Image-based Measurements in Solid Mechanics: A Brief History, Static and Dynamic Application Examples and Recent Developments

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Outline

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- Digital Image Correlation Methods
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    - Early Applications
  - 3D-DIC
    - Early Applications
  - V-DIC
    - Applications

- 3D-DIC Applications and Details
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  - Shingles in 340 km/h winds

- The Future
  - Integration with Design and Development
  - Future Trends in Digital Image Based Methods

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In the mid 20th century, experimental methods in solid mechanics focused on point-wise measurements for quantitative data.

- Early full-field measurements were made in photo-elastic, polymeric materials:
  - Through-thickness average effects
  - Local effects using a complex method known as “stress-freezing”

- The advent of lasers and interferometry methods circa 1960s provided investigators with new full-field measurement capability.
  - Recording was via film media.
Vincent J. Parks, 1980
- Experimentally showed that the range of displacement measurements was limited due to de-correlation.
1980, William F. Ranson and Walter H. Peters III
- For 2D, through-thickness averaged, ultra-sound applications, proposed approach for conversion of digitized ultra-sound images into estimates for local surface displacements by employing continuum-based matching principles.

1982, Cheng and Sutton; Sutton and Wolters
- Developed non-linear least squares approaches using first-order gradients in a matching function to obtain local displacements.

1985, TC Chu et al
- Using a DAGE MTI analog camera to record images of a speckle pattern at 8 bits, demonstrating conclusively that the method could be used to measure deformations:
  - Translations, large or small
  - Rotations, large or small
  - Strains, large and relatively small
Brief History: Digital Image Correlation

- **1989, Bruck et al**
  - Developed and demonstrated order of magnitude speed improvement using Hessian-based methodology for computing iterative improvements in optimal matching positions of subsets
  - Used linear shape functions for subset-based matching

- **1993, Luo, Chao et al**
  - Developed a stereo-vision system and verified the ability to make local strain and deformation measurements in cracked material

- **1996, Helm, McNeill et al**
  - Developed a robust stereo-vision system and demonstrated used on full-scale aero-structures as well as on laboratory-scale specimens

- **2000, Bay et al**
  - Extended 2D and 3D methods to volumetric images and performs digital image correlation on volumetric elements on the interior of a material
  - Limited to those materials providing sufficient contrast during tomographic imaging
  - Requires a tomographic imaging facility
The rapid growth of computer technology that spurred continued growth of computational methods also provided the foundation for the explosion of growth in vision-based full-field experimental measurement method.

- 2D-DIC for SEM, AFM and planar loading and surfaces
- 3D-DIC for general motion and deformation of curved or planar surfaces
- V-DIC or Digital Volume Correlation for interior deformation measurements in opaque solids

Today, the methods are used worldwide by scientists and investigators seeking to obtain full-field quantitative measurement of motions and deformations.
Single CCD camera positioned perpendicular to object surface.

- Specimen has a random pattern on its surface
- Uniform illumination is provided by white light sources
- Loading nominally in-plane, minimizing out of plane motion
General Remarks

- Relatively simple to use under both laboratory and field conditions
- Relatively simple pattern application for many applications
  - Not so simple for microscale applications
- Data acquisition and data analysis procedures are well established
- Successfully used to make measurements on a range of specimen sizes from 0.01 mm to 2m
- Near real time analysis, with data analyzed at > 15000 subsets per second
- Accuracy nominally unaffected by large in-plane rotations or translations
  - Strain levels over 300% have been successfully measured
- Variability less than 0.01 pixels in displacement on a point-to-point basis are commonly obtained
- Accuracy of 100 μs or smaller in strain on a point-to-point basis through differentiation of smoothed displacement data.
- Effect of out-of-plane displacement is readily estimated and minimized using equation w/Z, where w is out-of-plane motion and Z is distance from specimen to camera
2D Image Correlation: Key Developments

- First LEFM measurements with DIC (1985-1987)

- Improving and speeding up DIC; differential corrections for efficient DIC (1987-1989)
First high temperature measurements with DIC (1994-1996)

First long-duration creep fracture w/DIC measurements. IN800 at 650°C for 147 hrs in lab air. Ceramic paint and pattern (1995-1998).
2D Image Correlation: Key Developments

- Ductile fracture at high mag. (1990-1994)
First two papers providing theoretical error predictions for 2D DIC

INTERPOLATION INDUCED BIAS (1998-2000)

THEORY (cubic polynomial)

VARIANCE AND NOISE-INDUCED BIAS (2005-2009)
Simulation process for each sub-pixel translation.
2D Image Correlation: Key Developments

- SEM DIC with distortion corrections (2003)

(1) Spatial distortion in an SEM which varies from experiment to experiment

(2) Drift distortion which is non-linear and varies over time
Two or more CCD cameras positioned to view same object area

- Specimen has a random pattern on its surface
- Uniform illumination is provided by white light sources
- General loading of specimen is allowed, while maintaining images of same object region in at least two cameras
- Images acquired simultaneously by all cameras
3D Image Correlation: Basic Concepts

General Remarks

- Full, three-dimensional displacement measurements obtained in laboratory and field conditions
- Calibration of camera system is required to convert image motions into accurate 3D measurements
  - Initial shape and 3D displacements are measured
- Data acquisition and data analysis procedures are well established
- Curved or planar objects from 0.50 mm to several meters in size
- Includes effect of perspective in image analysis
- High speed data analysis with data analyzed at > 3000 subset pairs per second
- Accuracy unaffected by large rotations or translations
  - Out-of-plane motion is measured, so does not affect accuracy of the in-plane measurements
- Accuracy of 3D displacement data is a function of camera system and camera noise level
  - Both variance and bias equations are available for estimating displacement errors
- Accuracy of 100 μs or smaller in strain on a point-to-point basis through differentiation of smoothed displacement data.
2D Image Correlation: Key Developments

- Early 3D vision system and 3D-DIC (1990-1994)
  - Table 1: Calibration point locations in reference coordinate system and image points in computer-image coordinate system for 3D DIC.

  - Accuracy Estimate:
    - $\pm 100 \mu m$ in-plane
    - $\pm 50 \mu m$ out of plane
  - Experiments vs. Theory
Error Propagation in 3D DIC (2006-2010)

- \((x,y)\) = sensor position of a grid pt.
- \(M_{ij}\) = matrix from sensor to 3D location
- \(\xi\) = vector of 26 camera parameters used in \(M\) matrix.
Volumetric DIC: Basic Concepts

- System shown uses fan beam scanning approach
- Raw scan data file is digitally stored for each line and rotation angle
- Data is transferred to algorithms embedded in CT system and used to reconstruct images for each loading state
- Image data for each loading state used with optimization algorithms to determine internal deformations
Volumetric DIC: Basic Concepts

General Remarks

- Requires volumetric imaging system
- Pattern generally comes from natural internal sources, unless seeding of material is viable
  - When seeding material to improve pattern, may affect material response
- Image acquisition is slow, with lab CT images requiring up to several hours to complete high resolution scanning
- Noise levels are relatively high, with 3% noise or higher common in CT systems
- Data acquisition and image reconstruction procedures are well established, though prone to introduce artifacts
  - Image artifacts commonly seen in volumetric images can reduce accuracy of the matching process.
- Images can be obtained for small and large specimens
- Images are large, requiring efficient memory management and fast matching algorithms to reduce analysis time
- Accuracy nominally unaffected by large rotations or translations
  - Requires robust “initial guess” methods for estimating local motions
- Accuracy of +/-0.02 voxels in displacement on a point-to-point basis have been obtained in recent CT studies with high contrast patterns
CT images of trabecular bone. Note the excellent contrast obtained throughout volume.
3D-DIC Applications

- Heterogeneous material
  - Woven glass-epoxy composite
  - Combined compression-bending loading
  - Large out-of-plane displacements
- Roofing Shingles
  - Background
  - Preliminary Experiments
  - Simulations
Woven Glass-Epoxy Composite

Material Specifics

- Thin sheet composite
- Glass-halogenated epoxy, NP-130
- Glass fibers approximately 7μm diameter
- Five-six layers of orthogonally woven composite in plain weave structure for 1m by 1.3m sheets
- Rectangular specimens removed with razor knife

Specimen geometry

- TH: 1mm
- W: 17mm
- L: 150mm.
Woven Glass-Epoxy Composite

- Out-of-plane motions up to 40mm
- Compression side cameras
  - rotated counterclockwise by \( \approx 20^\circ \)
  - moved closer to specimen
  - specimen at front of focus volume
- Tensile side cameras
  - rotated clockwise by \( \approx 20^\circ \)
  - move away from specimen
  - specimen at back of focus volume
Woven Glass-Epoxy Composite

Axial strain on compression and tension surfaces during combined compression-bending loading for +/- 45° specimen.

- Localized effects evident as w increases
- Critical regions have different spatial trends
- Effect shown is muted for low fiber angles
Axial strain for $\Theta = 0^\circ$ and 20mm of axial displacement is in very good agreement with the large deformation results of the modified Drucker formulation on both surfaces.

The elevated compressive strain in critical region appears to be due to localized damage, including fiber buckling and matrix failure.
Woven Glass-Epoxy Composite

Effective stress vs effective strain in critical region near mid-span of specimen

$$\tilde{\varepsilon}_\theta = \frac{\varepsilon_\theta}{h(\theta)} \quad \tilde{\sigma}_\theta = \sigma_\theta h(\theta)$$

$$h(\theta) = \sqrt{\frac{3}{2} \left[ \cos^2(\theta) + \frac{d_2}{d_1} \sin^4(\theta) + \frac{d_3}{d_1} \sin^2(\theta) \cos^2(\theta) \right]}$$

$$d_1 = \frac{1}{E_1}, \quad d_2 = \frac{1}{E_2}, \quad d_3 = \frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}$$
Woven Glass-Epoxy Composite

- **FE Simulations and Large Deformations**
  - Abaqus
  - Hashin damage model
  - 5 layers through total thickness-laminate construction modeled (not woven)
  - Alternating orthogonal fiber directions for layers (0-90-0-90-0) assumed
    - Layers modeled as individual orthotropic material (depending upon orientation of “fibers” relative to loading), with linear-elastic response and damage accumulation.
    - Hashin model parameters selected based on (a) literature data for glass-epoxy specimens of similar construction and (b) fitting of off-axis $P-\delta$ response of bending-compression specimens.
  - Fibers are not modeled.
• Differences between 15 and 75; 30 and 60 apparently due to CT-observed difference in fiber number in 0 and 90 orientations
Coordinate System

$e_{xx}$ along L0

$e_{yy}$ along L1

Front surface (compression side) of specimen
Woven Glass-Epoxy Composite

Compression side $e_{xx}$

Tension side $e_{xx}$

Compression side $e_{yy}$

Tension side $e_{yy}$
Woven Glass-Epoxy Composite

Compression side $e_{xx}$

Strain, $e_{xx}$

Location (mm)

Compression side $e_{yy}$

Strain, $e_{yy}$

Location (mm)

Tension side $e_{xx}$

Strain, $e_{xx}$

Location (mm)

Tension side $e_{yy}$

Strain, $e_{yy}$

Location (mm)
Woven Glass-Epoxy Composite

60° at D = 40 mm, Tension side
Woven Glass-Epoxy Composite

60° at D = 40 mm, Compression side
Applications

- Heterogeneous material
  - Woven glass-epoxy composite
  - Combined compression-bending loading
  - Large out-of-plane displacements

- Roofing Shingles
  - Background
  - Preliminary Experiments
  - Simulations
Roofing Shingles

- Roof asphalt shingles
  - The most common type of sloped-roof cover for residential construction in the US
  - Shingles consist of:
    Two layers of asphalt, fiberglass mat and granules
  - Sealing strip (introduced in the 1950s):
    - Minimizes the water penetration
    - Resists against wind-induced uplift
  - Nails (4 or 6 per shingle)
Roofing Shingles

Experimental Program

- 3D-DIC setup and wind load

- Cannot paint surface due to stiffening effect on soft shingle material
- Cameras: Two 5 MP (Point Grey Grasshopper GRAS-50S5M-C)
- Lenses: 28-mm lenses (AF Nikkor 28 mm f/2.8D)
- Cameras were mounted on a fixed wood frame to minimize wind-induced vibrations
- Roof cover was built to minimize changes in ambient light
- 5 Hz frequency was used to acquire and store thousands of images
Roofing Shingles

- 340kmph wind. Time sped up by 10X.
- Audio turned off due to high dB noise.
Roofing Shingles

Wind flow
0 mph
84 mph
113 mph
127 mph
141 mph
155 mph

Uplift [mm]

Shingle uplift at Marker (1) [mm]

Time [s]
Simulation of Shingle Response and Sealant Separation

- Beam on elastic foundation (BOEF) model is employed with finite sealant
  - "Foundation" represents effect of sealant material
  - Assume elastic response throughout deformation process. Beam and sealant lengths and properties obtained experimentally from commercially available shingle samples.
- Uplift pressure $p_1$ measured independently for winds up to 200km/hr
- Energy release rate at each edge of sealant strip is $\frac{1}{2} S v_2^2$
- Drag force, $P$, not included in these results
- Solution requires determination of 12 parameters

\[ F_{ef} = \int S v_2 \, dx \]

\[ I_1 + I_2 \]
Roofing Shingles
Preliminary Experiments

Shingle length, \(0 \leq l_1 \leq 0.1204\) m
Sealant length, \(l_2 = 0.0127\) m
Overhang length, \(l_3 = 0.0254\) m
Sealant thickness: \(t = 2.8\) mm
BOEF Sealant Parameter: \(S = 4.53\text{Gpa m}^{-1}\)

Compressive axial stress vs. axial strain measurements for sealant specimen at 23°C.
Applied $G_i$ at the interior and exterior edges of sealant as function of sealant location, $\xi$, with constant sealant and overall beam lengths. Solid lines represent $G_i$ at interior sealant edge and dashed lines represent $G_i$ at external sealant edge for different pressures.
Simulations to Assess Potential to Quantify Pressures Using 3D-DIC

\[ \sigma_w = \text{variability in 3D-DIC measurements} = 50\mu m \]

\[ \sigma_{P1} = \text{variability in applied pressure} \]

Inset:

Nominal \( \sigma_w/l_1^4 \)

Since \( P_1 = 12.5\text{Pa} \), for nominal geometry the standard deviation for a single measurement is nearly 60Pa. Thus, one must take nearly 1800 image pairs to obtain variability of 1.25Pa in the predicted pressure….
Concluding Remarks

- The rapid growth of computer hardware speed since mid-1990s has resulted in both the expansion of computational methods and the explosive growth of digitally-based experimental methods.
- Digital image correlation methods provide a platform for the recording large quantities of full-field deformation data under a broad range of conditions:
  - High rate loading (cameras can record images every 5 nanoseconds)
  - High temperature (cameras can acquire usable images for DIC on specimens where $T > 1200^\circ C$)
  - Small (down to $20\mu m \times 20\mu m$) and large (full-scale aircraft) regions can be measured.
  - Long term studies (experiments lasting several days or longer) have been reported.
- The combination of full-field measurements with theoretical and computational models provides a rich framework for improving our understanding of the physical world.
The Future

"The future of science is neither vague nor unimaginable. It is the result of what we do now."

- Integration with Design and Development
  - Data-driven simulations for design
- Future Trends in Digital Image Based Methods
  - Multiple measurement system integration
  - Continued growth of data-driven parameter estimation approaches
  - Full integration of analysis and measurements for multi-physics studies
Image correlation based methods provide unique capability to make the measurements required to implement such integrated simulation-measurement design concept.
The ability to smoothly integrate full-field measurements using 2D-DIC, 3D-DIC and/or V-DIC with design simulations requires efficient and robust optimization methodologies that can effectively identify the constrained optimal combination of:
- Material parameters
- Structural configurations
- Operational conditions

Successful implementation of DIC-based measurement methods with simulation platforms offers opportunities to replace existing “testing standards” with a far more robust design methodology.

Education level of the next generation of designers must be adequate for this approach to be viable.
Integration of multiple measurement systems

- *Synchronized measurements with multiple measurement technologies*
  - CT systems for slow speed events
  - Stereovision systems
    - Slow speed events
    - High speed events
  - Thermographic camera systems
  - Multiple average or local sensor measurements
    - Pressure
    - Loads
    - Moments
    - Voltage
    - Current
    - Other environmental variables
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Future Trends in Digital Image Based Methods

- **Continued expansion of parameter identification**
  - Common optimization metric;
  
  \[ E = \sum_i \sum_j (F(x_i, t_j; \beta), - f(x_i, t_j))^2 \]

  - F() = theoretical function for measurable quantity
  - f() = experimental measurements for quantity
  - \( x_i \) = \( i^{th} \) spatial position on specimen
  - \( t_j \) = \( j^{th} \) time of interest
  - \( \beta \) = vector of unknown parameters by minimizing \( E \)

  **Examples:** mixed mode stress intensity factors using full-field crack tip data, composite material parameters
Future Trends in Digital Image Based Methods

- Full integration of analysis and measurements for multi-physics studies
  - Experimental measurements combined with multi-physics models coupling effects from multiple environmental factors.
    - Multi-physics model validation using estimated parameters
    - Model employed for predictions in regimes where experimental measurements are more difficult

“The future? It is impossible to envision the unimaginable, and wonderful to see it happen.”
Recent DIC-Related Activities

• Article in Applied Mechanics Reviews (6/2013)

• Special issue in Experimental Mechanics focusing on Digital Image Correlation (1/2015)

• 2nd edition of book is under development, highlighting the most recent trends in DIC and applications
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References


Issues associated with extraction of deformation information using film as a recording media

- Non-linearity in film
- Film processing (*darkroom*)
- Film stability and handling
- Laser illumination
- De-correlation effects (*previous slide*)
- Exorbitant time requirements
- Inaccuracies in reconstruction process
  - fringe location
  - film expansion/contraction
  - relationship of object to image coordinates
  - distortions in imaging process