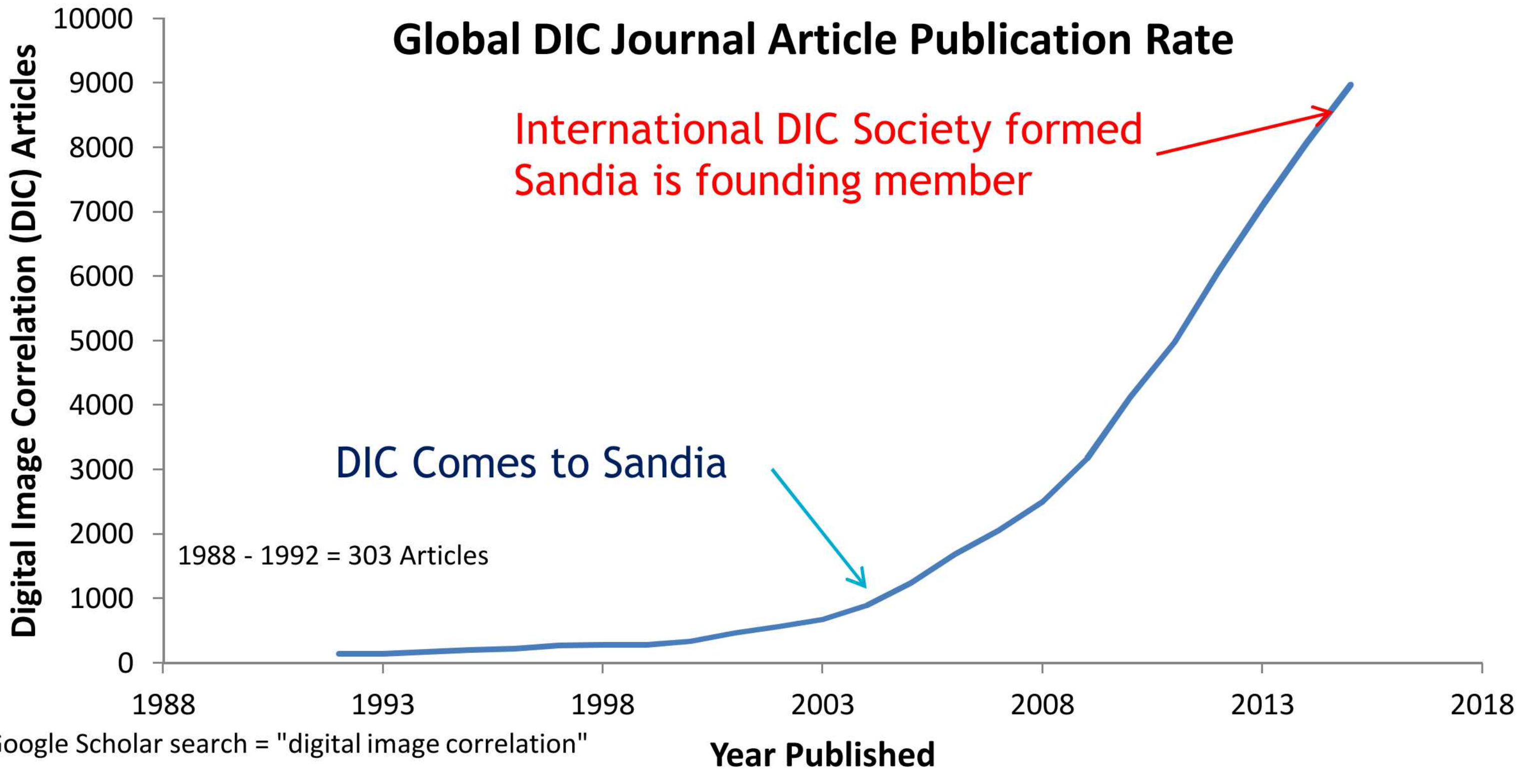
- Camera 1
  - Center x: 620.77 pixel
  - Center y: 368.819 pixel
  - Focal length x: 7300.19 pixel
  - Focal length y: 7298.06 pixel
  - Skew: -1.78958
  - Kappa 1: 0.0454422
  - Kappa 2: 0
  - Kappa 3: 0
- Camera 2
  - Center x: 621.265 pixel
  - Center y: 426.103 pixel
  - Focal length x: 7287.66 pixel
  - Focal length y: 7286.16 pixel
  - Skew: -1.35447
  - Kappa 1: 0.0363301
  - Kappa 2: 0
  - Kappa 3: 0
- Transformation
  - Alpha: 27.6014 deg
  - Beta: 2.1582 deg
  - Gamma: -2.70103 deg
  - Tx: -43.6947 mm
  - Ty: 1255.27 mm
  - Tz: 325.903 mm
  - Baseline: 1297.63 mm



DIC has revolutionized experimental testing, model validation and material testing at multiple scales.

Impacts of Image Based Measurements at Sandia and Globally

- International DIC society (First conference Philadelphia 2016 – 200 Attendees)
- Uncertainty Quantification
- High-Rate and Ultra-high rate testing
- Material property measurements
- FE Model validation



Google Scholar search = "digital image correlation"

Digital Image Correlation publishing.xlsx (OneNote)

There are a large number of commercial vendors and professional societies supporting DIC

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

Mission: Extend – Improve – Train

Extending the Frontiers: Training the next Generation: Standardizing for Industry: Improving our Practice

Committee Meetings

- Standards & Best Practices – Mark Iadicola
- Training & Certification – Tim Schmidt
- Applications – Dave Dawicke
- Education – Mark Pankow
- DIC Challenge – Phillip Reu

Sister Societies

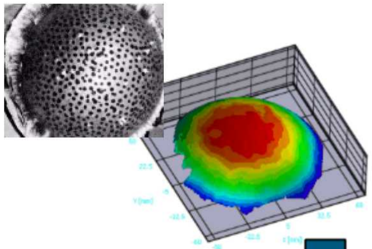
SEM · BSSM British Society for Strain Measurement · ASEM · ICEM 2018 · PM 2018 Photo Mechanics

IDICs Corporate Members and Commercial DIC Vendors

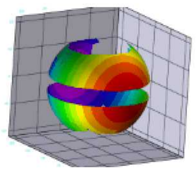
Sandia National Laboratories · NIST National Institute of Standards and Technology U.S. Department of Commerce · correlated SOLUTIONS · gom · Specialised Imaging · LaVision · DANTEC DYNAMICS Turn Measurements into Knowledge · MatchID Metrology beyond colors · HADLAND IMAGING · nac IMAGE TECHNOLOGY · Photron · Trilion · RuituoTech · image systems · dom13 · Correli STC Link between Experiment and Simulation

Digital Image Correlation at Sandia

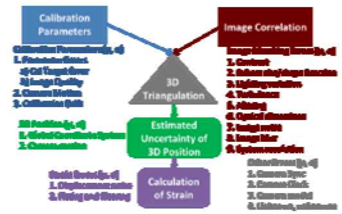
Displacement, velocity and strain
Up to 5 MHz



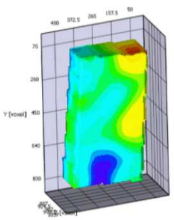
360° coverage



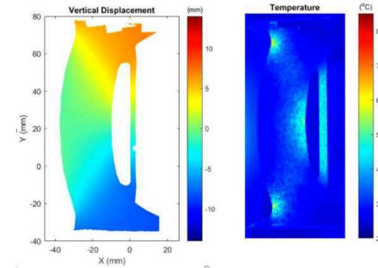
Stereo-DIC Uncertainty Quantification
From colors to metrology.



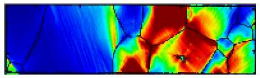
Volumetric DIC



Advanced Material Testing

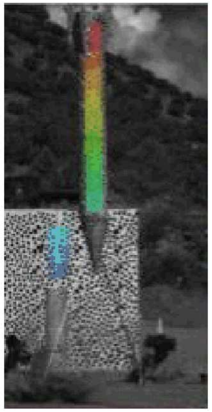


Grain Scale strain

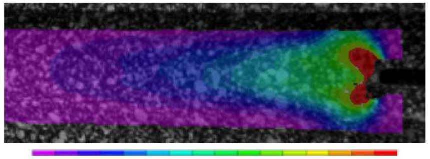


2005 | 2007 | 2009 | 2011 | 2013 | 2015 | 2017

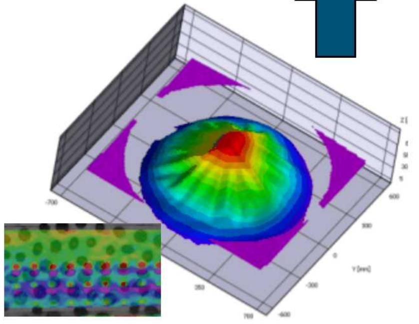
Introduction of DIC
to Sandia



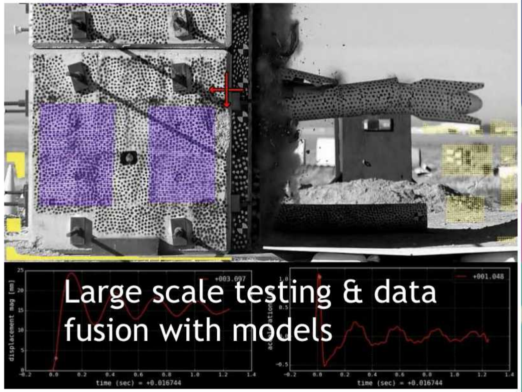
Crack-tip and Fracture Strain



0% 5% ε 15%

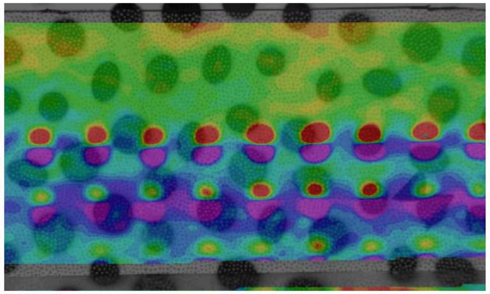


Explosive Panel Deformation

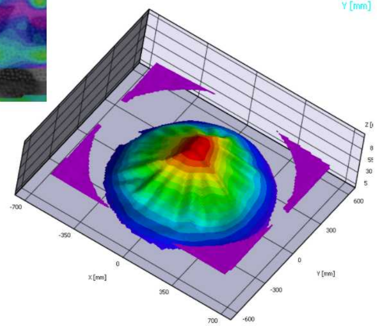


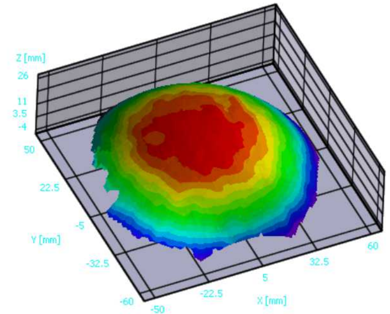
Sandia's growing use of quantitative image based measurements.

Imaging equipment has revolutionized experimental measurements.

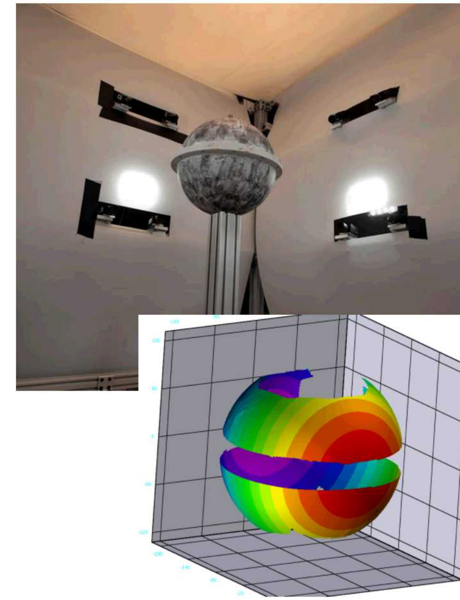


www.visionresearch.com





www.shimadzu.com

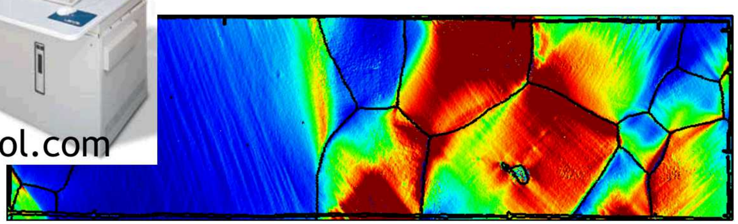


High Speed Displacement and Strain

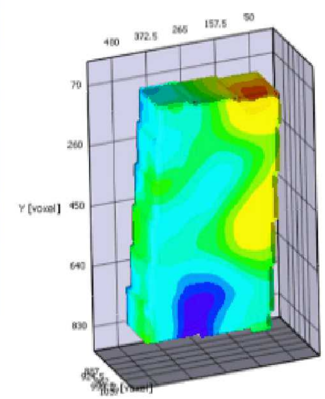
5 Million FPS

Multi-System

www.jeol.com



www.exactmetrology.com

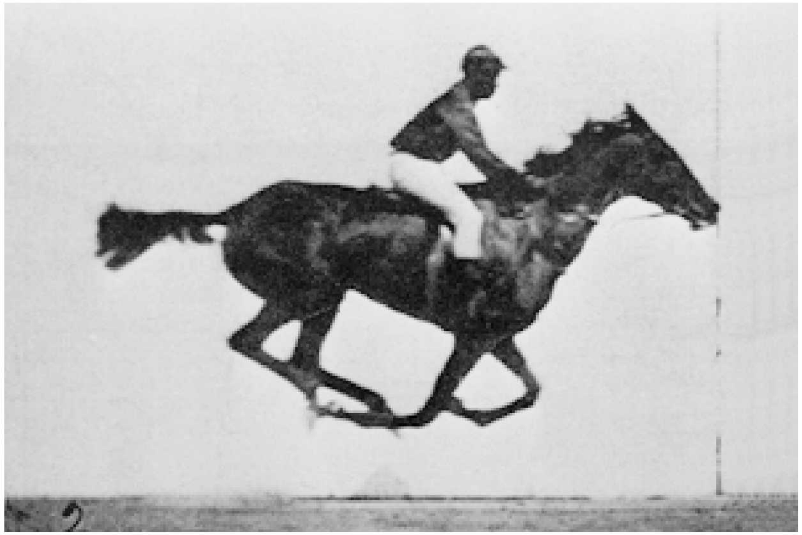


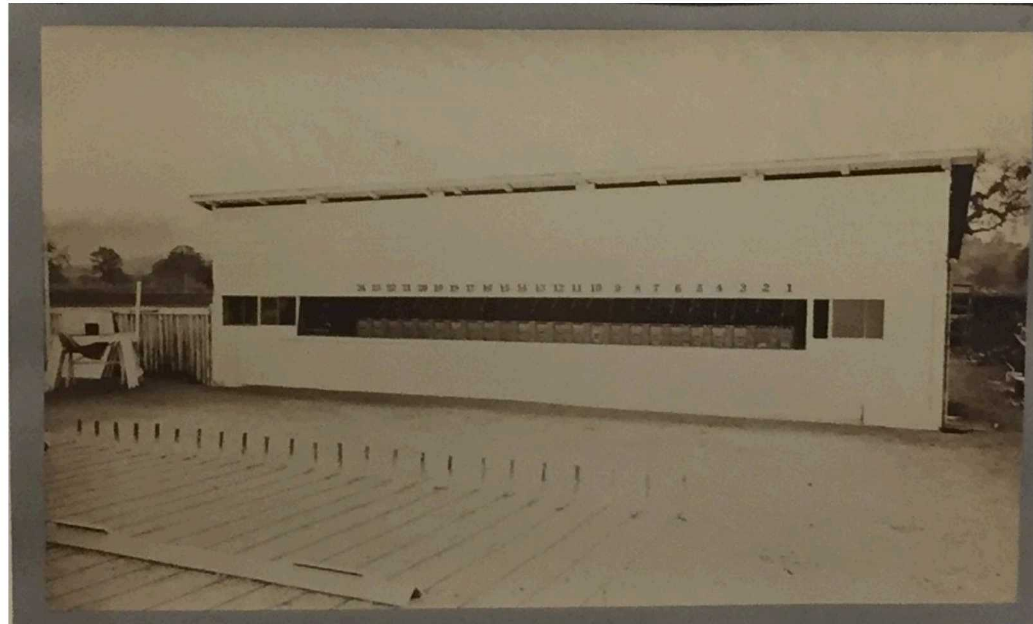
Grain scale strain measurement (optical)

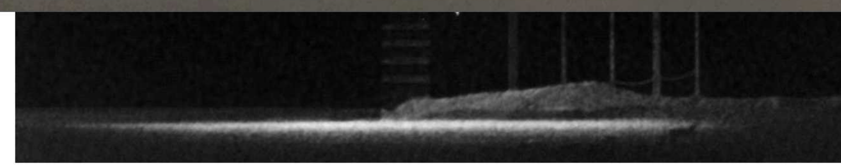
Volumetric strain fields

Grain Scale: J. Carroll

High speed helps to understand things too fast for human perception.





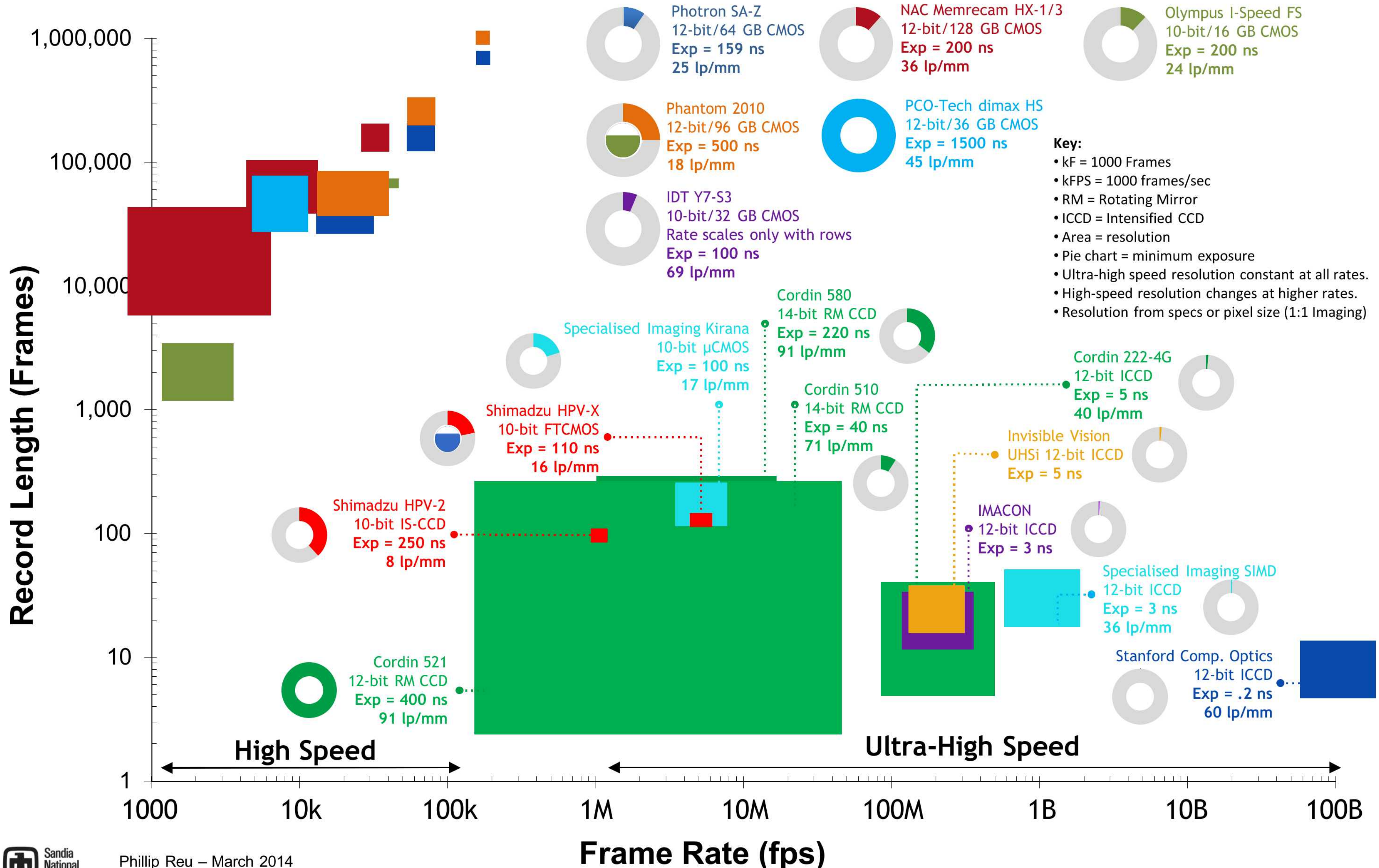


Eadweard Muybridge (1878)
- Multiple cameras lined up and triggered by a thread.
- Later used clock work timing.

Harold Edgerton (1940s)
- Nanosecond to microsecond exposures.
- Done with polarization and Faraday or Kerr cells for shuttering.

http://en.wikipedia.org/wiki/High-speed_photography

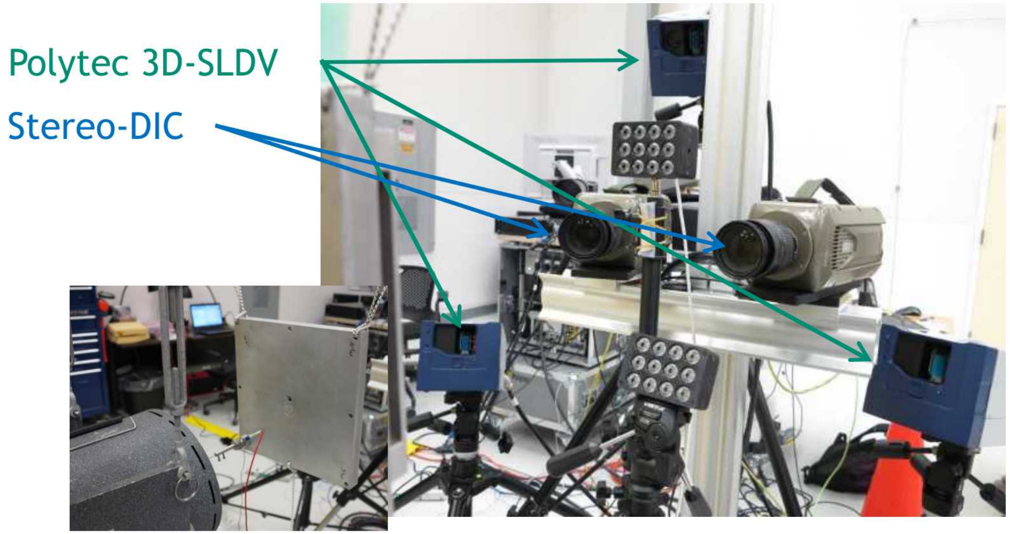
The state of high-speed imaging



DIC has begun to be used for full-field modal testing. It can yield strain mode-shapes.

Why full-field?

- Captures peak location.
- Allows visualization of the entire mode shape.
- Does not mass-load the structure.

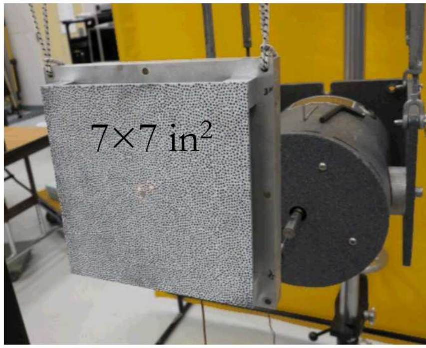


Experimental Setup

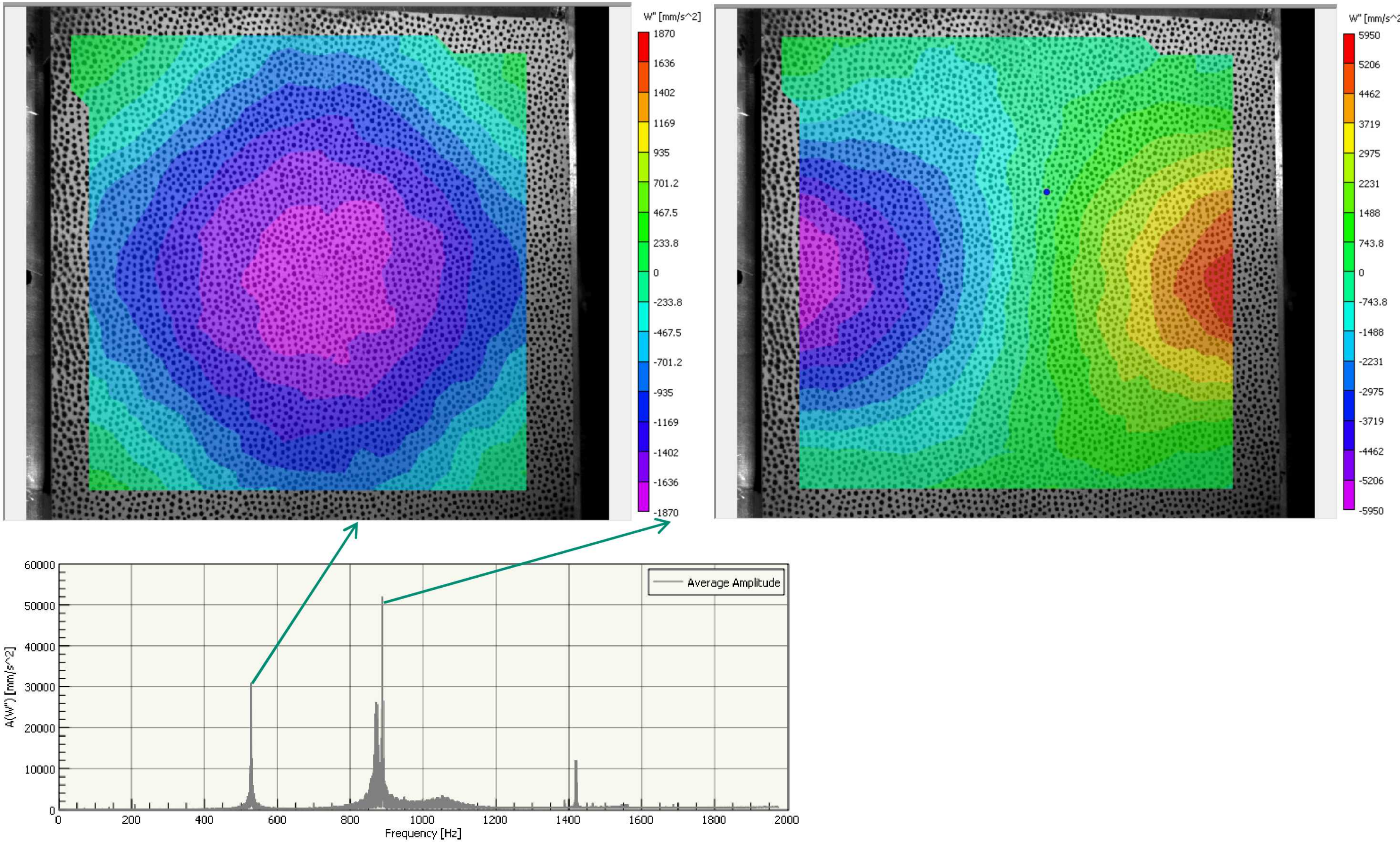
- Polytec PSV-500 3D-Scanning LDV system.
- Vic3D and Phantom 611 Cameras (800×800)
- 3906.25 Hz (200 μs exposure) to match LDV
- MB-50 Shaker on a shaker stand (Pseudo-Random)
- Speckle painted surface (not ideal for LDV)
- Retro surface (not possible for DIC)

What we investigated

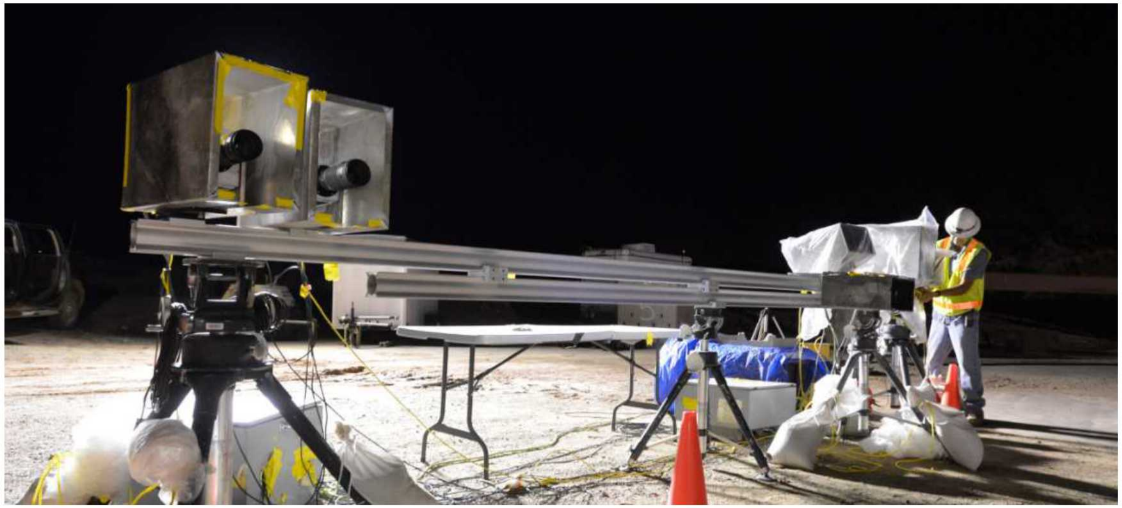
- Time to measurement (setup)
- Cost (not really)
- Measurement time
- Analysis time/data point
- Noise floor/resolution
- Ease of use (subjective)



Mode shapes with nanometer displacements and sub-microstrain can be measured.

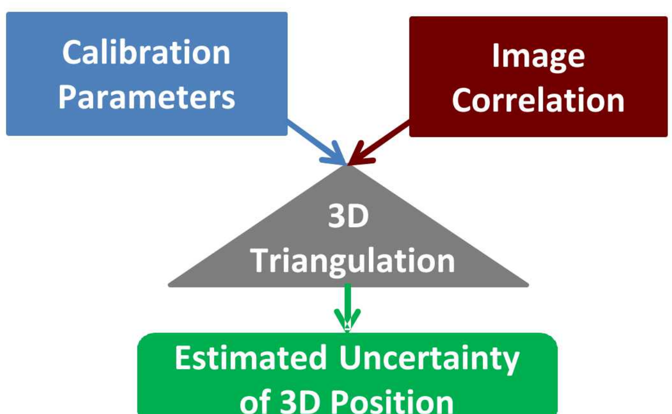


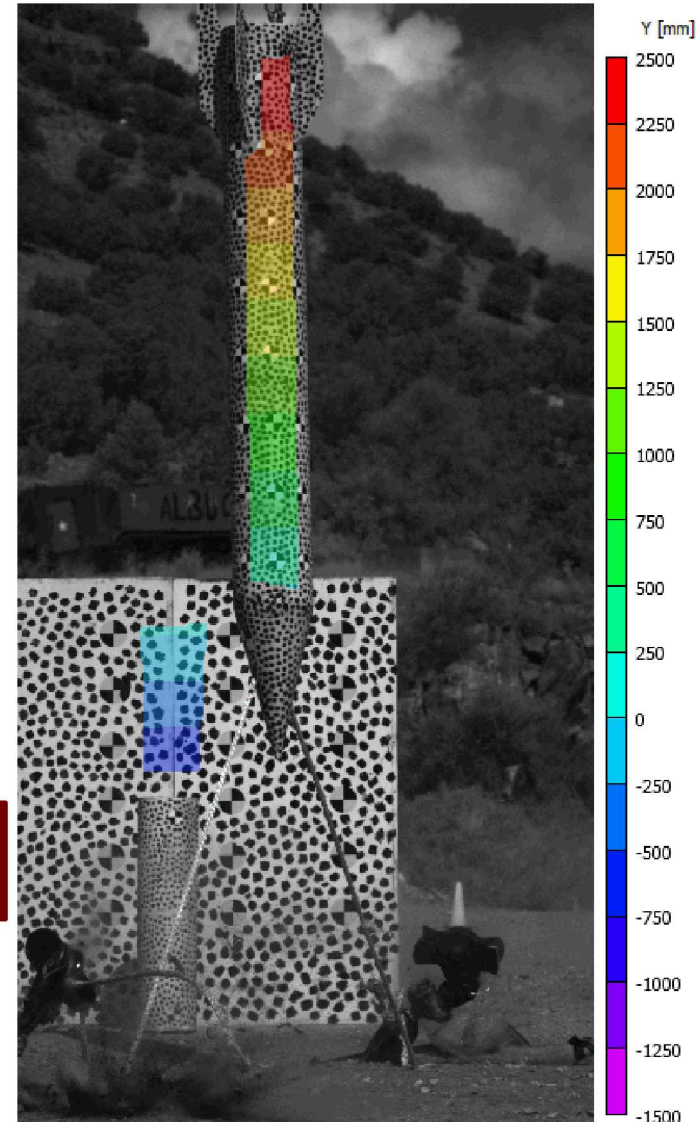
Photogrammetry and DIC have moved high speed imaging from qualitative to quantitative.



Goal: 1-mm resolution in 6 meters

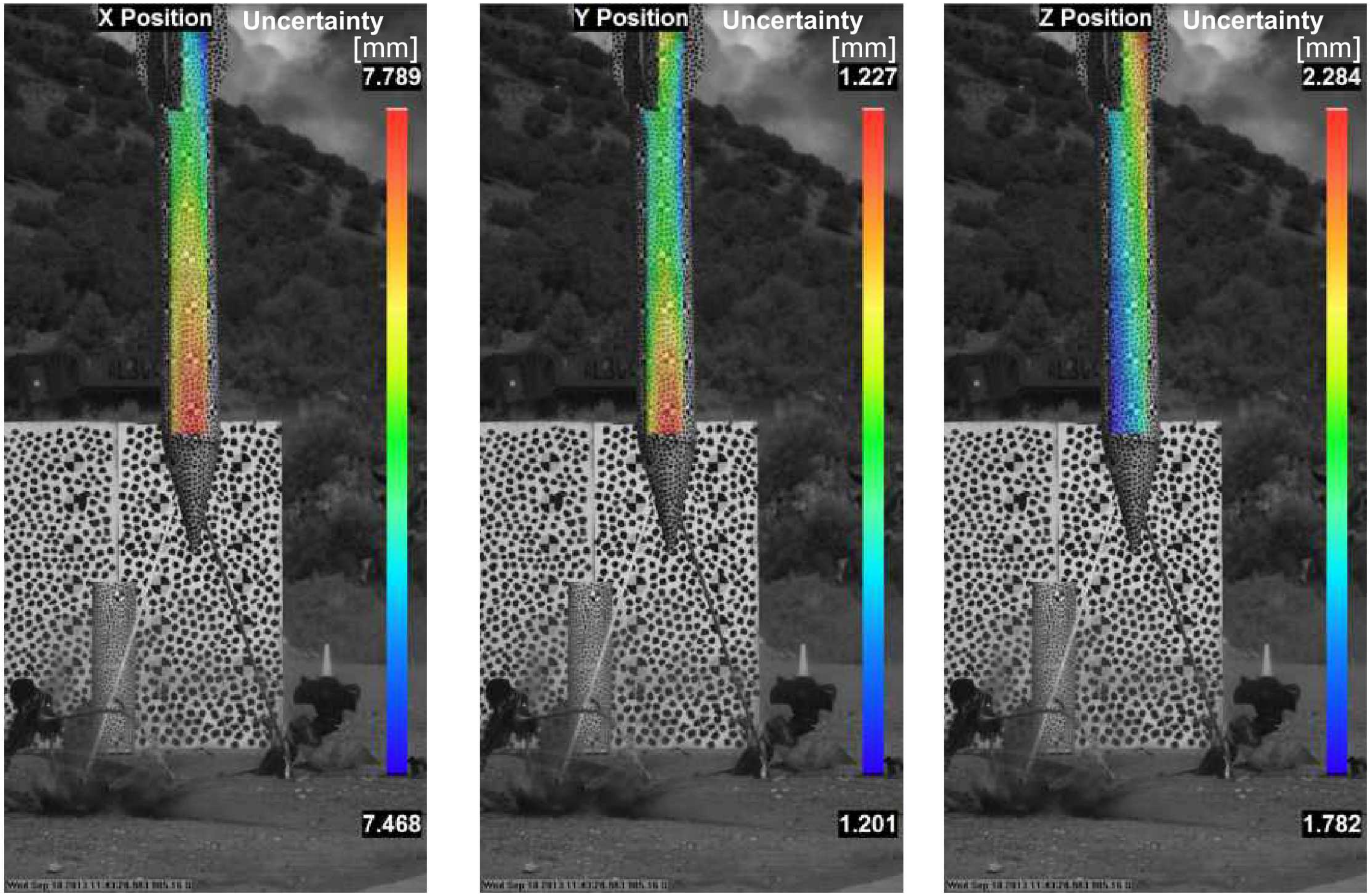
- That is 0.02% error.
- 180 parts-per-**million**
- 0.25 pixel error





The errors can be propagated to calculate a 3D uncertainty.

Includes Calibration and Sensor Uncertainty

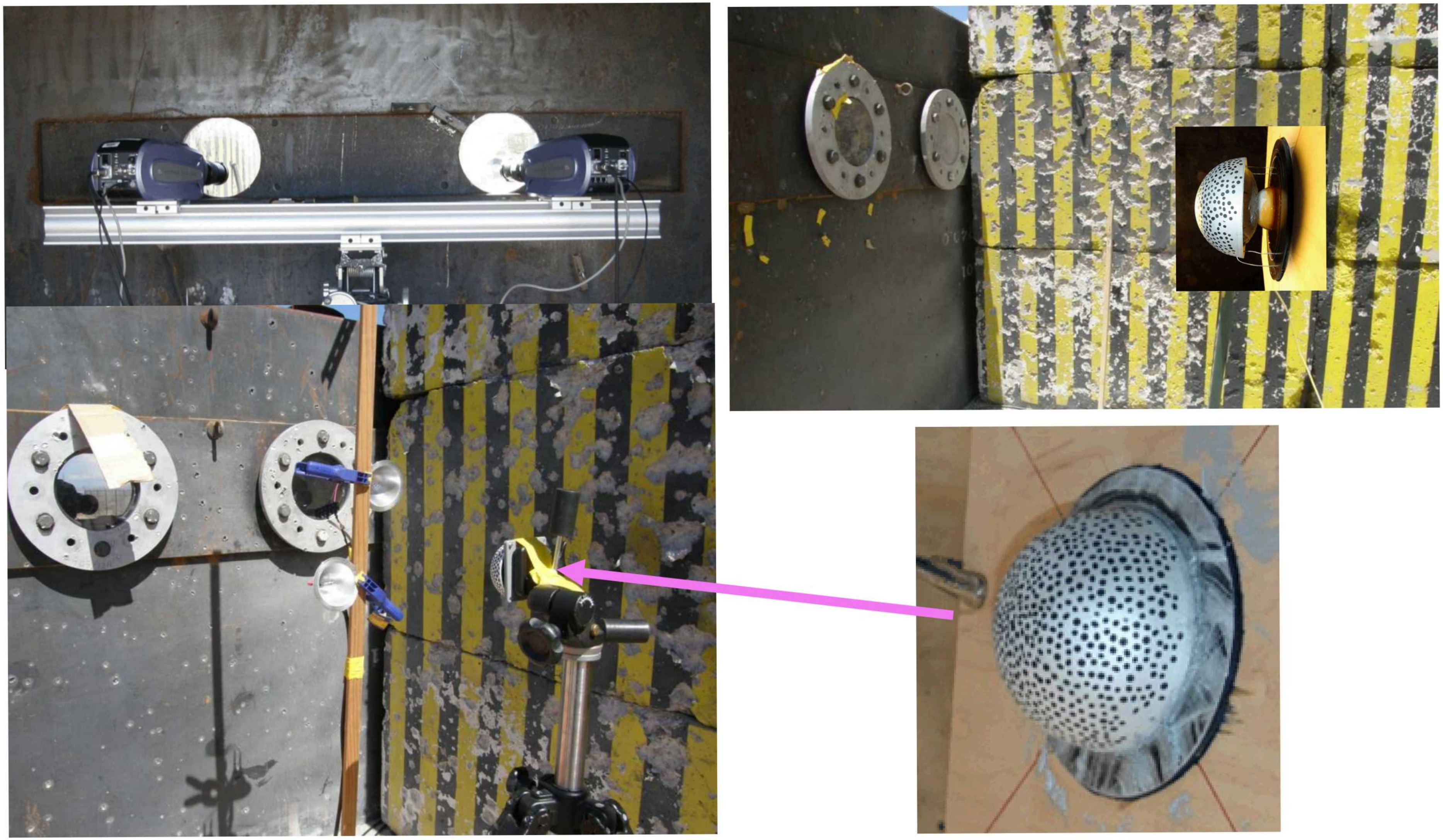


Achieved: 7.5-mm in 6 meters

- 0.125% Field-of-View
- 1.9 pixel error.

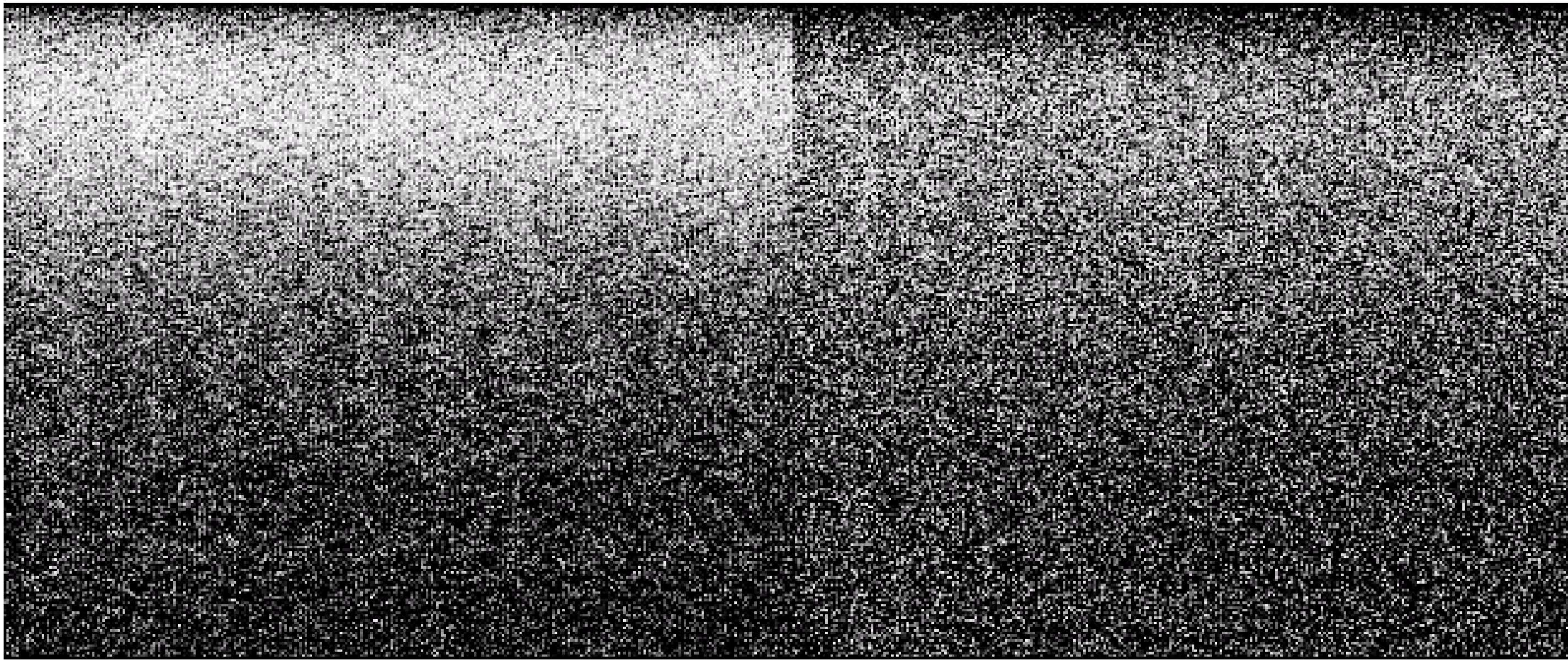
Key: Errors in DIC can be estimated.

Ultra-high speed DIC Example: Cased explosive at 1 MHz

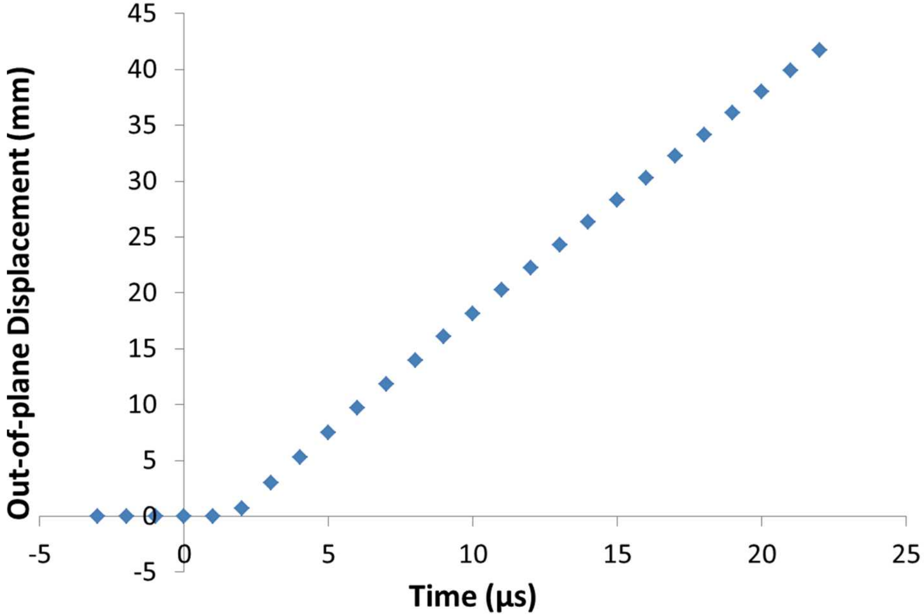


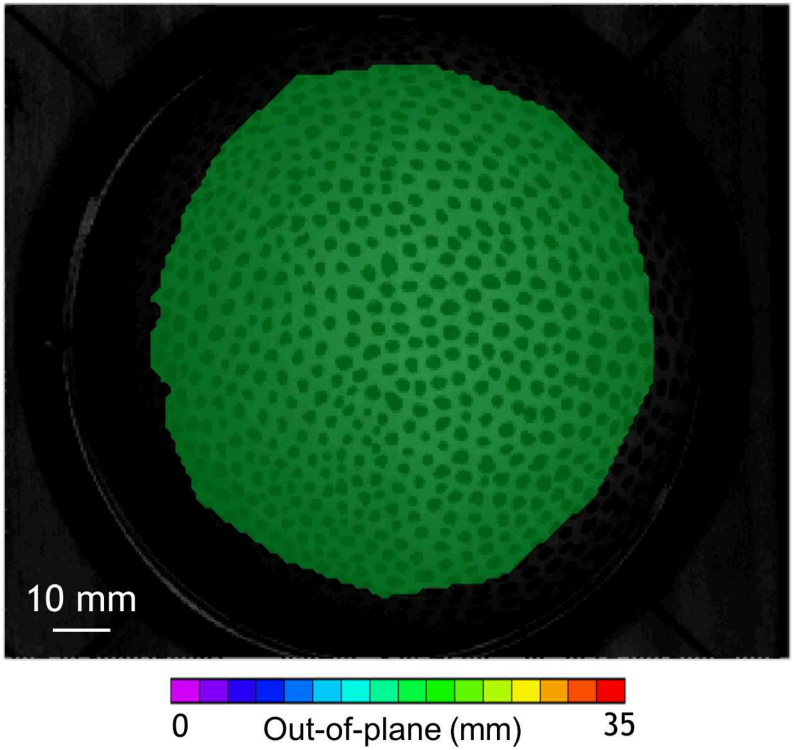
Work with Marcia Cooper

The ability to image at MHz puts nearly all *physical* phenomena within experimental range.



We can now conduct tests at all physically relevant mechanical rates.



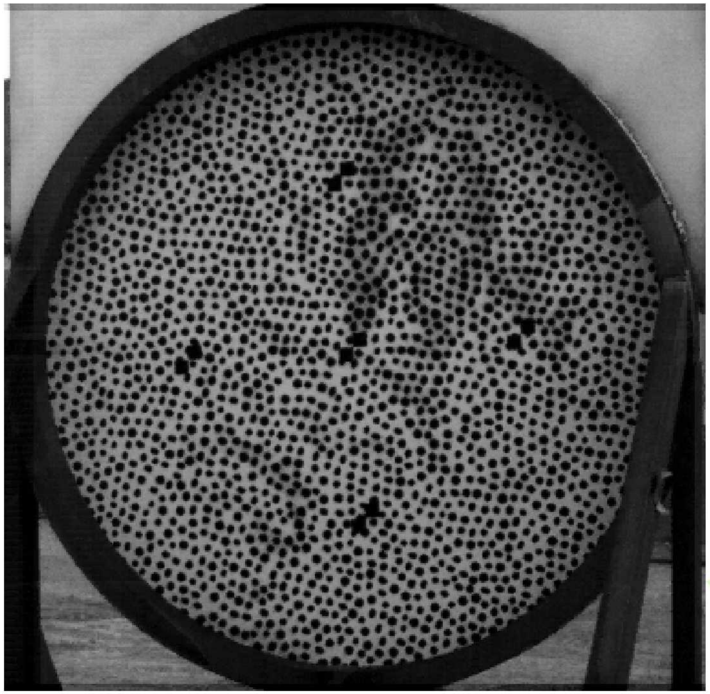


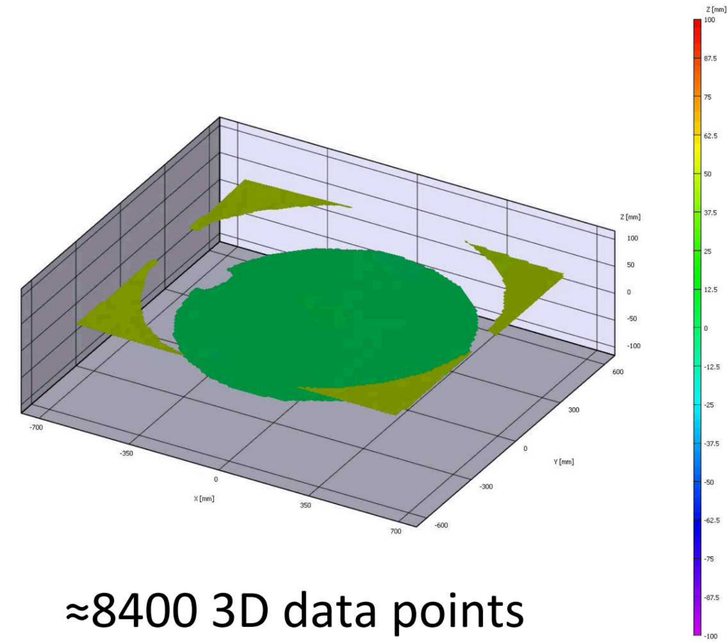
Experimental Data at all relevant rates

- Up to 5 MHz
- Explosive behavior study
- Material failure study – no need to extrapolate material models.
- Model validation at the relevant rates and size scale.

Key: All relevant rates can be tested.

Example: Blast loaded plate at 35-kHz

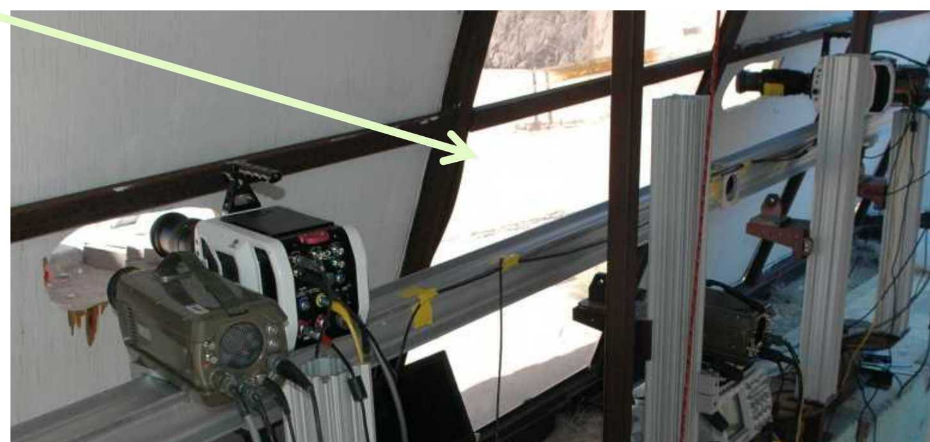




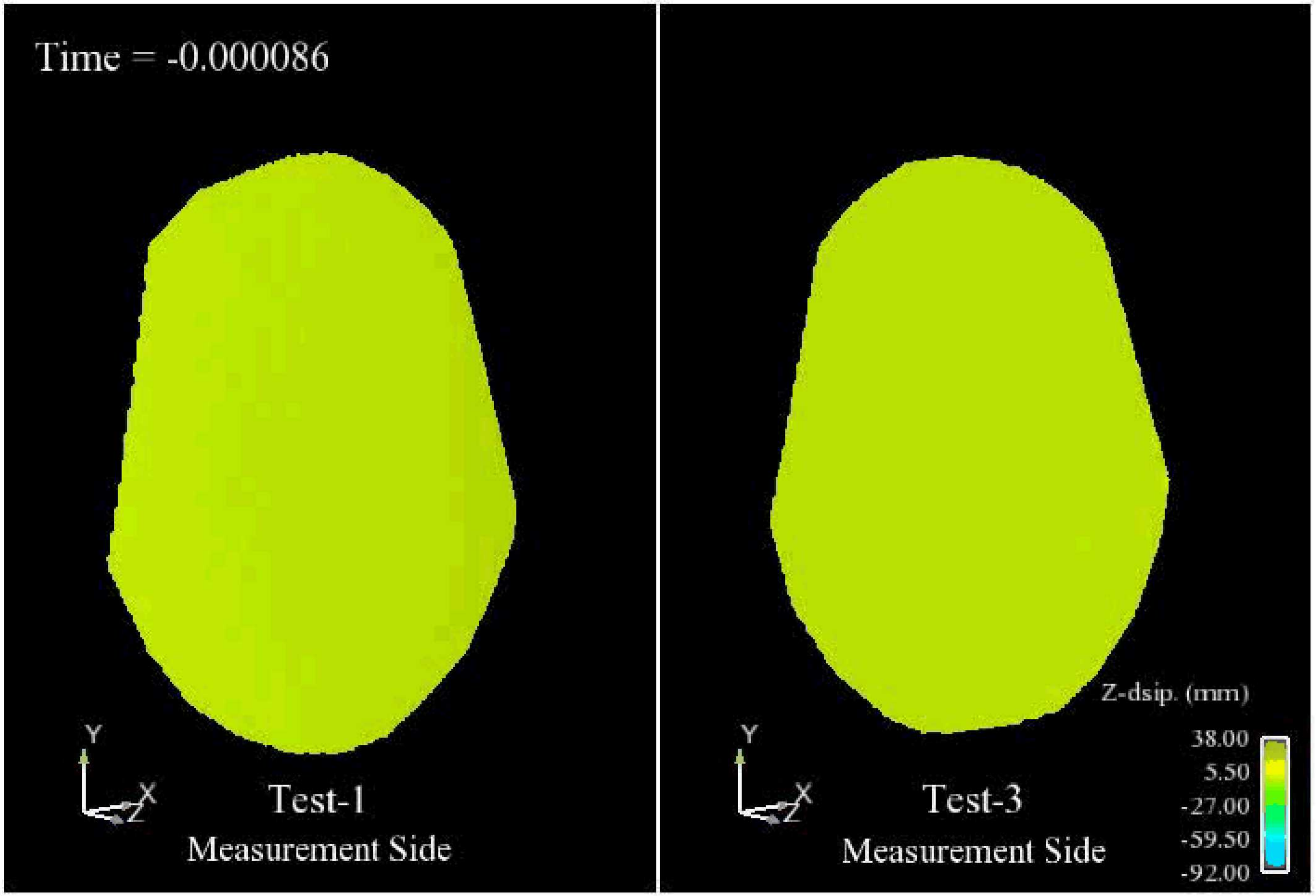
≈8400 3D data points

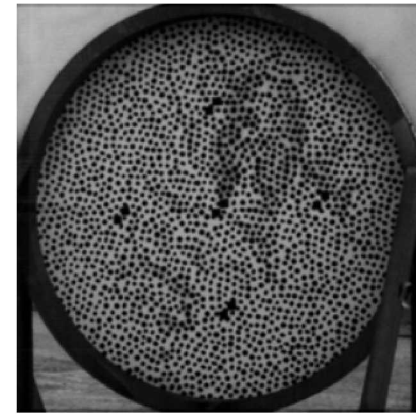
≈25 ft

1 Stereo-DIC System
≈37,000 fps 368×360 Wide View



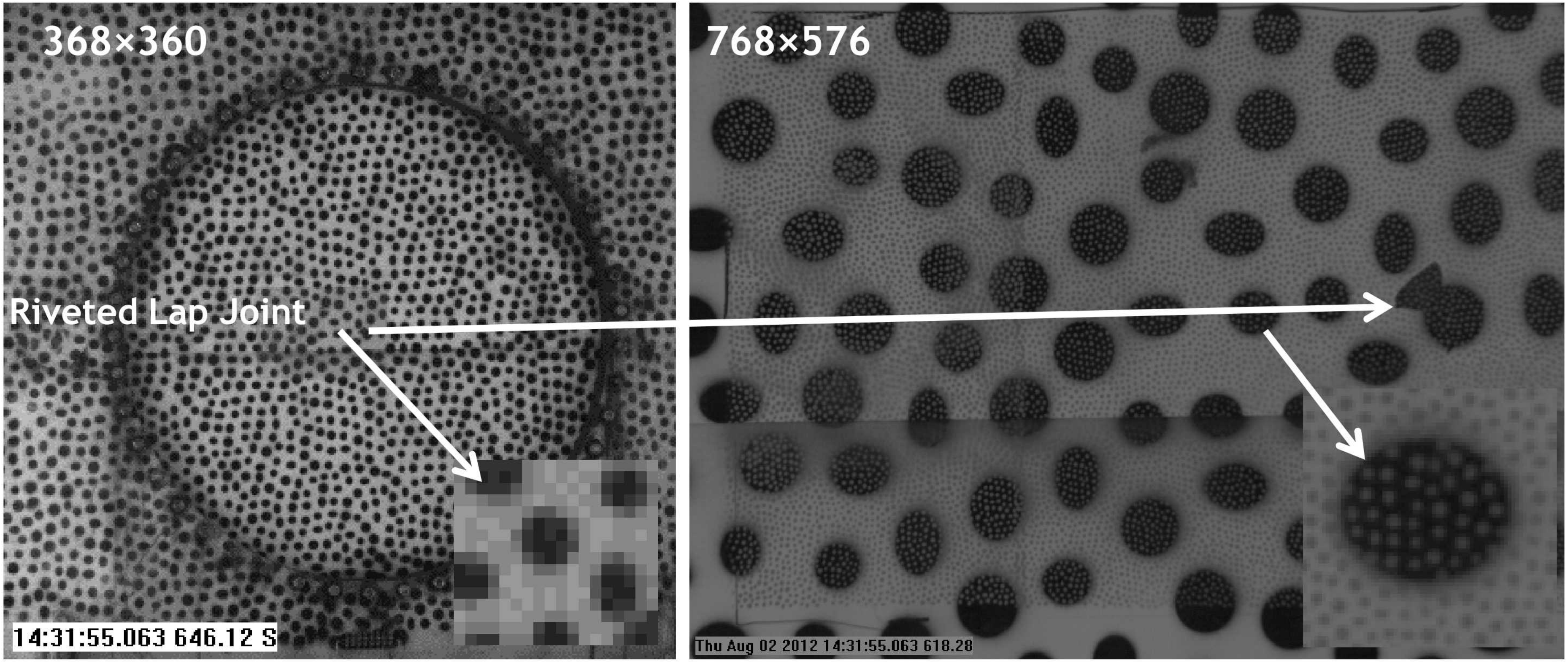
Full-field data helps with understanding the experiment.





Key: Boundary conditions can be measured. Extremely important for finite element validation.

Collection of model validation data for complex experiments using DIC.



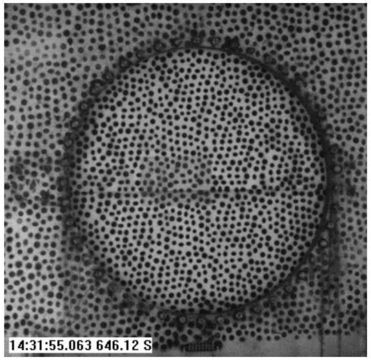
4 mm/pixel

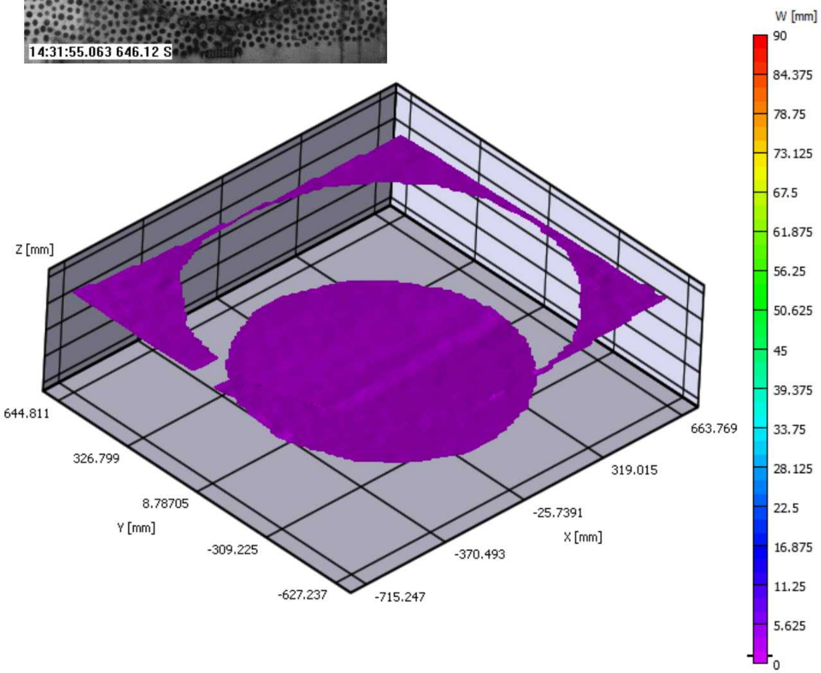
0.4 mm/pixel

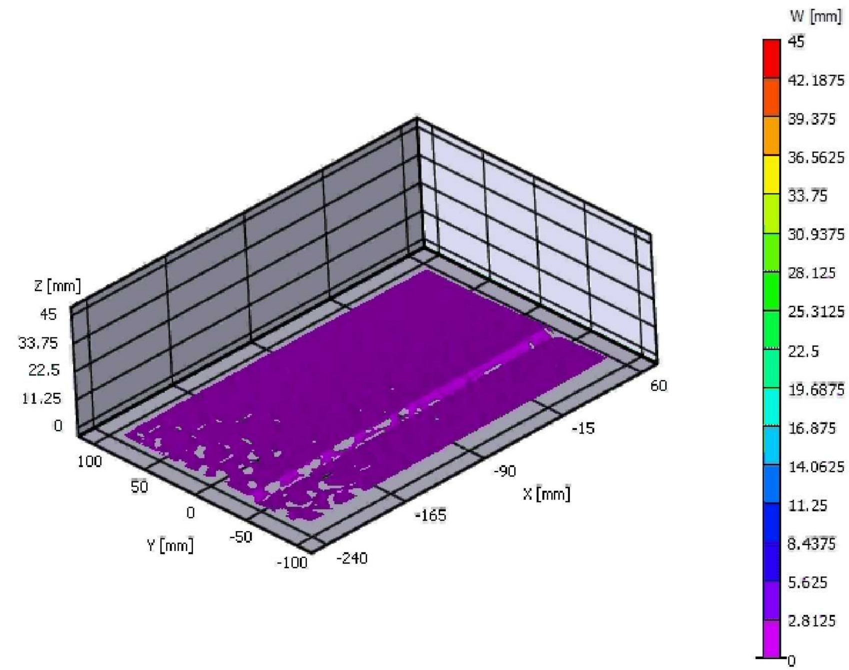
Example: Complex riveted lap joint explosively loaded.

This works because the small speckles are severely aliased in the wide FOV.

We have two systems to measure at two different spatial resolutions.



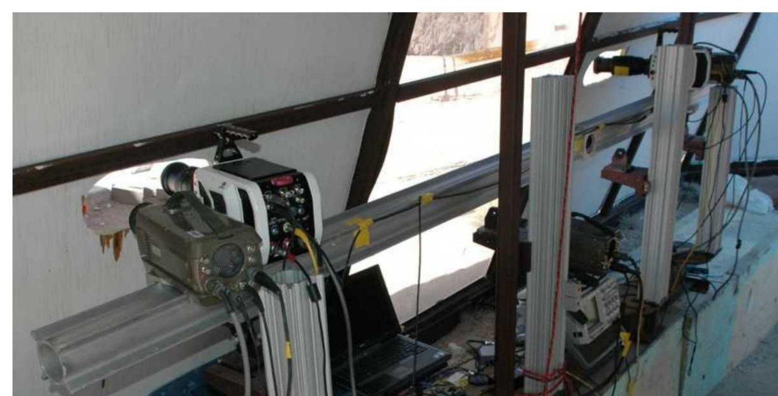




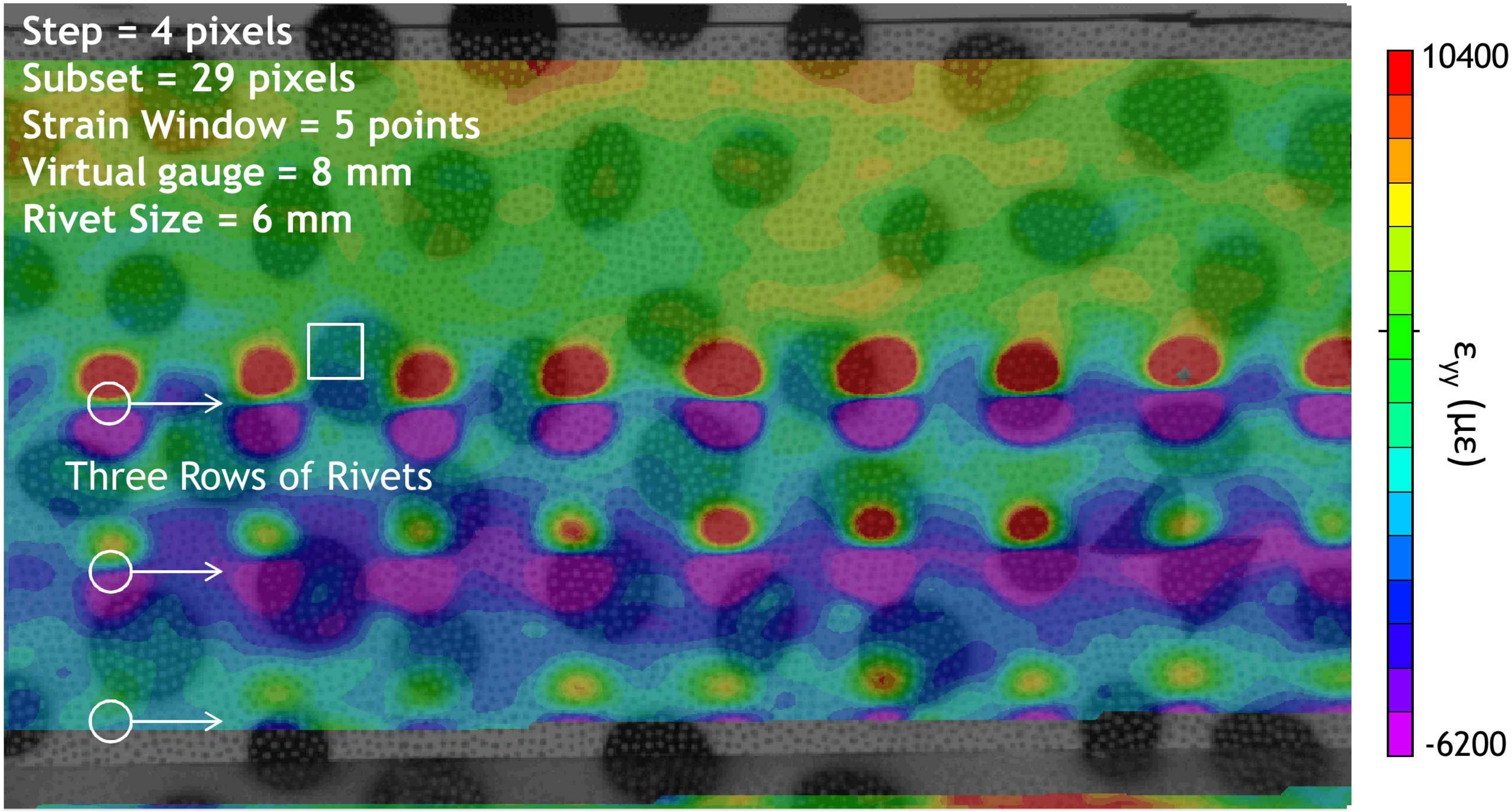
2 Stereo-DIC Systems

≈37,000 fps 368×360 Wide View

≈33,000 fps 768×576 Tight View



With proper experimental design small virtual gauge regions can be measured.



4.6L×5.8W mm

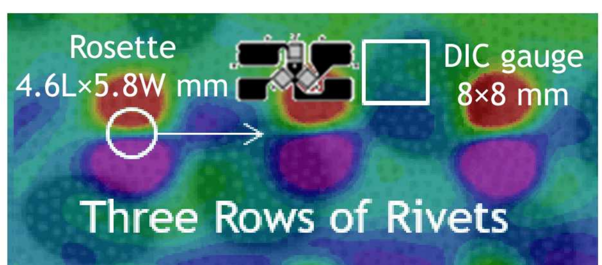
Virtual Strain Gauge 8×8 mm

And at 37 kHz!

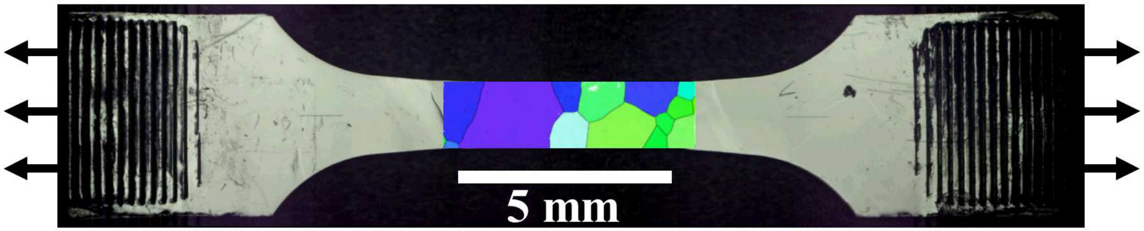
Key: Careful experimental design yields appropriate strain gauge size. With DIC you can explore the effect of gauge size.

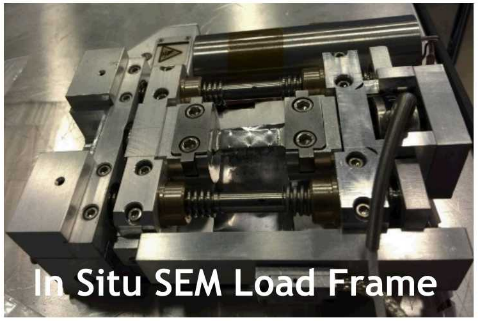
Strain gauges versus Digital Image Correlation

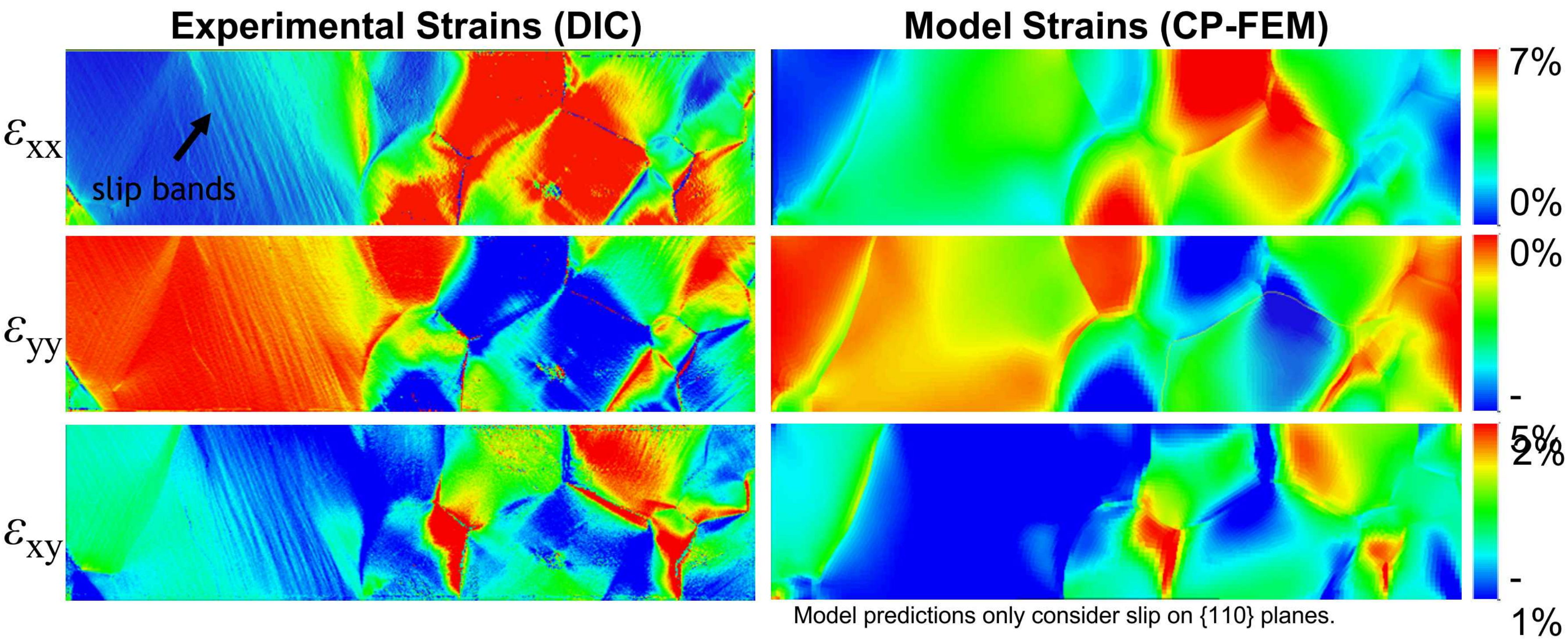
Parameters	DIC	gauge	Comments
Number of measurement locations	👍		Easily 1000's
Strain gauge size	👍 ❓		Depends on Field-of-view for DIC
Smallest measurable strain		👍	DIC ≈ 100 με : gauge ≈ 5 με (Depends on averaging)
Largest measurable strain	👍		DIC > 30% : gauge < 5%
Wide area measurements			DIC – Tradeoff with Field-of-view
Cost	❓		Up front versus per test & analysis time considerations
Traceable Uncertainty	❓	👍	Standards are needed for DIC
Acquisition Rate	👍		DIC = MHz : gauge = kHz
Hidden areas		👍	DIC must have visible access (X-ray in development)
Hot spot detection	👍		DIC does not need to know where the maximum is
Strain bias detection	👍		VSG size study possible with DIC



In situ microscale DIC in optical or scanning electron microscope to validate crystal plasticity models



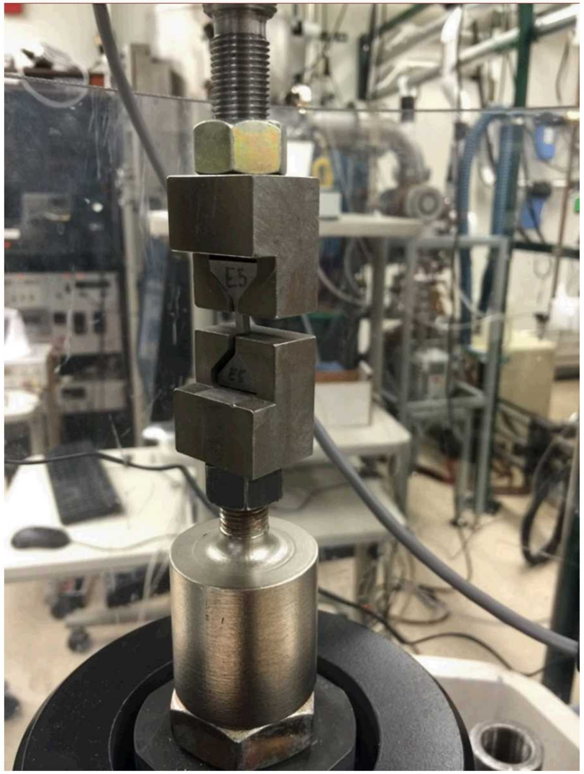


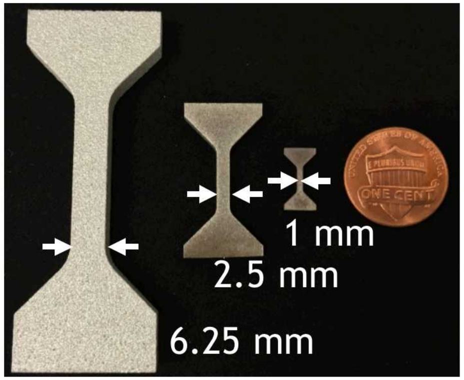


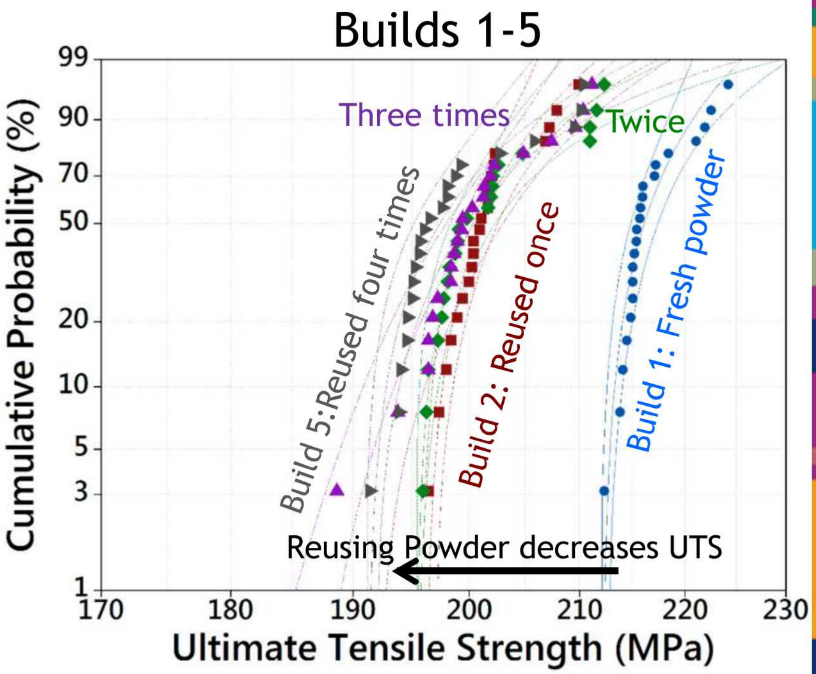
Model predictions only consider slip on {110} planes.

Key: Measurements at all scales.

DIC and high-throughput testing can gather tensile data 20x faster than traditional techniques.



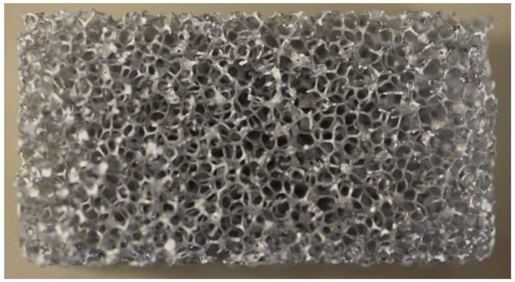


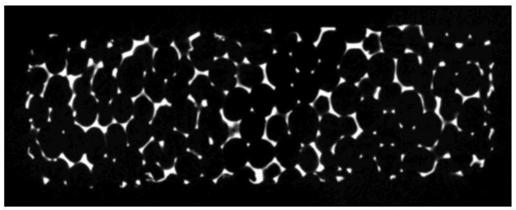


- Tension tests can be performed ~20x faster providing material property distributions with thousands of data points.
- Allows for high-throughput testing to quickly find material property changes in additive manufactured parts.

Key: Rapid automated testing to gather statistical failure: “Big Data”

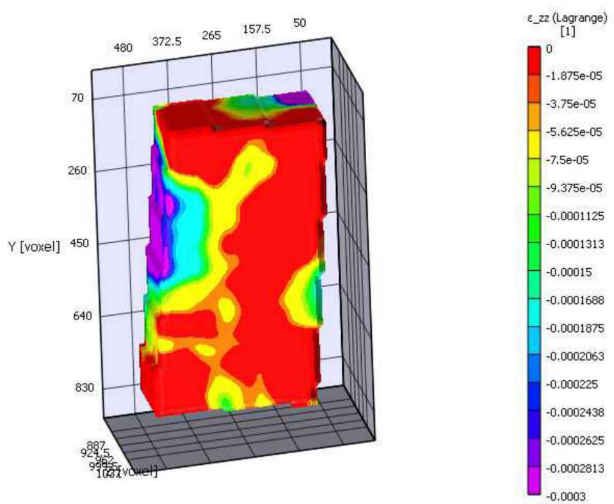
Volumetric DIC using CT scans provides data in all three displacement and strain directions.



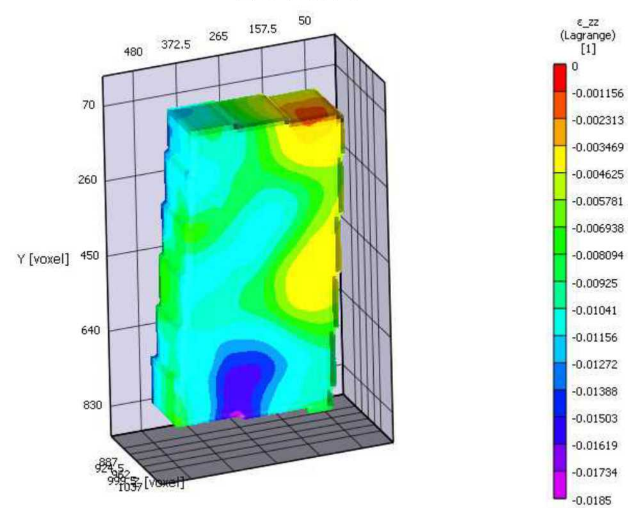


- Volumetric DIC compression of aluminum foam.
- Sample: 38.3mm×20mm×12.6mm
- 2.6x magnification (49.6μm effective voxel size)
- 150kV and 375μA (50W) – 75 minute scan
- Strain in all three directions available: ε_{xx}, ε_{yy}, and ε_{zz}
- Research problems remain for volumetric DIC
  - CT stability
  - Reconstruction algorithms
  - CT calibration

50N



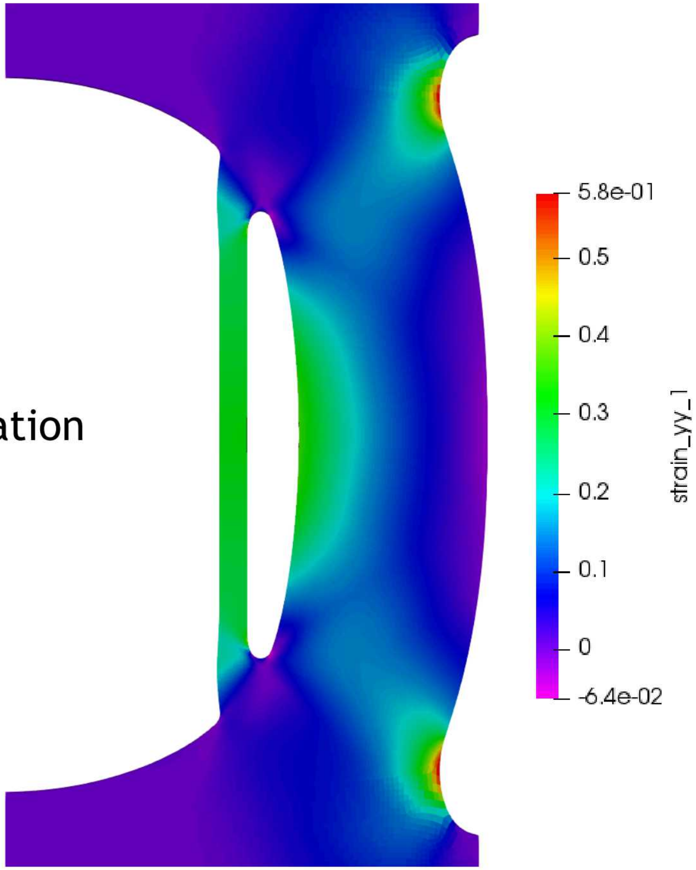
1000N



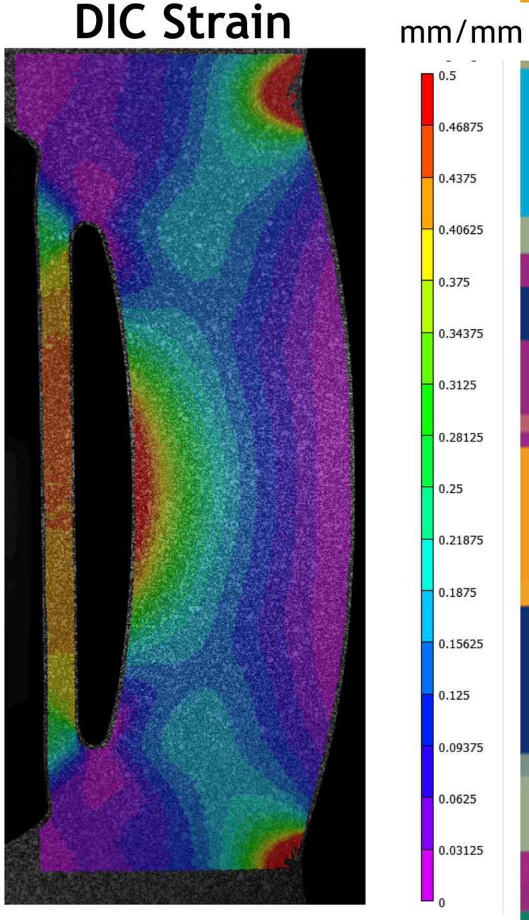
Key: Deformations "inside" samples can be measured. With some caveats.

Finite Element validation is an important use of DIC data. But how do we compare?

FEA Strain



DIC Strain

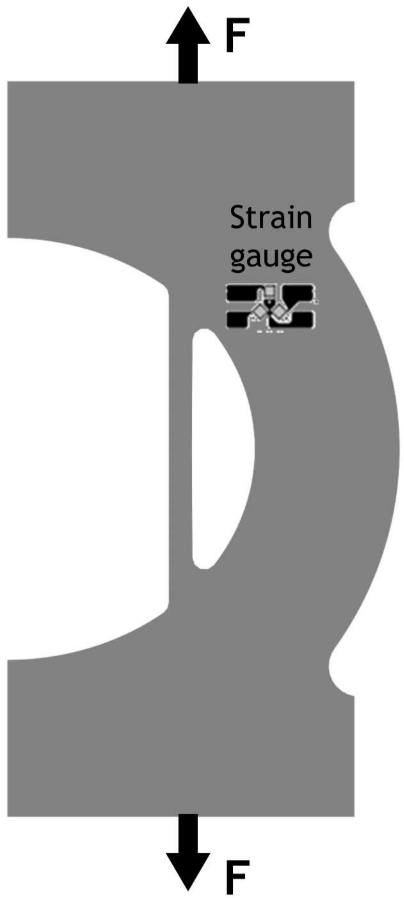


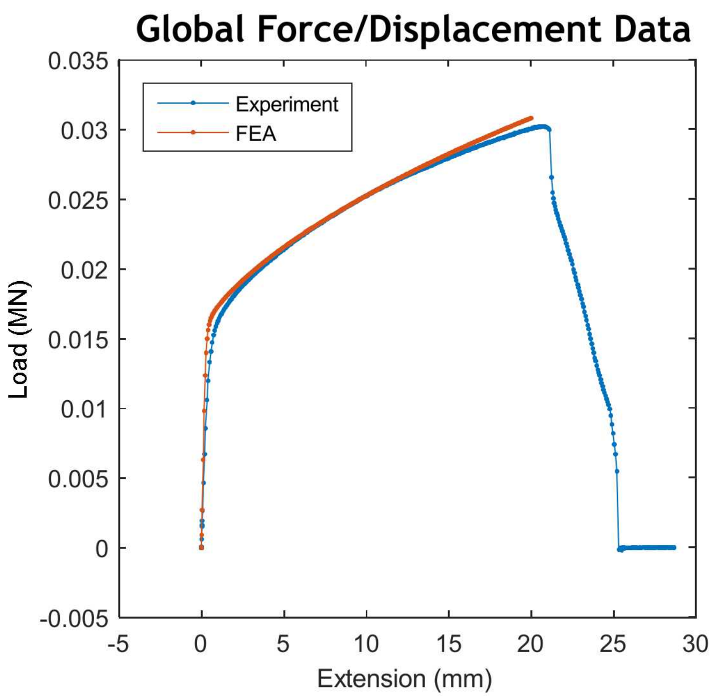
Various solutions are possible
(Vendors have some solutions)

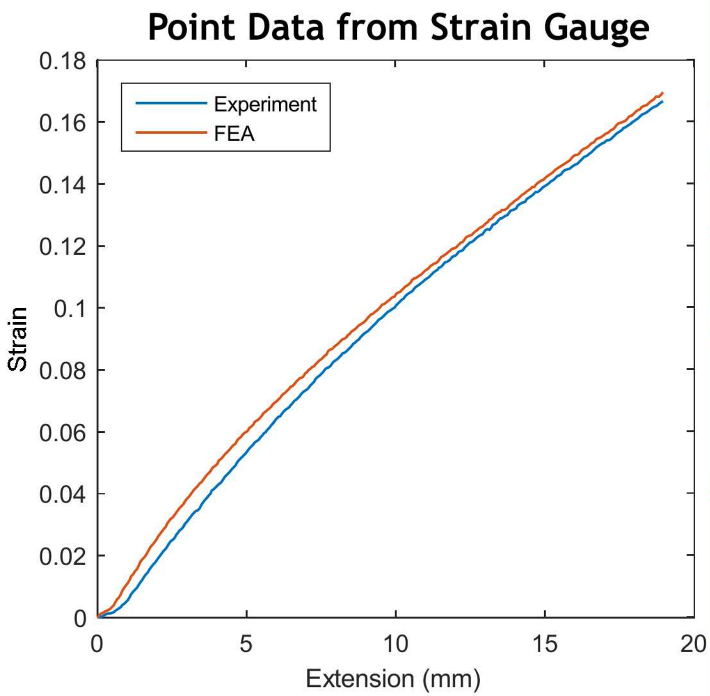
- DIC simulator for comparison
- Data registration and differentiation
- Image decomposition
- Single point comparison

- "View graph norm" – Useful for rough comparison; see if locations of hot spots are the same.
- Quantitative information, though, is better!

FE model validation traditionally uses only global or local point data.

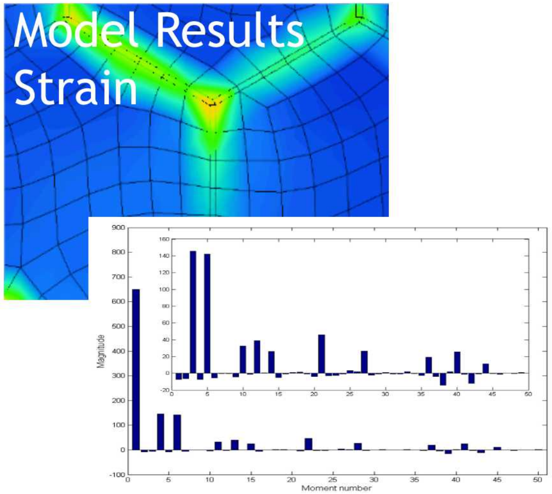


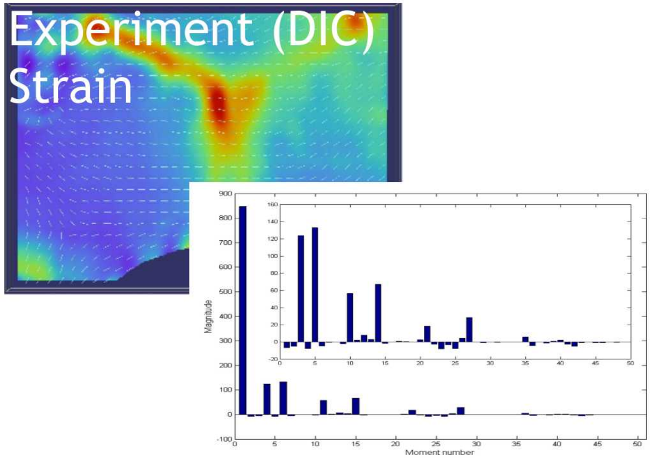


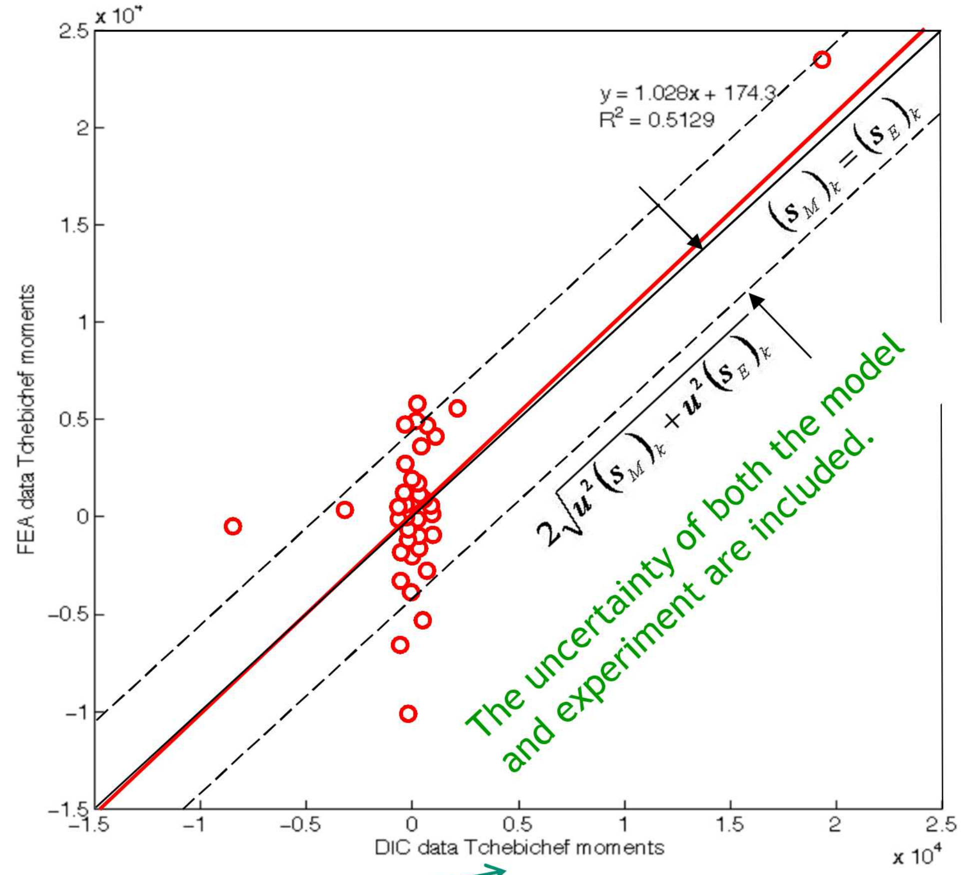


Global and point data does not present a full picture of accuracy of FE model!

Image decomposition is similar to modal analysis: Break the deformation into various shapes.

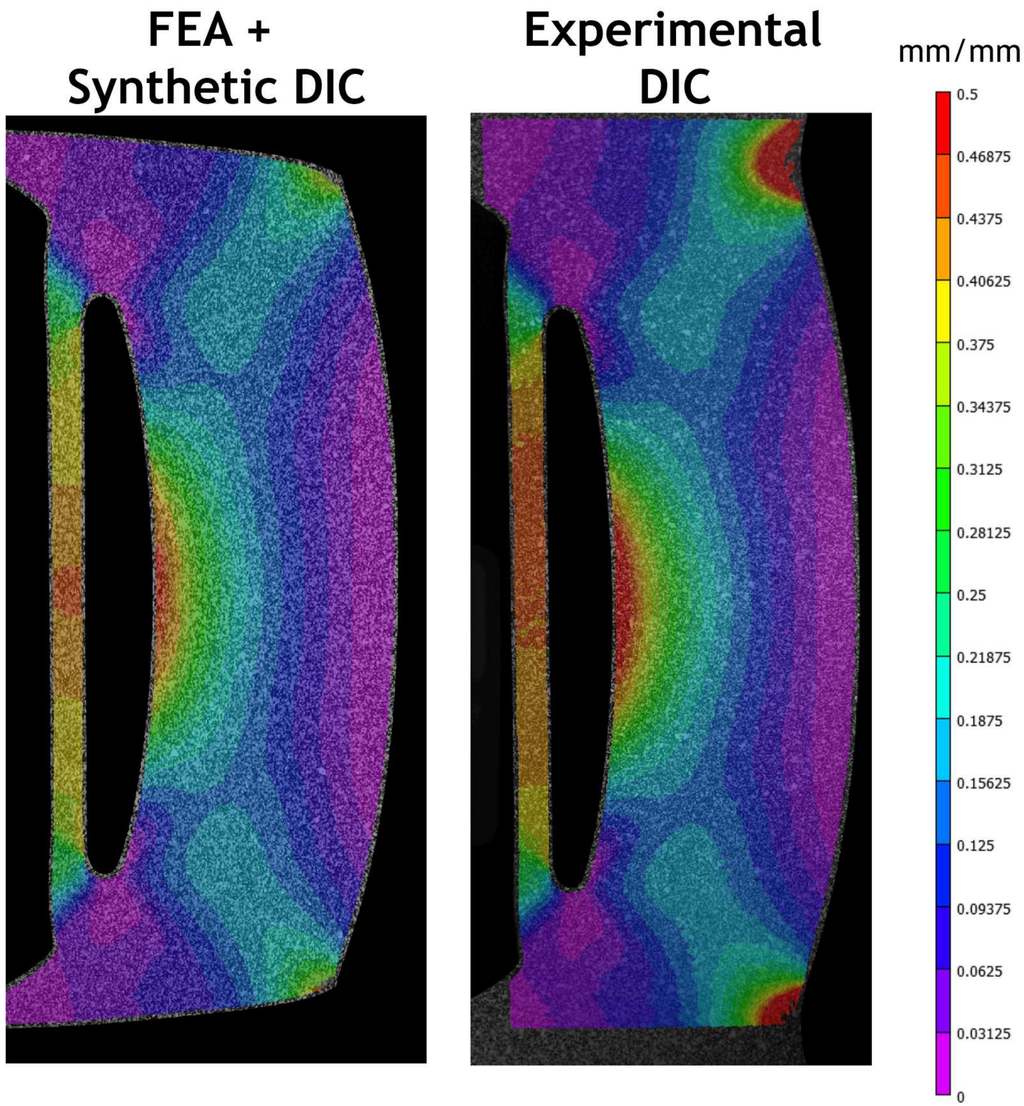






Sebastian, C.M.P., Eann A.; Ostberg, D., *Comparison of Numerical and Experimental Strain Measurements of a Composite Panel Using Image Decomposition*. Applied Mechanics and Materials, 2011. **70**: p. 63-68.

Synthetically-deformed images provide a route for comparison.



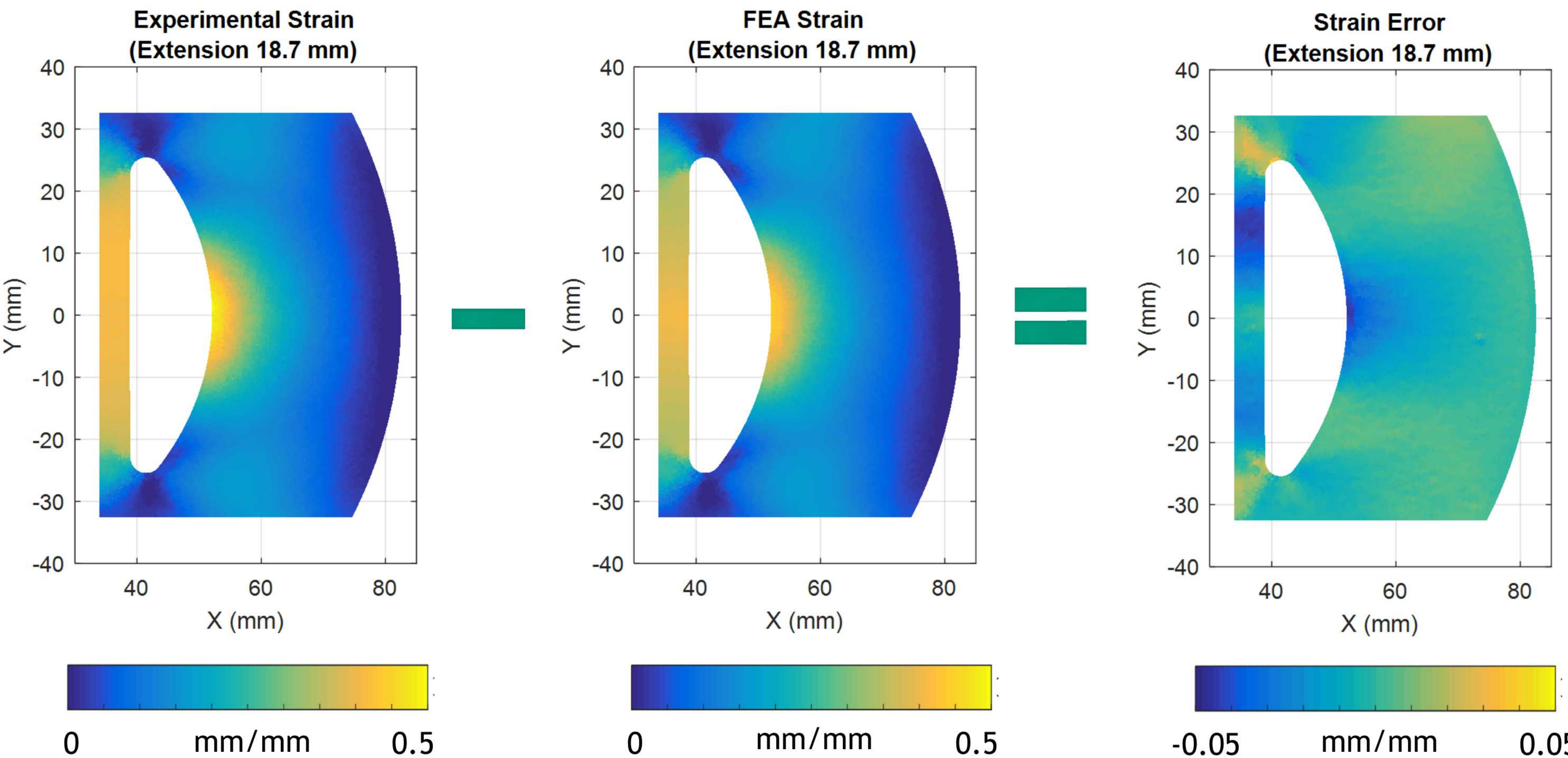
Data processed the same way as experimental images.

- Similar grid of data points
- Same strain calculation method
- Same DIC filtering (subset size, step size)
- Same spatial resolution
- Similar noise sources

Even qualitative comparisons are easier!

Balcaen R, Wittevrongel L, Reu PL, Lava P, Debruyne D (2017) Exp. Mech 57 (5):703-718.

FE and experimental data sets can now be directly compared.



But, how much of the error is caused by experimental noise?

FE model validated if strain error is less than the noise floor.

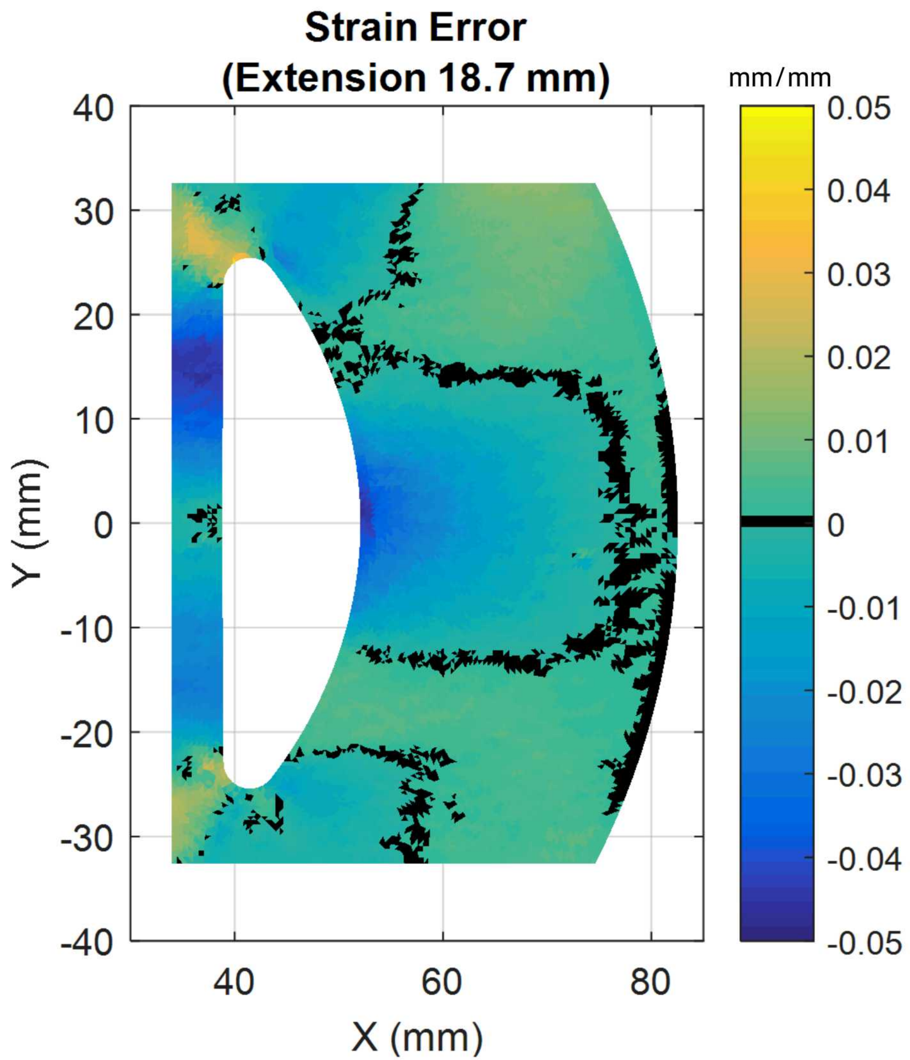
- Black regions are where the FE model and experiment agree to within experimental error.

→ Strain error < noise floor

- Colored regions indicate where the FE model conflicts with experimental results.

→ Strain error > noise floor

- For this particular example, most of the sample has significant (~10%) strain errors, that are above the experimental noise floor.



Traditional material identification can be improved.

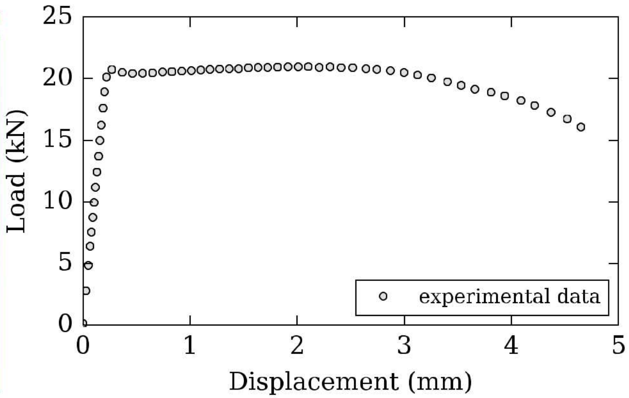
Limitations

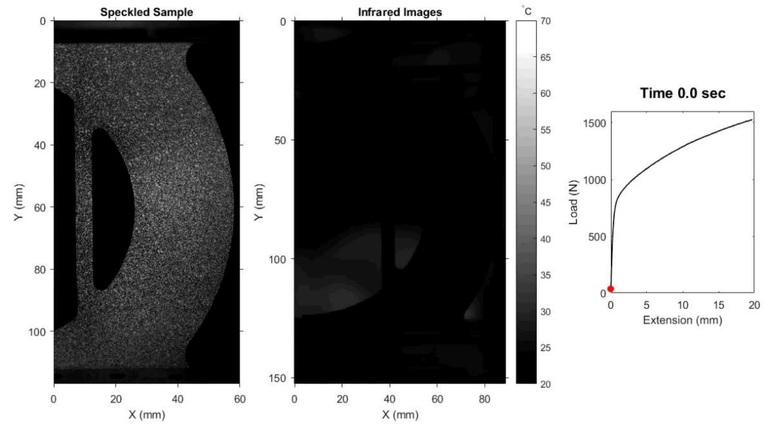
- Global information misses local deformation (Extensometer)
- Many tests to calibrate complex models (Linear superposition)
- Simple stress state does not reflect complex loading conditions (Mechanical Regularization)

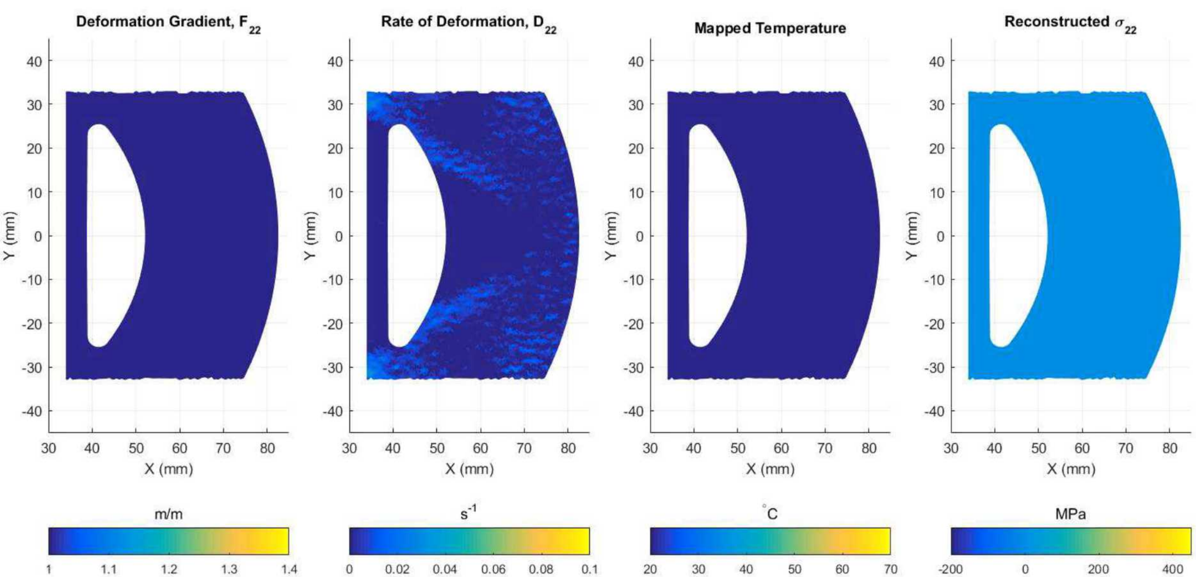
≠

Key: Can we change how material testing is done?

Diagnostics have leapt beyond our ability to use the data in the last 10 years.







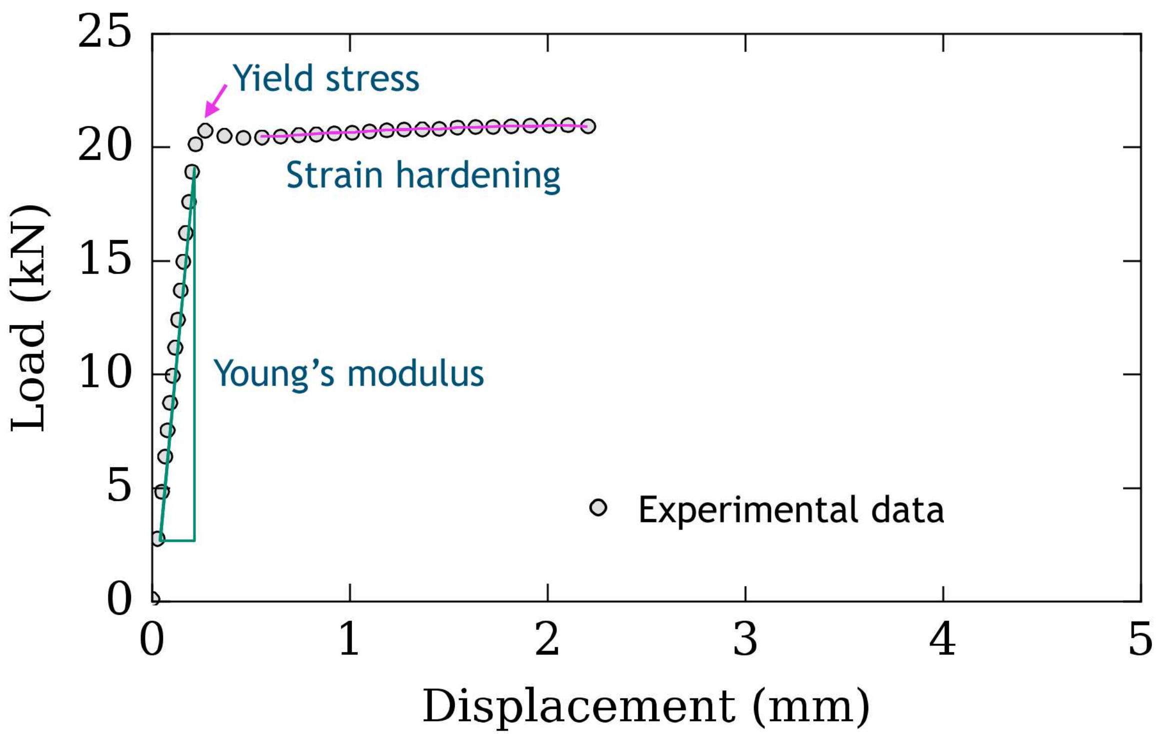
Going From
- Simple specimen, Simple data
- Many assumptions to find parameters
- Poorly constrained fitting space

Going To
- Complex specimen, Dense data
- Optimized specimen
- Data driven material model exploration
- Optimized material model
- Parameter ID
- Room for experimental improvements!

Tensile Testing 2.0: More data per test.

The goal is to get a couple of parameters really well and set the rest to zero.

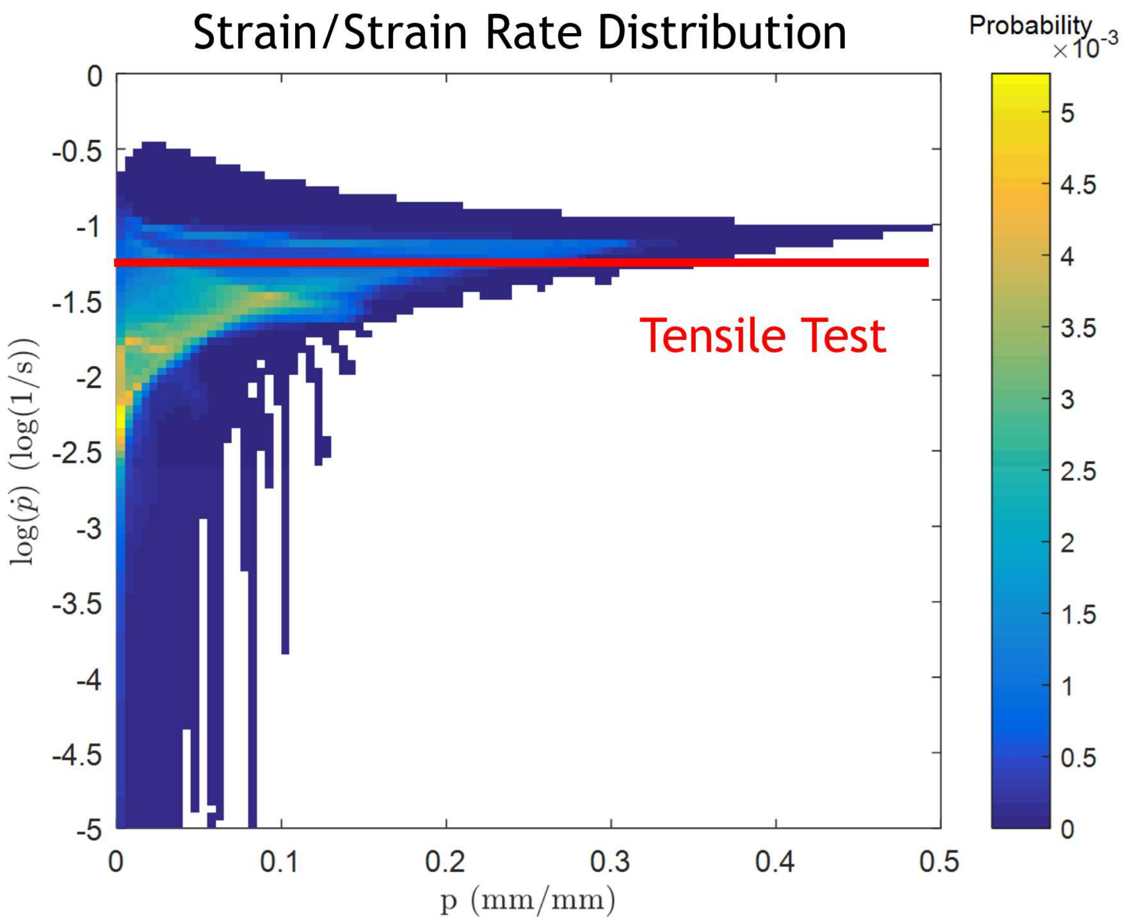
1. Tensile test: Modulus and maybe Poisson.
2. Maybe the yield stress.

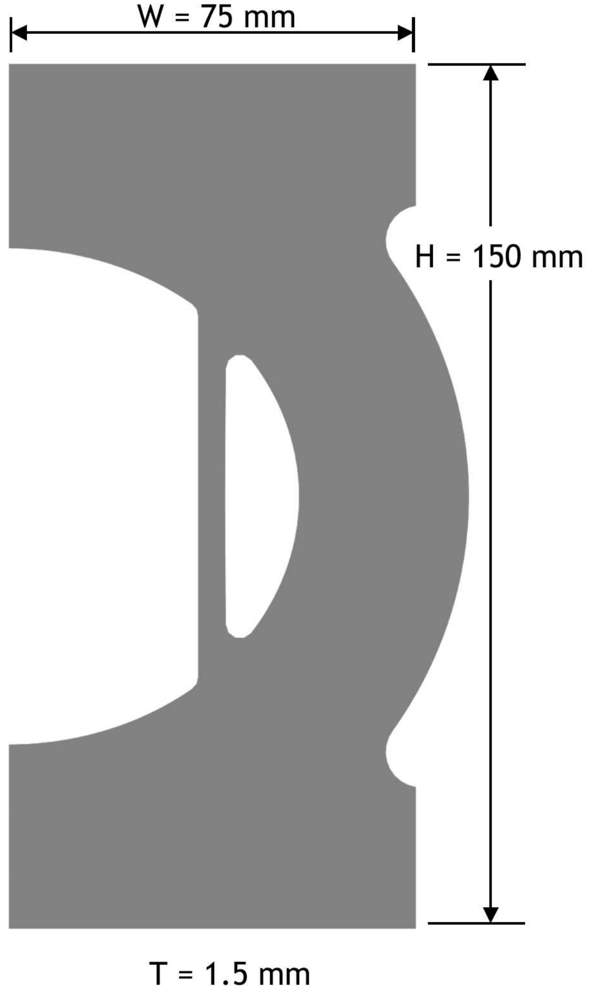


Complex specimen geometry induces strain rate heterogeneity in sample.

$$\sigma_f(p,\dot{p},\xi) = \sigma_o\left\{1 + \operatorname{asinh}\left[\left(\frac{\dot{p}}{b}\right)^{1/m}\right]\right\} + \frac{H}{R_d}\left[1 - \exp(-R_d p)\right]$$

σ_f	flow stress
p	equivalent plastic strain
$\dot{p}$	equivalent plastic strain rate

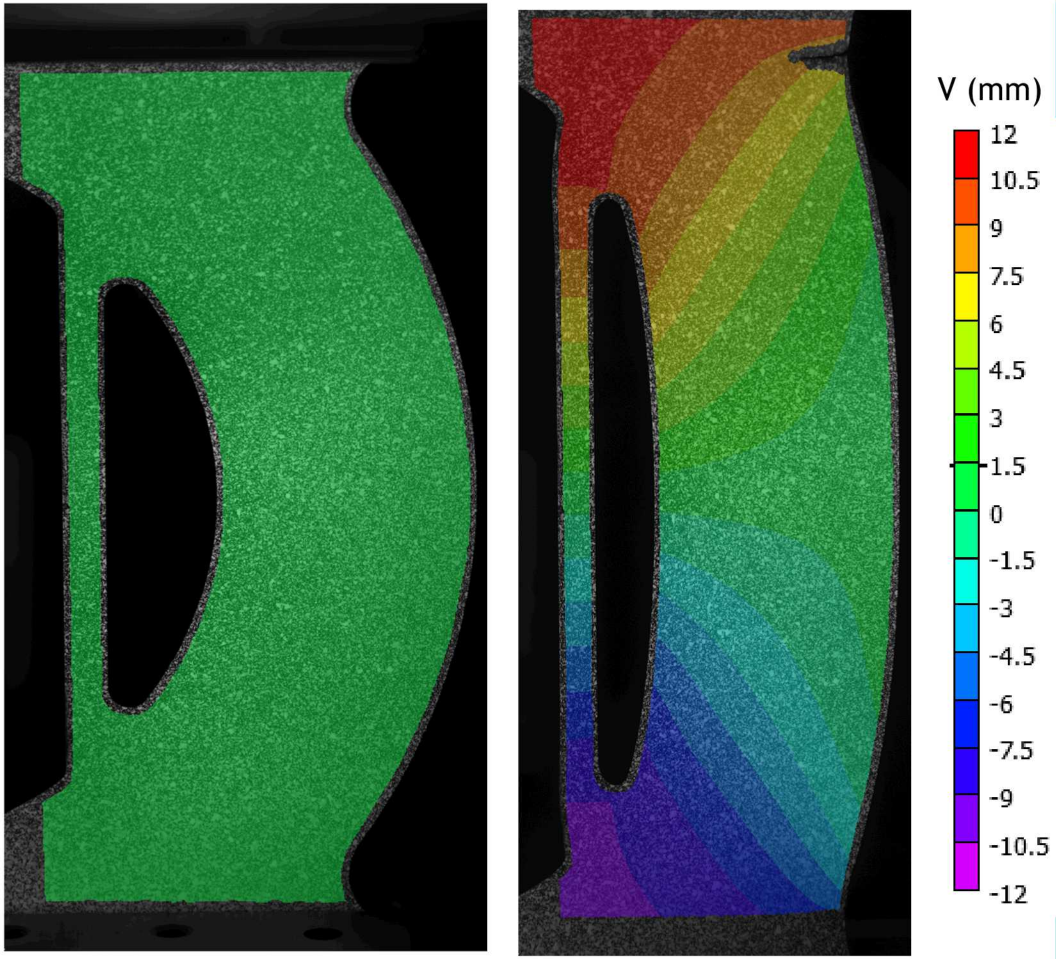




Full-field displacements and inverse methods are used to identify model parameters.

Inverse Methods

- Virtual Fields Method (VFM)
- Inverse Finite Element
- Integrated DIC



Key: More model parameters per test.

iDICs – A society to provide training, certification, standardization and guidelines for DIC.

International DIC society (www.iDICs.org)

- 1st Annual conference: Philadelphia 203 attendees 2nd Annual Conference: Barcelona, Spain – 150 attendees
- 3rd Annual Conference: Hongzhou China – Oct. 2018
- Prof. Mike Sutton – President, Phillip Reu – Vice President

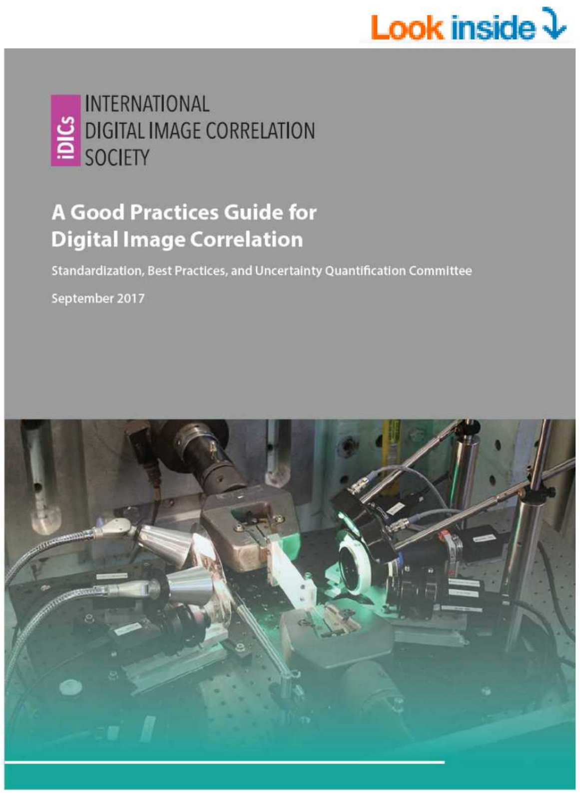
Committees

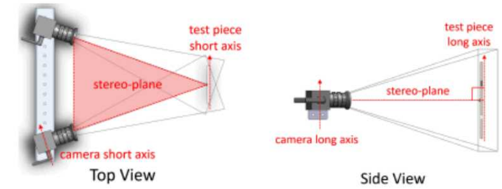
- Standards & Best Practices – Mark Iadicola
- Training & Certification – Tim Schmidt
- Applications – Dave Dawicke
- University Education – Mark Pankow
- DIC Challenge – Phillip Reu

Mission: Extend – Improve – Train

Extending the Frontiers: Training the next Generation: Standardizing for Industry: Improving our

DIC Good Practices Guide is under review. Release will be mid-2018.





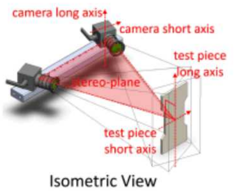


Figure 2.1: Cartoon depicting the recommended orientations of the cameras in a stereo-camera pair with respect to the test piece. In this cartoon, the long and short axes of the test piece ROI are assumed to align with the long and short axes of the test piece.

- For stereo-DIC, mount both cameras rigidly together to avoid relative camera motion.[3] See Sec. 2.2.2.2 for more information on common types of mounting systems.

Caution!

Any relative motion of one camera with respect to the second camera will induce errors in DIC measurements.[a] While these errors can be compensated for to some degree with post-processing calibration corrections,[b] avoiding relative camera motion is much more strongly preferred. Therefore, rigid mounting is critical!

[a] If both cameras move together rigidly with respect to the test piece, only rigid-body DIC displacements are affected. For most applications where rigid-body motion is not important (e.g. strains are the quantity-of-interest), this rigid-body displacement error is inconsequential.

[b] Rigid-body motion of the stereo-camera *pair* can be corrected for in post-processing if there is a fixed reference point somewhere in the field-of-view. However, correcting for relative motion of one camera with respect to the second camera requires adjusting the extrinsic parameters of the calibration (Sec. 3.2), but this type of correction is outside the scope of this edition of the guide.

6 | Reporting Requirements

With all the variables that must be selected in a mechanical test with DIC measurements, such as parameters of the physical system (e.g. camera, lens, patterning method, etc.) and parameters of the data analysis process (e.g. subset size, virtual strain gauge size, etc.), justification and documentation of the choices made is critical. The lists below present the minimum reporting requirements as well as suggested, detailed reporting recommendations. All documentation of DIC data — both internal reports and published journal articles — should contain this information.

Tip

Depending on the application of the DIC data, some of the reporting recommendations may not be necessary while others not listed here may be important. The key, though, is to document all relevant information!

6.1 Experimental Parameters

6.1.1 Required

- Camera Make and Model, and Image Resolution
- Lens Make, Model, Focal Length[1]
- Field-of-View
- Image Scale[2]
- Stereo-Angle[3]
- Stand-Off Distance
- Image Acquisition Rate
- Patterning Technique
- Approximate Speckle Size[4]

[1] If variable focal length, report both range and focal length used.
[2] For stereo-DIC, report the average image scale or the image scale in the center of the FOV.
[3] Applicable for stereo-DIC; not applicable for 2D-DIC
[4] Specify method used to determine speckle size. Note that both black and white regions are considered speckles.

Mark A. Iadicola and Elizabeth M. C. Jones
Co-chairs of the iDICs Standardization, Best Practice, and Uncertainty Quantification Committee

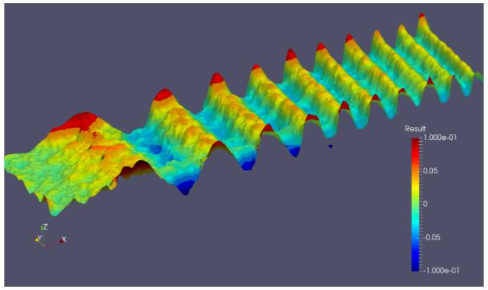
Important Dates

December 4, 2017: Deadline to email guide@idics.org to opt-in to vote and receive a copy of the draft version of the Guide.

January 15, 2018: Deadline to return your vote and comments by emailing the voting and comment form to guide@idics.org.

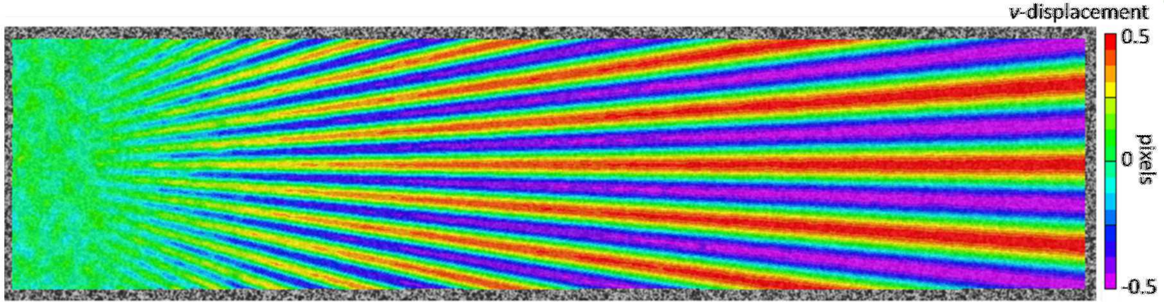
http://idics.org/guide/

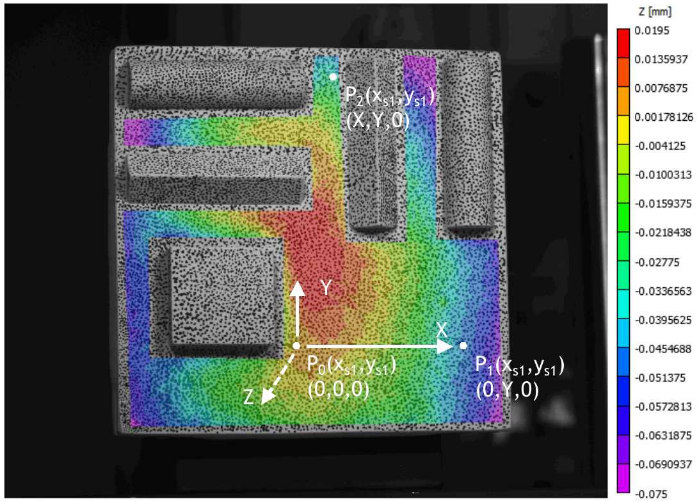
DIC Challenge is supplying images for DIC code verification and validation.

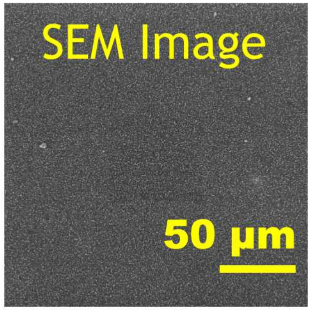


DIC Challenge (https://sem.org/dic-challenge)

- International DIC board of experts developing image sets to be used for verification and validation of DIC codes.
- Scanning Electron Microscope Challenge
- Computed Tomography Challenge
- Stereo-DIC Challenge







Current Challenge Board

Phillip Reu – Chair
Mark Iadicola (NIST) – co-chair
Elizabeth Jones (Sandia) – Results analysis
Evelyne Toussaint (Univ. Clermont Auvergne, France)
Ruben Balcaen (MatchID) – Stereo-DIC
Hugh Bruck (Univ. of Maryland) – Advisor at large
Helena Jin (Sandia) – Digital Volume Correlation (DVC) lead
Will LePage (Univ. of Michigan) – SEM Lead
Benoît Blaysat (Univ. Clermont Auvergne) – 2D Challenge

Reu, P. L., et al. (2017). "DIC Challenge: Developing Images and Guidelines for Evaluating Accuracy and Resolution of 2D Analyses." Experimental Mechanics.

Acknowledgements

Staff contributors

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Student Interns

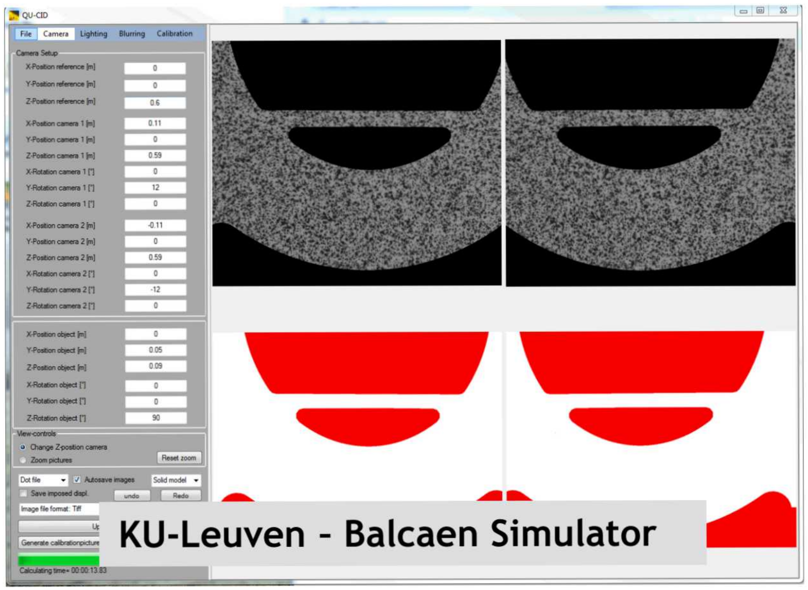
- Carl Stahoviak, Hailey Stock, TDaniel Barnhouse, Mindy Lake

External Collaborators

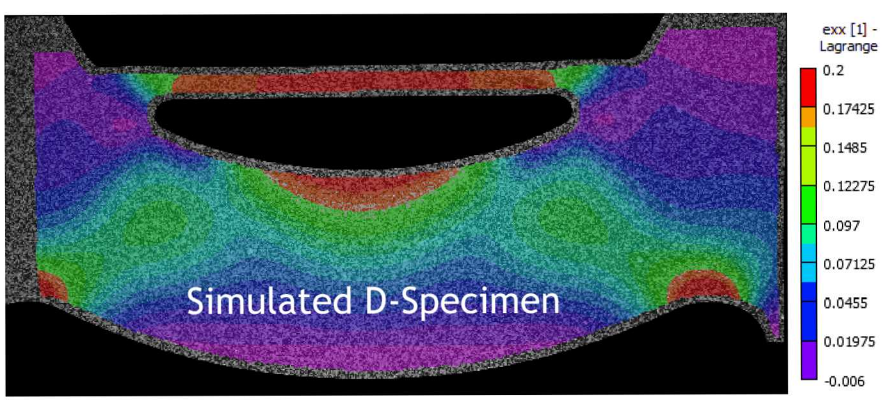
- Prof. Mike Sutton, Hubert Schreier, Mark Iadicola, Micah Simonsen

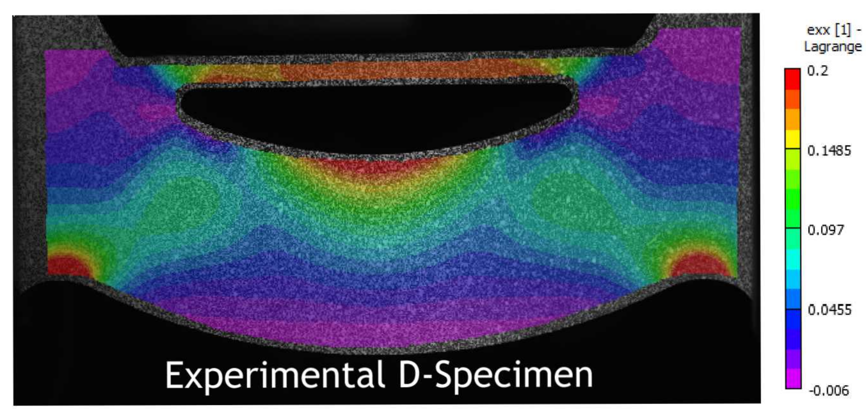
Question Time

Sandia requires "NIST traceable" measurements with uncertainty quantification



- Uncertainty quantification is difficult due to the complex measurement chain
- Stereo-DIC simulator in collaboration with KU-Leuven Belgium (Prof. Lava and Prof. Debruyne)
- Both experimental and simulated UQ research for DIC.
- Will be used for the Stereo DIC-Challenge
- Sandia has lead in DIC uncertainty quantification work.





Reu, P.L., *Experimental Mechanics, 2013.* ***53(9): p. 1661-1680.***