Aalto University
School of Engineering

MEC-E6007 Mechanical Testing of Materials

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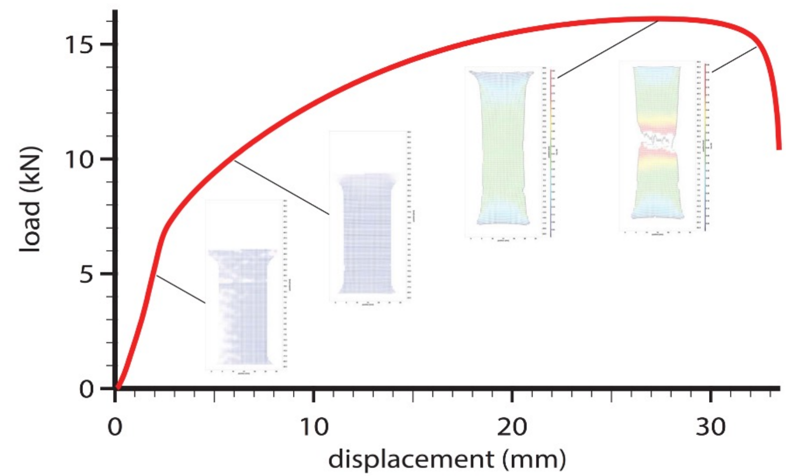
Course Content: *learning from breaking things*

- Load
  - *loadframes, actuators, and grips*
  - *quasi-static, dynamic, and cyclic loading*
- Measure
  - *measurement of force, displacement, and strain*
  - *digital image correlation and other full-field measurement techniques*
- Analyse
  - *selected special challenges in mechanical testing (ask for yours!)*
  - *introduction to inverse problem methodologies in experimental mechanics*



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DIC measurement procedure

iDICs Good Practices Guide

- organized by users, not vendors
  - *vendors do participate in technical committees*
- separate guides for advanced applications
  - *mostly still under development*
- freely available at https://idics.org/guide

- if you deviate from this, you should be able to explain why

Main steps in a DIC measurement

- design of the DIC measurement
- sample preparation (patterning)
- pre-calibration routine
- calibration
- post-calibration routine
- acquisition of images for measurement
- post-measurement routine
- calculation
- uncertainty quantification
- reporting

design of the DIC measurement

determine the requirements

- quantities of interest
- region of interest
- field of view
- position envelope
- 2D-DIC vs. stereo-DIC
  - *stereo angle*
  - *depth of field*
- spatial gradients
- acceptable noise floor
- frame rate
- maximum exposure time
- synchronisation and triggering

select the equipment

- camera and lens
- mounting equipment
  - *e.g., tripod and stereo bar*
  - *including adjustable camera mounts*
- lighting
- aperture and exposure

select the pattern

- application method
- feature size and density
- algorithm if numerically generated

sample preparation (patterning)

application methods

- natural contrast of sample
- spray paint or airbrush
- ink stamp
- flatbed inkjet printer
- printer with transfer film
- etching + photolithography
- …

potential issues

- lack of adhesion
- variable background
  - *specular reflections from rough metal*
- lack of contrast
- deformation-created fresh surface
- strain to fracture
  - *apparent cracks if pattern cracks*
  - *hidden cracks if pattern covers crack*

pre-calibration routine

set up hardware

- review test procedure
- clean detector & lens
  - *only if you know how to avoid damaging them*
- warm up cameras
- synchronise cameras
- adjust lighting
- adjust camera position & angles
  - *verify field of view*
- adjust aperture & polarizers
- adjust exposure
- adjust focus
  - *verify depth of field*
- lock lenses

acquire static images

- check for glare
- check DIC pattern
  - *to assess speckles < 2 px, higher magnification image is needed*
- check contrast & focus
- even lighting
- proper exposure

calibration

- calibration target
  - *should be nearly same size as FOV*
- clear space
  - *remove the test piece and move grips so calibration target can be held there*
  - *or move the DIC system (carefully)*
- adjust lighting for calibration targets
- acquire calibration images
  - *positions of calibration targets should cover measurement volume*
  - *rotations of calibration targets to connect them different ways*
  - *do not exceed depth of focus*
- run calibration software
- review calibration results
  - *check images as well as calibration parameters*

post-calibration routine

Don’t touch the lenses or cameras now, or you’ll need to recalibrate!

- position specimen
- adjust lighting for specimen
- acquire and review static images
- acquire and review rigid body motion images

verify calibration

- no strain bias when correlating rigid body motion images
- small epipolar error in stereo correlation
- distances correct

assess noise floor

- calculate quantities of interest from static and rigid body motion images
- assess their (spatial and temporal) standard deviation

acquisition of images for measurement

- specify file names and locations
  - *verify that adequate file storage capacity is available*
- synchronise force signal and other measurement signals with DIC image capture
- set up suitable triggering
- verify lighting, exposure, and frame rate

- do the test

- check that images and other files are saved where expected

post-measurement routine

- acquire static and rigid body motion images of reference object
- move or copy your data to suitable file storage
- switch off lighting and anything else that should be switched off
- clean up the experiment space

DIC displacement calculations

reference image

- single reference
- incremental
- partitioned

interpolant

subset size

- trade off between noise and spatial resolution

step size

- density of calculation points
- redundant calculations with points nearby if step size is very small

thresholds

- reject results that did not match very well

calculating strain from DIC results

virtual strain gauge

- region of the image that is used for strain calculation
- full-field strain calculation has array of virtual strain gauges

strain calculation methods

- deformed subset shape
- finite element shape function
  - *from global DIC method or fitting mesh displacements to DIC displacement field*
- function fitting to displacement field locally
  - *in simple cases this can be implemented as a convolution*
- function fitting to displacement field globally

uncertainty quantification

variance error or “noise”

- measurements of static images before the test should have zero displacement and strain
  - *calculation parameters are determined for the images from the test*
  - *redo the calculations of the images from before the test with these parameters*
- variance of the actual measurements is higher
- spatial variance across the specimen
  - *affected by DIC pattern, focus, and lighting*
- temporal variance for each subset
  - *camera sensor noise (heteroskedastic)*
  - *vibrations*
  - *heat waves*

uncertainty quantification

bias errors

- some bias errors may be unknown
- others are known but unmodelled
- modeled errors may be quantified or even corrected

known sources of bias error in DIC

- lens distortion
- out-of-plane motion in 2D-DIC
- interpolation
- over-smoothing from
  - *large subsets,*
  - *low-order subset shape functions,*
  - *large virtual strain gauge,*
  - *pre- or post-filtering*

virtual strain gauge study

- from the test choose an image with one of the largest strain gradients
  - *as well as the reference image and one with nominally zero force*
- analyse these images with different DIC calculation parameters
  - *subset size, step size, strain window + maybe others*
- extract strain results (+ maybe displacement) along line that cuts through the region of large strain gradient
- compare plots of the same quantities obtained with different DIC calculation parameters
- plot the quantity at chosen locations versus virtual strain gauge size
  - *maximum strain amplitude increases with decreasing virtual strain gauge size*
- if those plots do not converge to a constant value before they are dominated by noise, then the spatial resolution of the DIC measurement is insufficient to resolve the strain gradient

reporting

hardware

- camera: manufacturer, model, image resolution, and image noise
- lens: manufacturer, model, focal length, and aperture
- field of view
- image scale
- stereo angle
- stand-off distance
- image acquisition rate
- patterning technique
- approximate pattern feature size

calculations

- DIC software; name, version and manufacturer
- calibration parameters
- image filtering, if any
- subset size (in px and in mm)
- step size(in px and in mm)
- subset shape function
- interpolant
- matching criterion
- data processing and filtering for quantities of interest
- noise floor and bias of quantities of interest

related full-field measurement methods

grid method

- uses periodic grid as the pattern
- analysed using Fourier filtering
  - *local phase gives displacement*

moiré

- interference by non-linear effects like occlusion

deflectometry

- measures slope of surface from distortions of reflected image
  - *could use DIC, grid method, or moiré to quantify those distortions*

holography

- record interference pattern of coherent light

speckle interferometry

- difference image of laser speckle yields interferometry fringes

photoelasticity

- polarization changes as a result of stress-induced birefringence