Impact on decision-making of quantified uncertainty for DIC measurements

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European Commission projects

2002-2006

SPOTS

Standardisation Project for Optical Techniques for Strain measurement

2008-2011

ADVISE

Advanced Dynamic Validation by Integrating Simulation & Experimentation

2013-2014

VANESSA

VAlidation of Numerical Engineering Simulations: Standardisation Actions

2017-2020

Clean Sky MOTIVATE

Matrix Optimisation for Testing by Interaction of Virtual And Test Environments

Information continuum

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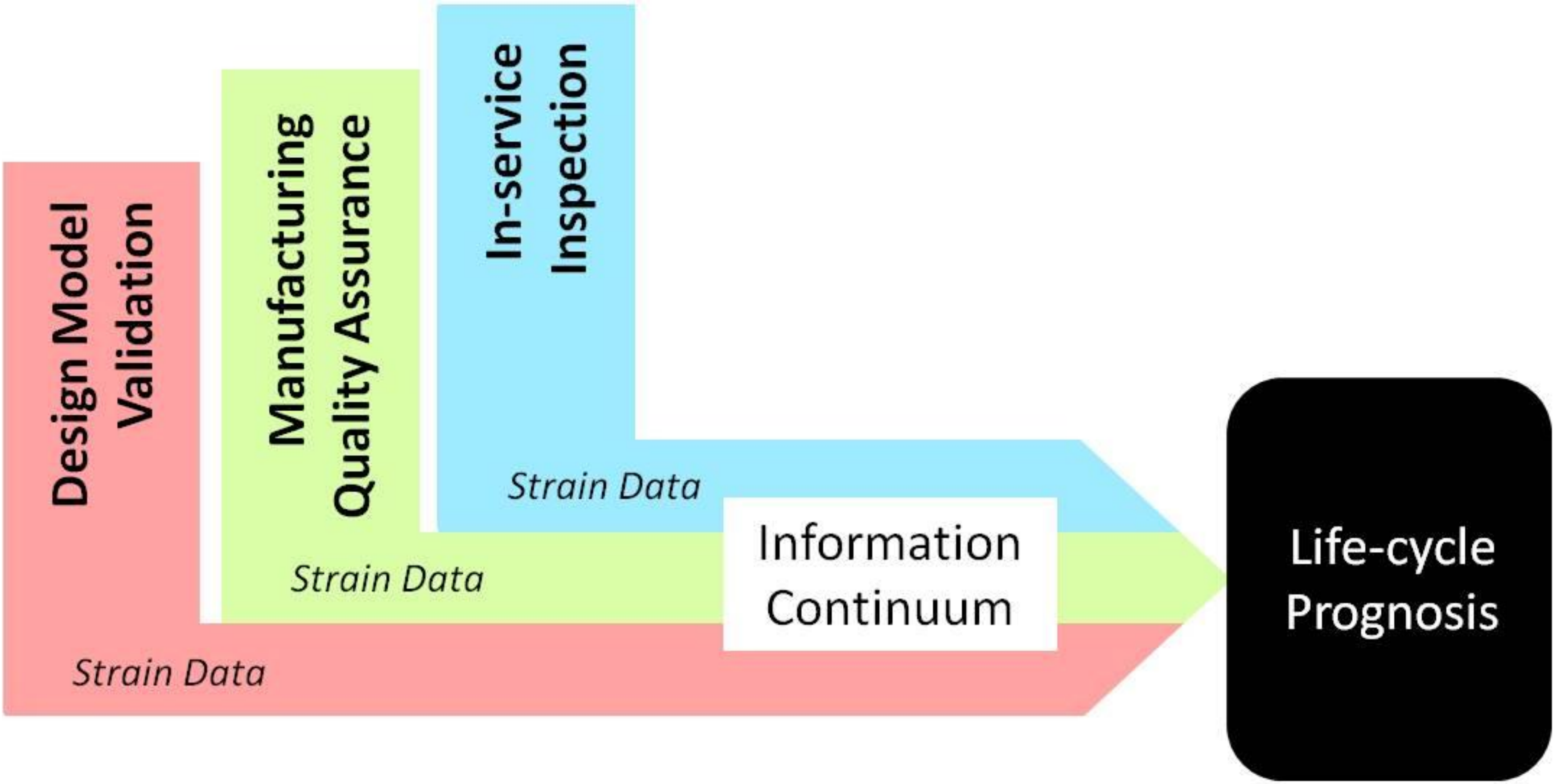


Patterson E.A., Feligiotti, M. & Hack, E., 2013, On the integration of validation, quality assurance and non-destructive evaluation, *J. Strain Analysis*, 48(1):48-59.

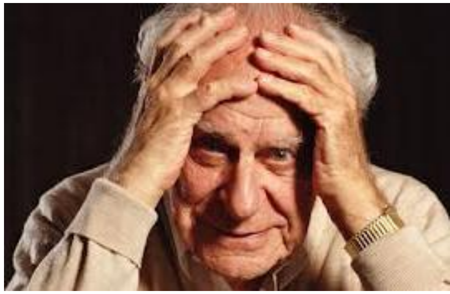
What is an acceptable model?

- **Hume [1748] suggested that observational evidence will never support any hypothesis about the unobserved.**

- **More pragmatic approach required...**

- **Popper [1959] proposed that observational evidence cannot prove a hypothesis correct, but it can demonstrate its inappropriateness or falsity**

- **Implies that there is always a possibility of making a mistake when accepting [or rejecting] a hypothesis**



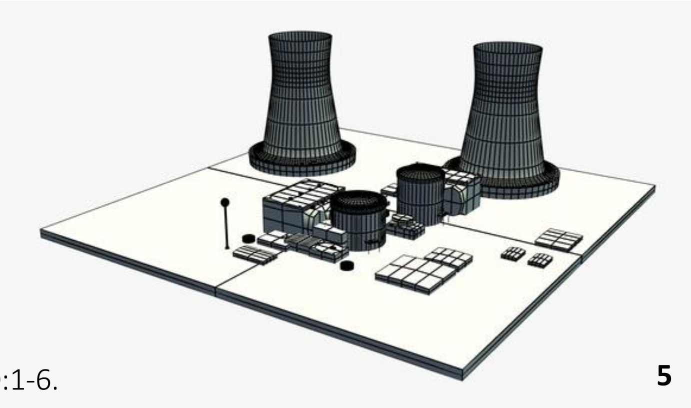
Hume, D., 1748 [1999], *An enquiry concerning human understanding*. Oxford Philosophical Texts, Oxford University Press, Oxford, edited by T.L. Beauchamp.
Popper, K., 1959, *The logic of scientific discovery*, Hutchinson, London.

Making mistakes

- **Rudner [1953] argued that the decision to accept or reject a hypothesis depends on the strength of the evidence**
  - And, our judgement on the strength of the evidence depends on the importance of making a mistake in accepting or rejecting a hypothesis

- **For engineering models**
  - Importance of making a mistake will be measured in economic cost and loss of life or injury arising from an engineering failure

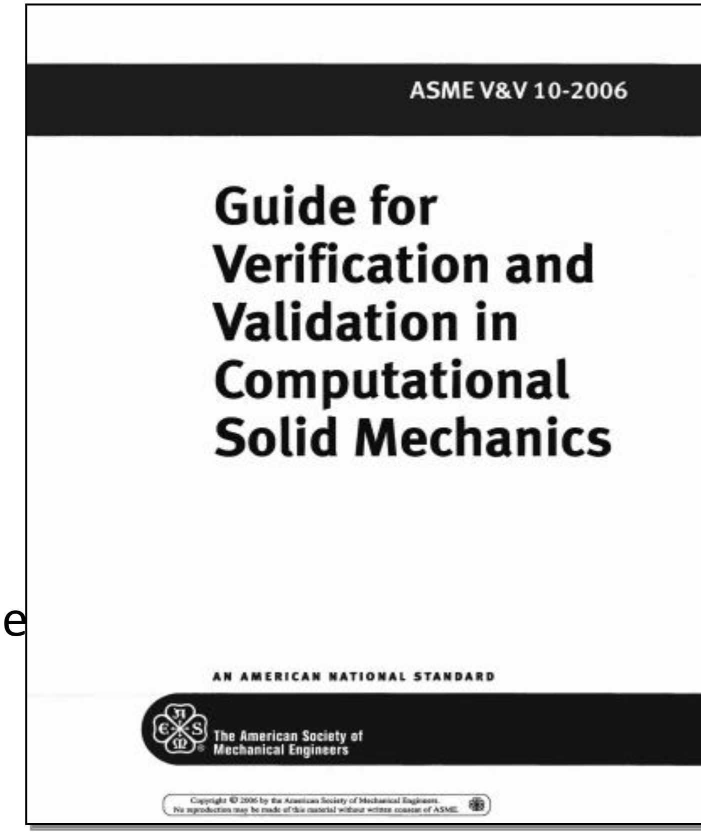
- **Strength of evidence required to accept a computational solid mechanics model could be very high in some cases**
  - e.g. design of an aircraft or nuclear power plant
  - So, need comprehensive validation of model



Rudner, R., 1953, The scientist qua scientist makes value judgements, *Philosophy of Science*, 20:1-6.

ASME V&V Guide

- **Verification**
  - ‘The process of determining that a computational model accurately represents the underlying mathematical model and its solution.’
- **Validation**
  - ‘The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.’
- **No methodology provided**


ASME V&V 10-2006

Guide for Verification and Validation in Computational Solid Mechanics

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

ASME V&V 10-2006, Guide for verification & validation in computational solid mechanics, American Society of Mech. Engineers, New York, 2006.

Experimental mechanics

- **Validity of computational models is analogous to scientific hypotheses**
  - Recognise that observational [experimental] data cannot prove its validity
  - Increasing body of evidence can increase degree of belief in the model[1]
- **obvious that current practices, based on the strain value at a small number of locations, are inadequate**
- **until now, obviousness over-powered by cost of experimental data**
  - alleviated by new technologies e.g DIC, DVC, ESPI & TSA

  and, lack of methods for quantitative comparisons of full-field data
  - Different orientation, coordinate system, scale, pitch of data
  - Resolved by use of image decomposition[2]
    - Reduces dimensionality of data & is invariant to rotation, scale & translation

1. Audi, R., 2011, *Epistemology: a contemporary introduction to theory of knowledge*, 3rd ed., Routledge, New York.
2. Wang, W., Mottershead, J.E., Sebastian, C.M., Patterson, E.A., 2011, Shape features and finite element model updating from full-field strain data, *Int. J. Solids Struct*. 48(11-12), 2011, 1644-1657.

Idealised image decomposition

Image of a three-dimensional shape

Matrix of grey-scale values, $I(i, j)$

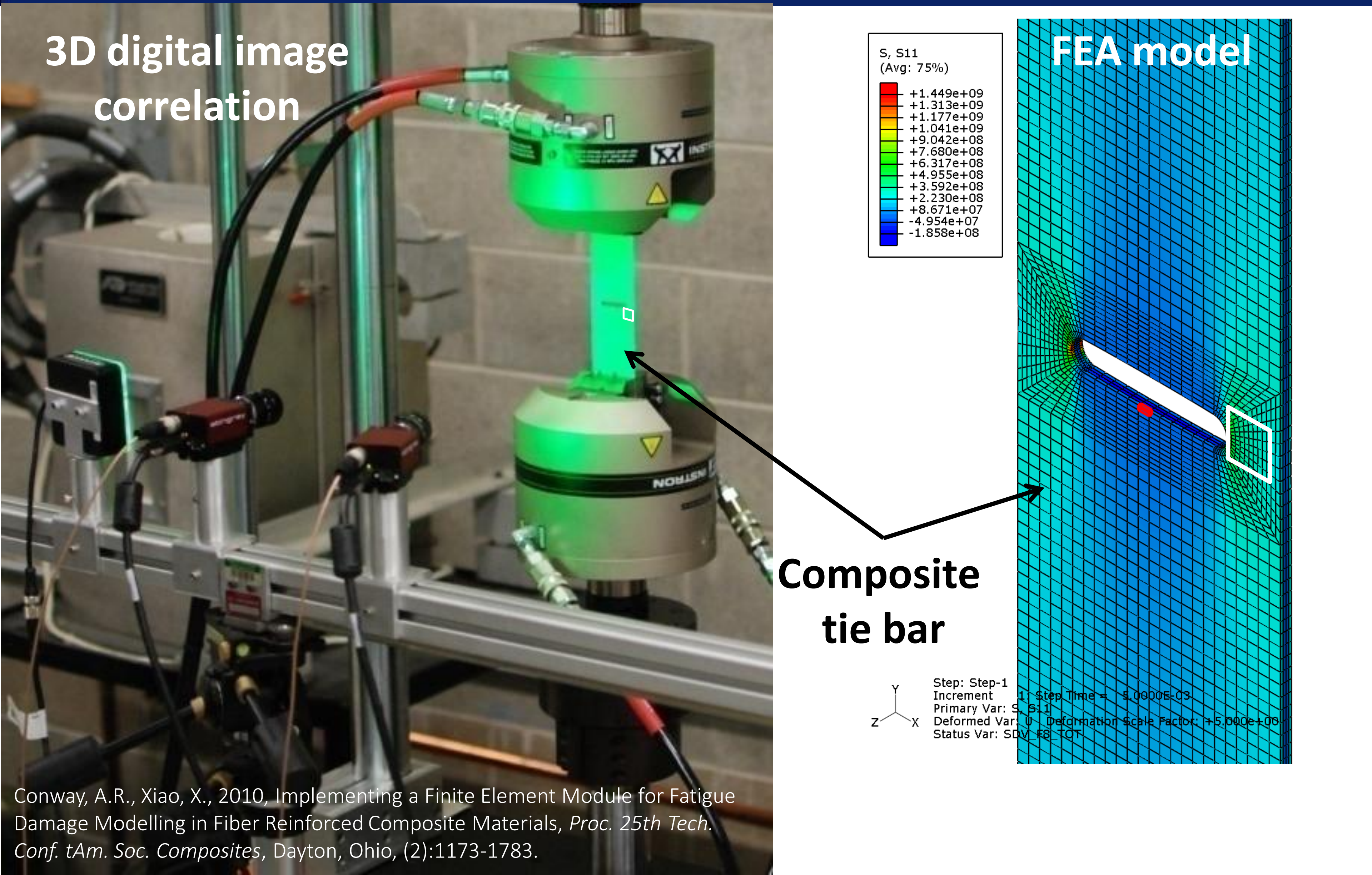
$$S = \begin{bmatrix} s_1 \\ s_2 \\ \dots \\ \dots \\ s_l \end{bmatrix}$$

Feature vector consisting of shape descriptors

Reconstruction

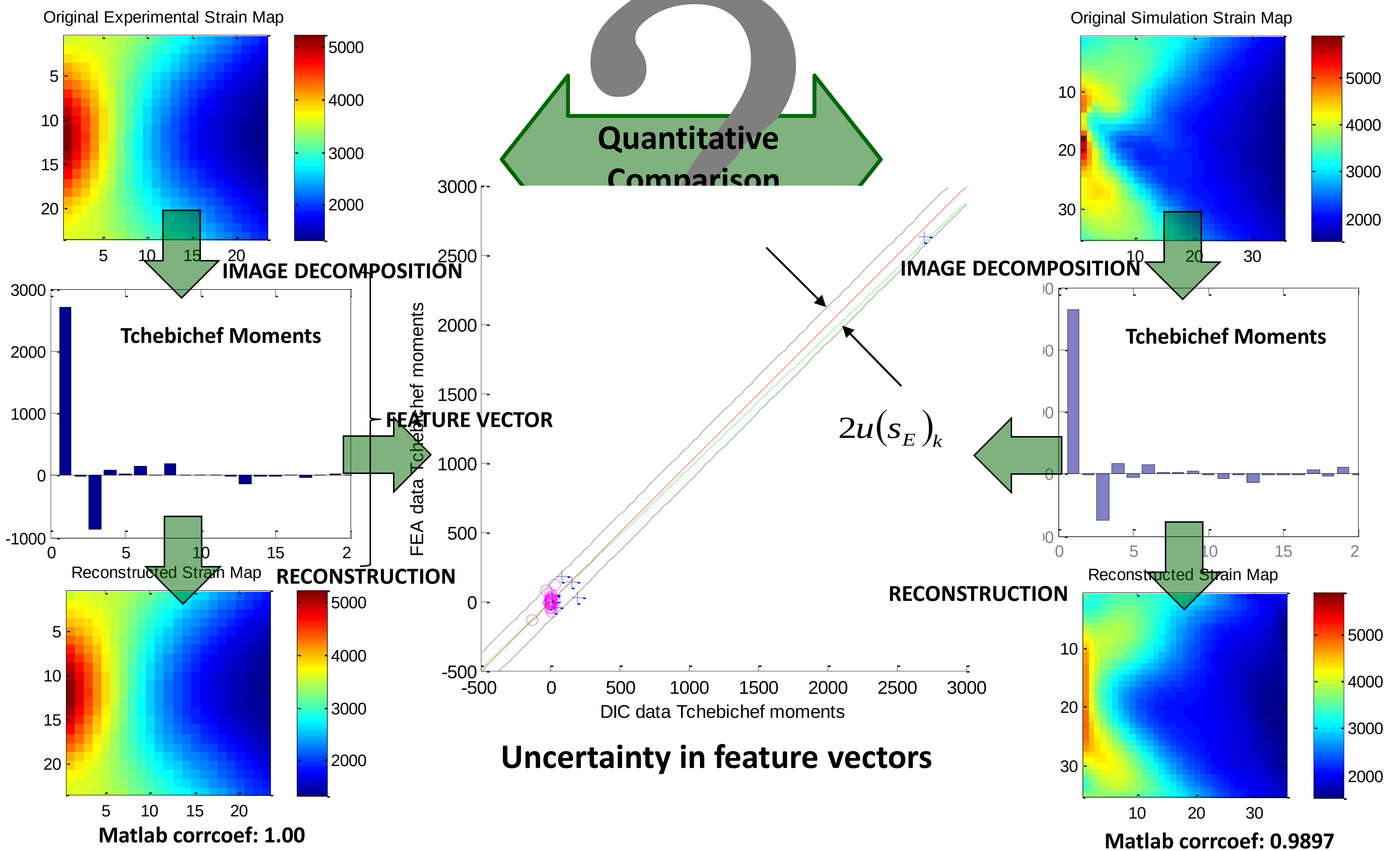
Patki AS & Patterson EA, Decomposing strain maps using Fourier-Zernike shape descriptors, *Experimental Mechanics*, 52(8):1137-1149, 2012.

Massive datasets: >10^5 values



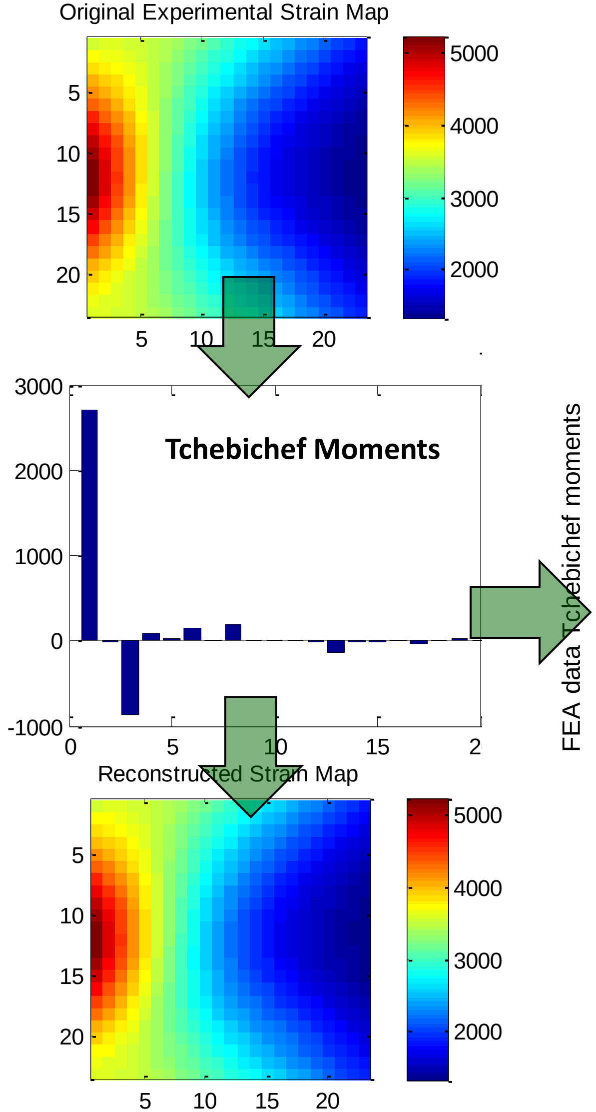
Conway, A.R., Xiao, X., 2010, Implementing a Finite Element Module for Fatigue Damage Modelling in Fiber Reinforced Composite Materials, *Proc. 25th Tech. Conf. tAm. Soc. Composites*, Dayton, Ohio, (2):1173-1783.

Validation procedure



Sebastian C, Hack E, Patterson EA, 2013, An approach to validation of computational solid mechanics models for strain analysis, *J. Strain Analysis*, 48(1):36-47.

Validation procedure

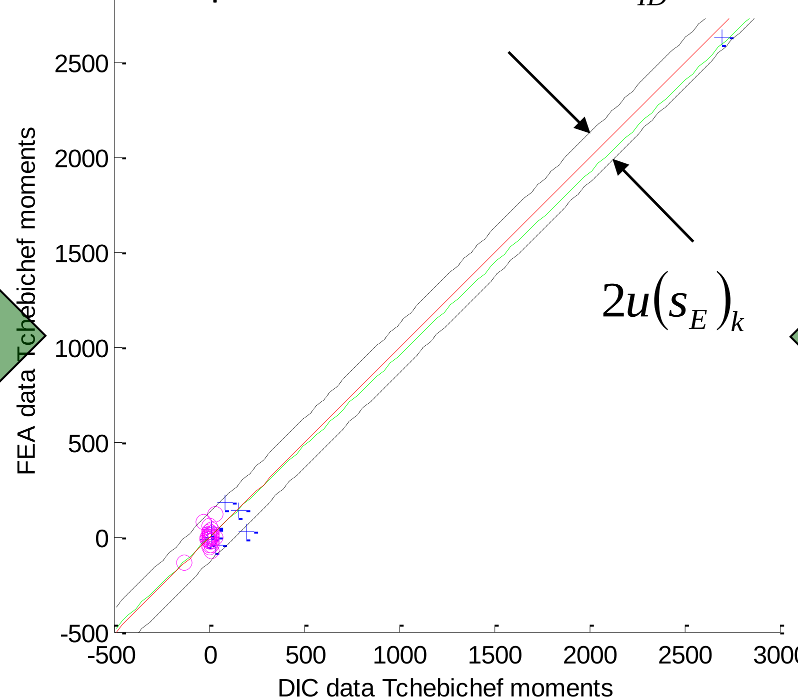


Matlab corrcoef: 1.00

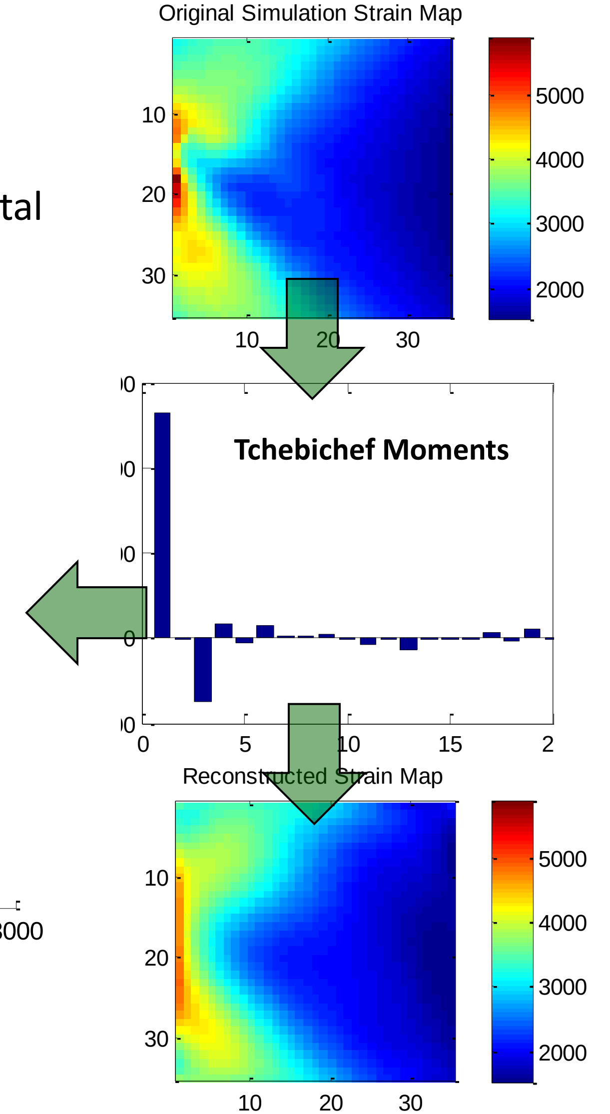
Image decomposition criteria

(a) $u_{ID}^2 < u_{cal}^2(\varepsilon)$

(b) No cluster of more than 0.3% total pixels with more than $3u_{ID}$



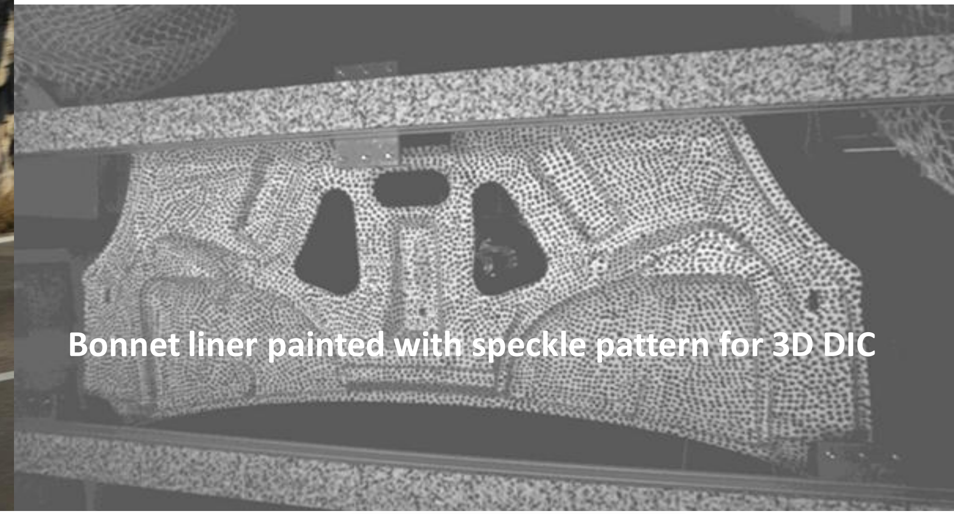
Uncertainty in feature vectors

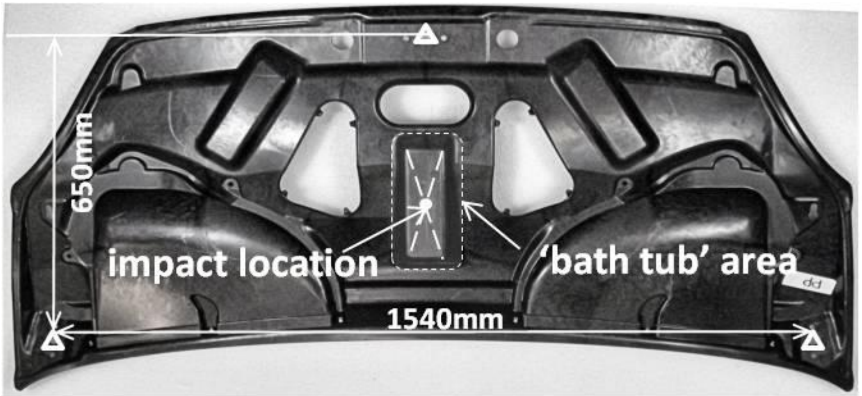


Matlab corrcoef: 0.9897

Sebastian C, Hack E, Patterson EA, 2013, An approach to validation of computational solid mechanics models for strain analysis, *J. Strain Analysis*, 48(1):36-47.

Impact on composite bonnet liner





Bonnet liner made with short fibres in polyamide matrix

Finite element model of bonnet liner

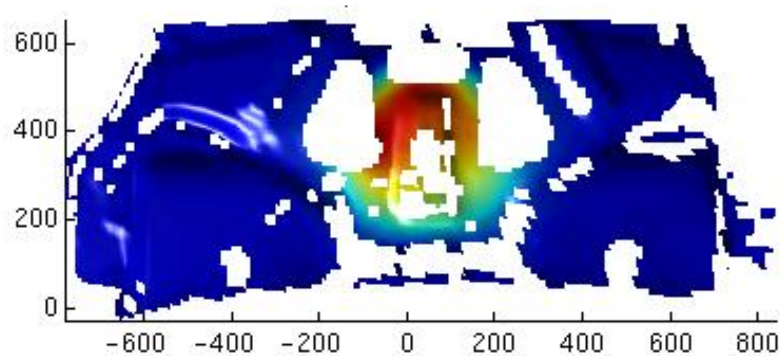
High velocity, low energy impact

About 0.5 milliseconds before impact by 50mm diameter, 125g projectile at 70m/s (=300J).

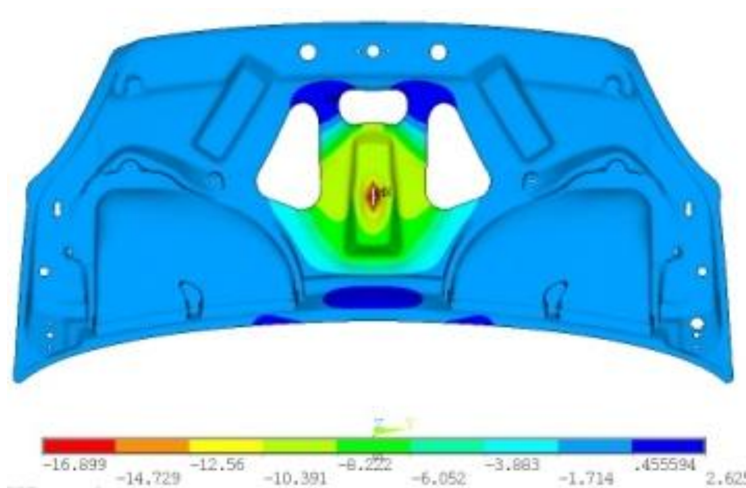
Dynamic analysis of bonnet

Displacements 40 msec after impact

from DIC

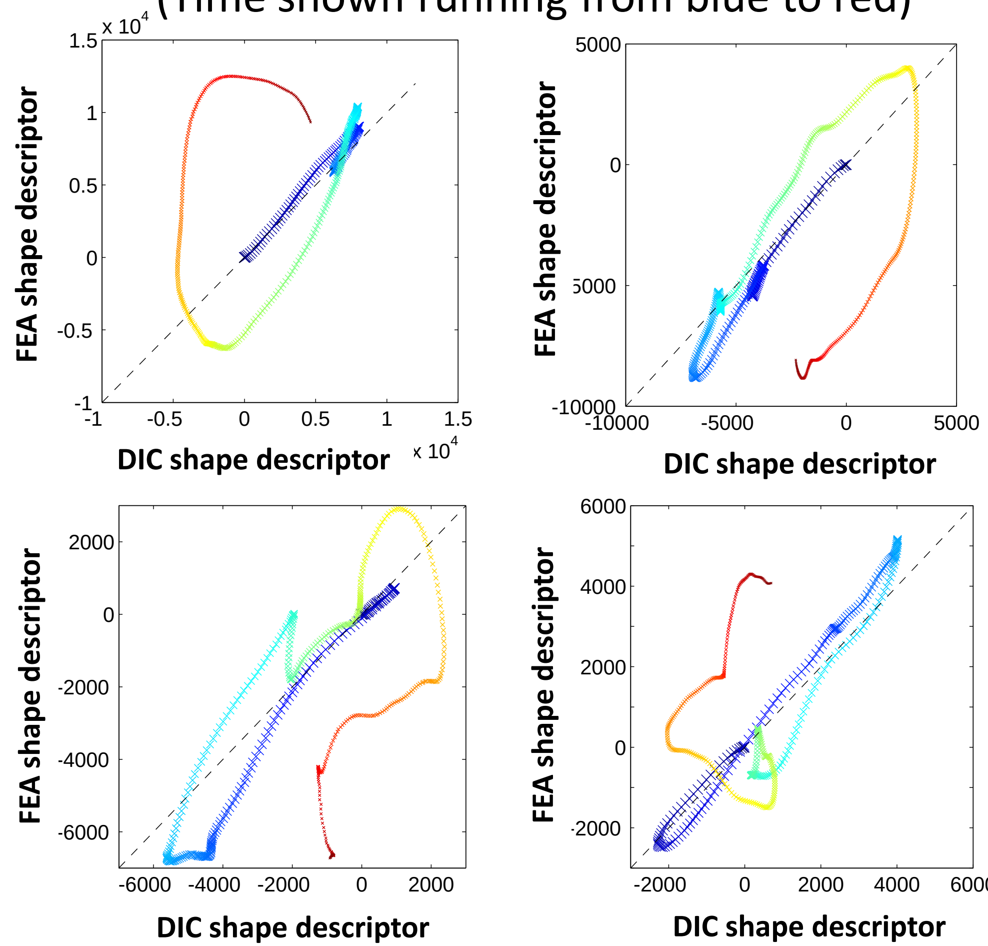


from FEA



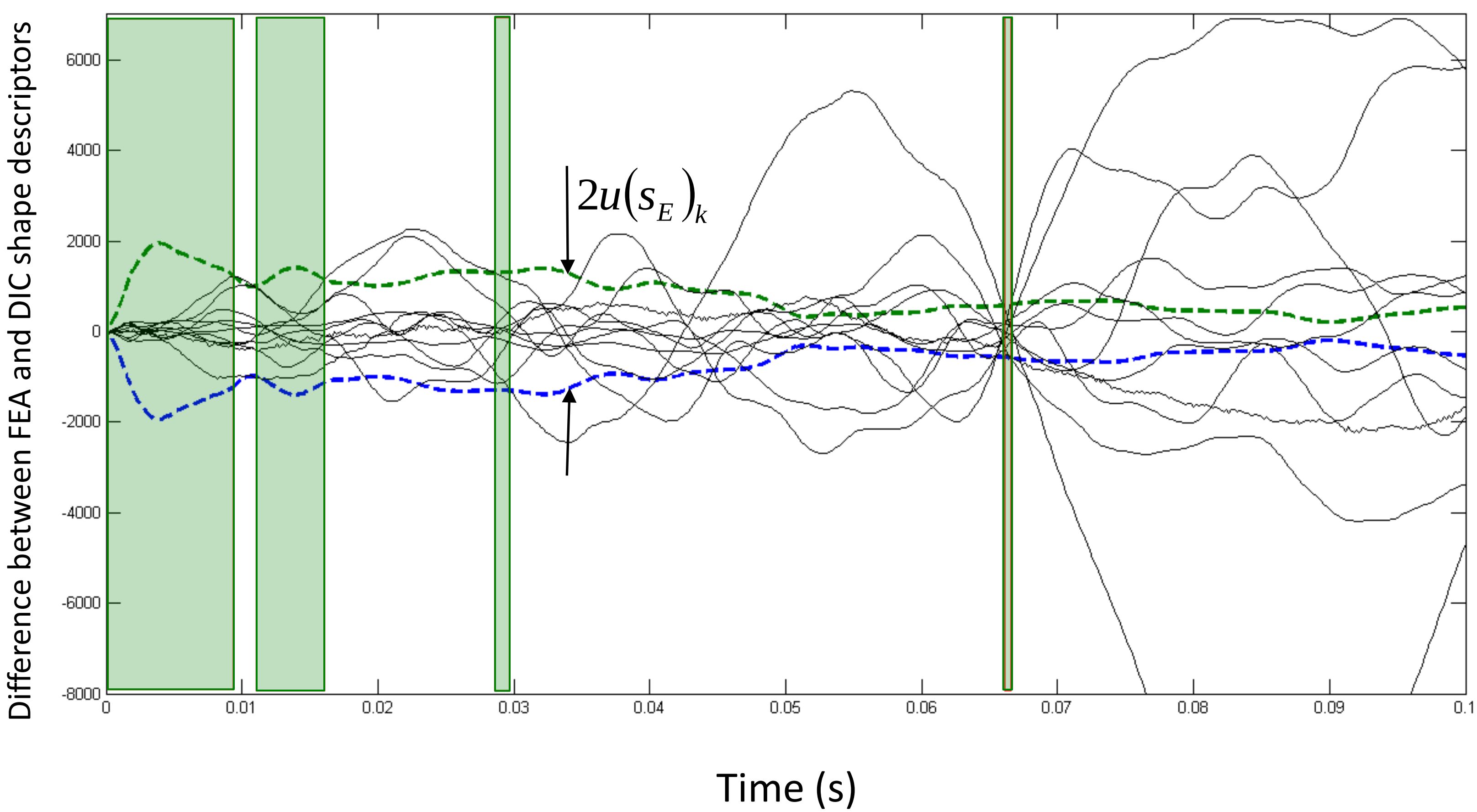
Largest four of 20 shape descriptors

(Time shown running from blue to red)



Burguete RL, Lampeas G, Mottershead JE, Patterson EA, Pipino A, Siebert T, Wang W, 2013, Analysis of Displacement Fields from a High Speed Impact using Shape Descriptors, *J. Strain Analysis*, 49(4): 212-223.

Comparison for validation of model



Burguete RL, Lampeas G, Mottershead JE, Patterson EA, Pipino A, Siebert T, Wang W, 2013, Analysis of Displacement Fields from a High Speed Impact using Shape Descriptors, *J. Strain Analysis*, 49(4): 212-223.

Consequences/Opportunities?

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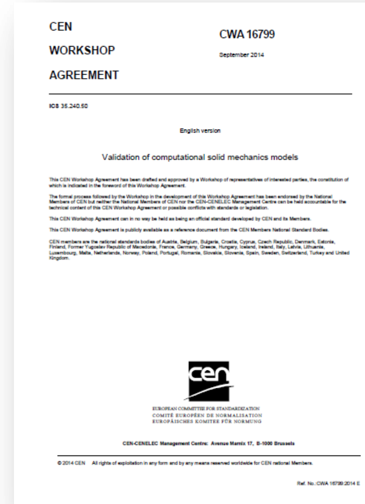
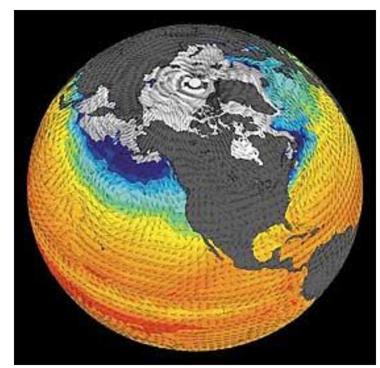
Experimentalists: "How do I implement all this?"

- **CEN Workshop Agreement 16799: 2014**
  Validation of computational solid mechanics models


CEN
WORKSHOP
AGREEMENT
CWA 16799
September 2014
ICS 35.240.50
English version
Validation of computational solid mechanics models

Modellers: "Do we have to do all of this?"

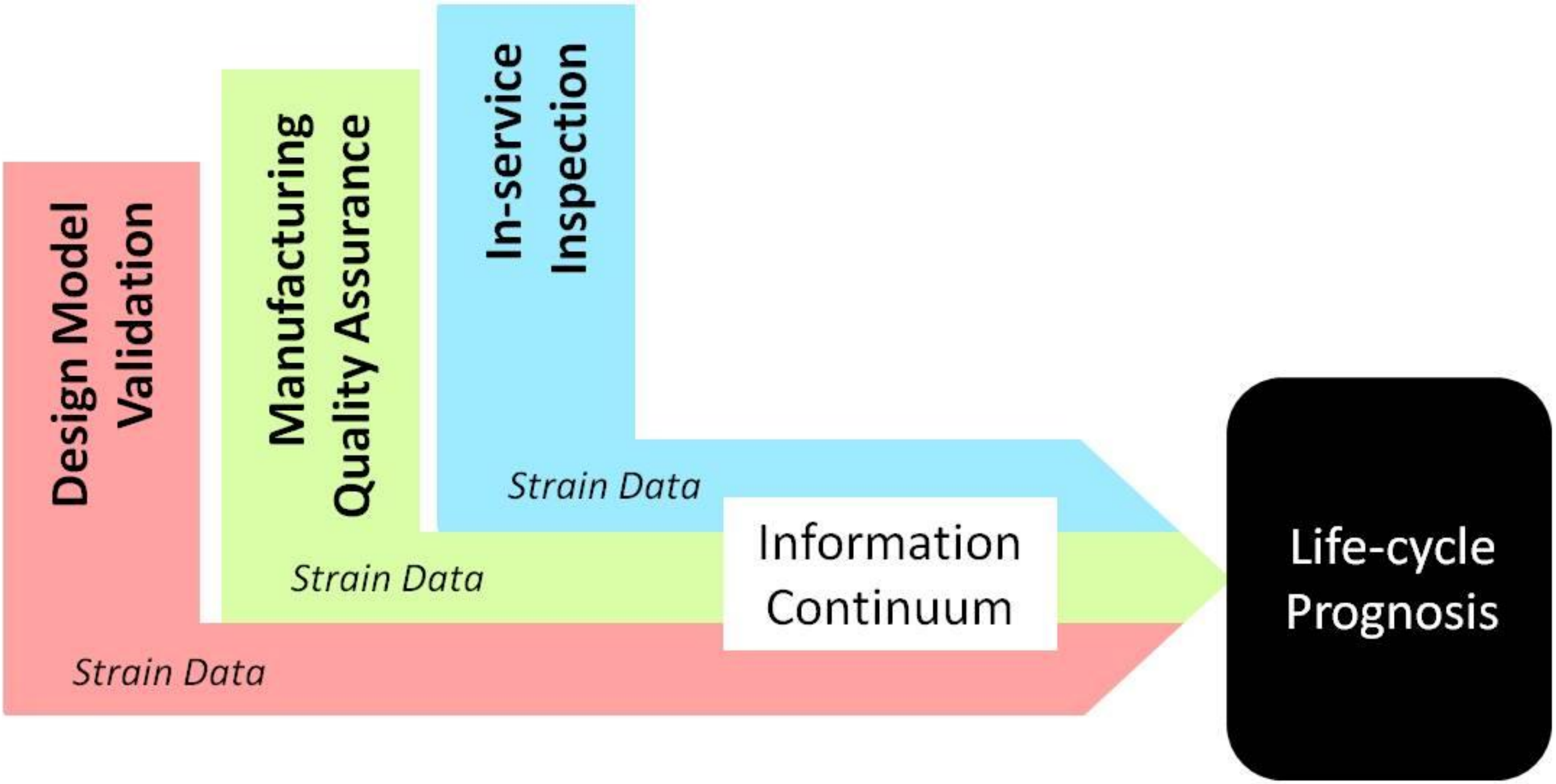
- **Well, yes and no**
- **No, for product designs that evolve relatively slowly**
  - models with epistemic values are more likely reliable
  - epistemic values include: simplicity, explanatory power, internal consistency, external consistency
- **Yes, for radical design innovation**
  - Models unlikely to have epistemic properties
  - Comprehensive validation required to support credibility
- **Yes, for high risk applications**



www.globalchange.umich.edu/globalchange2/current/lectures/climate_change/the_science.htm

Biddle, J., & Winsberg, E., 2010, Value judgments and the estimation of uncertainty in climate modeling, in *New Waves in Philosophy of Science* edited by P.D. Magnus & J. Busch, Palgrave MacMillan, Basingstoke.

Information continuum



Patterson E.A., Feligiotti, M. & Hack, E., 2013, On the integration of validation, quality assurance and non-destructive evaluation, *J. Strain Analysis*, 48(1):48-59.

Strain fields in damaged laminates

Virgin & impact damaged 9-ply GFRP 3.5mm thick [0/90/0/90/0/90/0/90/0]° 240x60mm laminates

Time of flight ultrasound with binary filter

DIC strain fields in tension

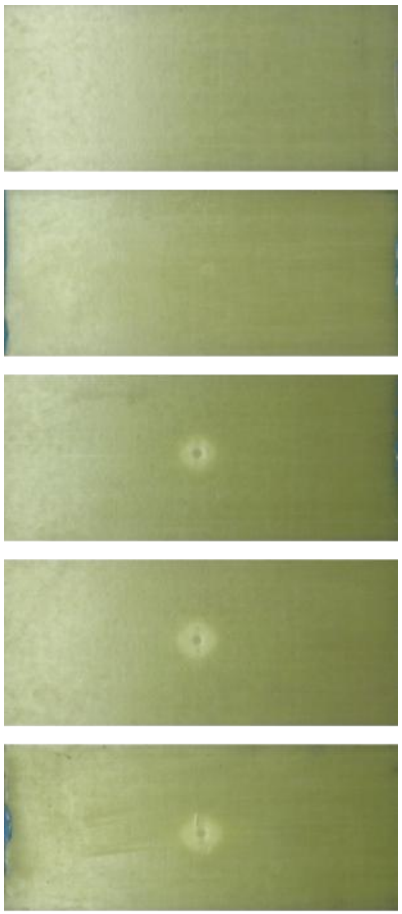
0J

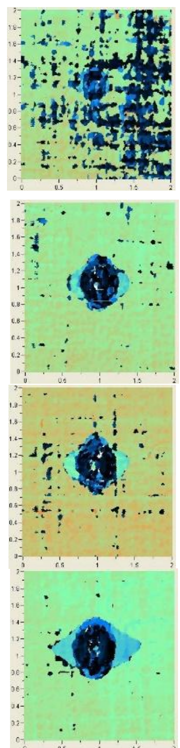
30J

32.5J

35J

37.5J





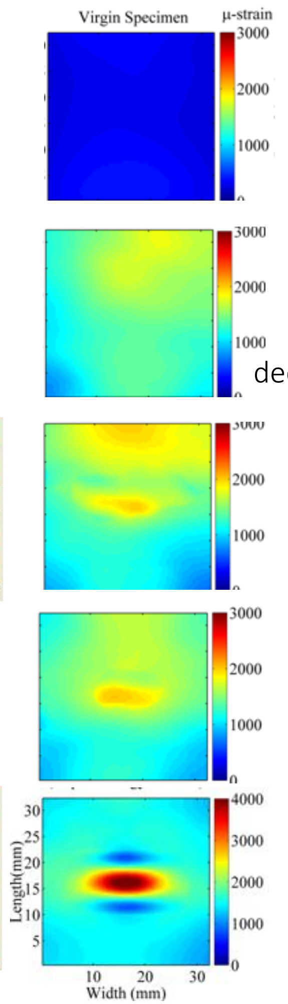
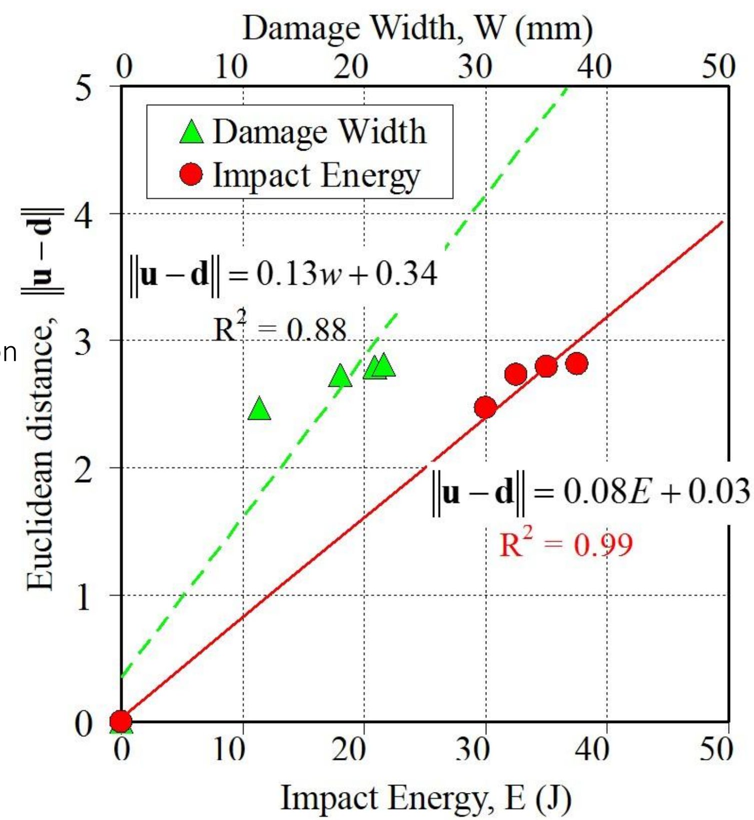


Image decomposition

Euclidean distance between DIC strain fields in damaged and virgin specimen is excellent indicator of impact energy & damage



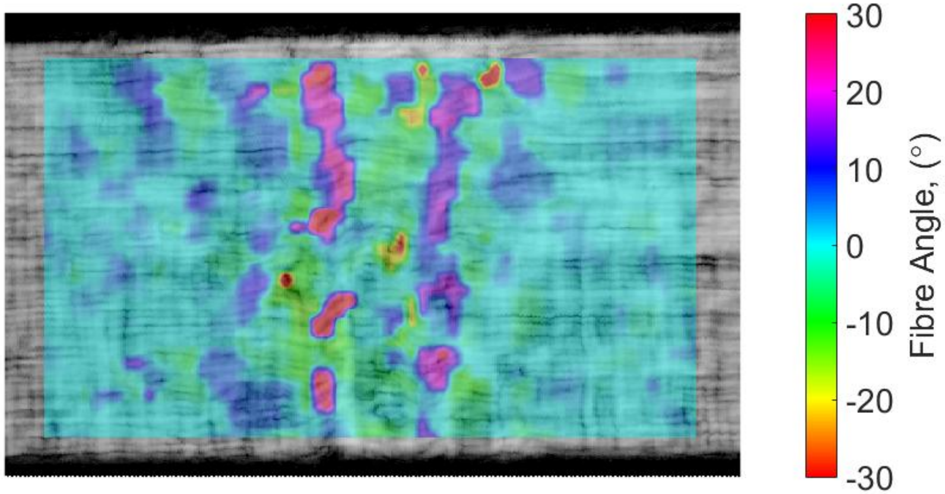
$$\|\mathbf{u}-\mathbf{d}\| = \sqrt{\sum_{i=0}^{N}(u_i - d_i)^2}$$

u_i , d_i are feature vector coefficients representing undamaged /damaged strain fields

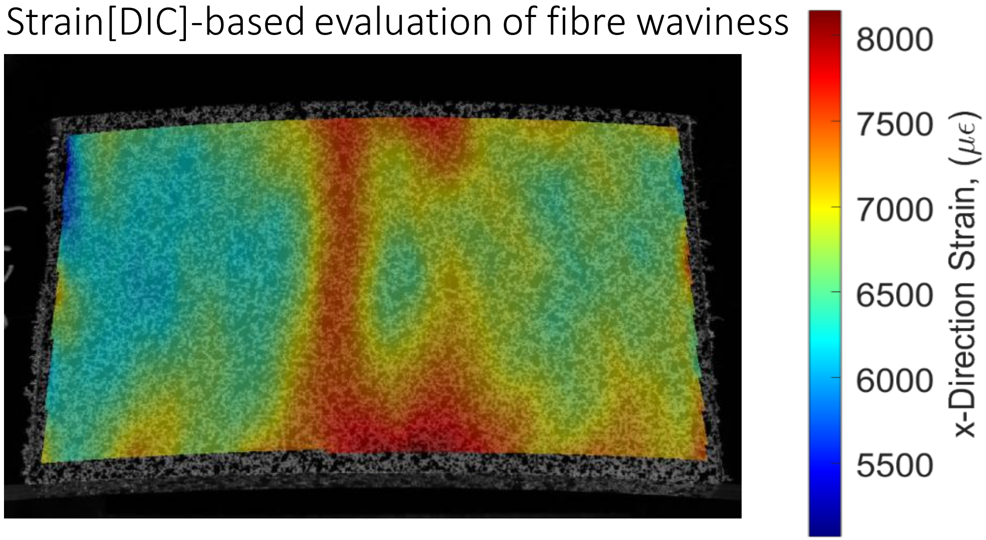
Patki AS & Patterson EA, Damage assessment of fibre reinforced composites using shape descriptors, *J. Strain Anal.* 47(4):244-253, 2012

Manufacturing Quality Assurance

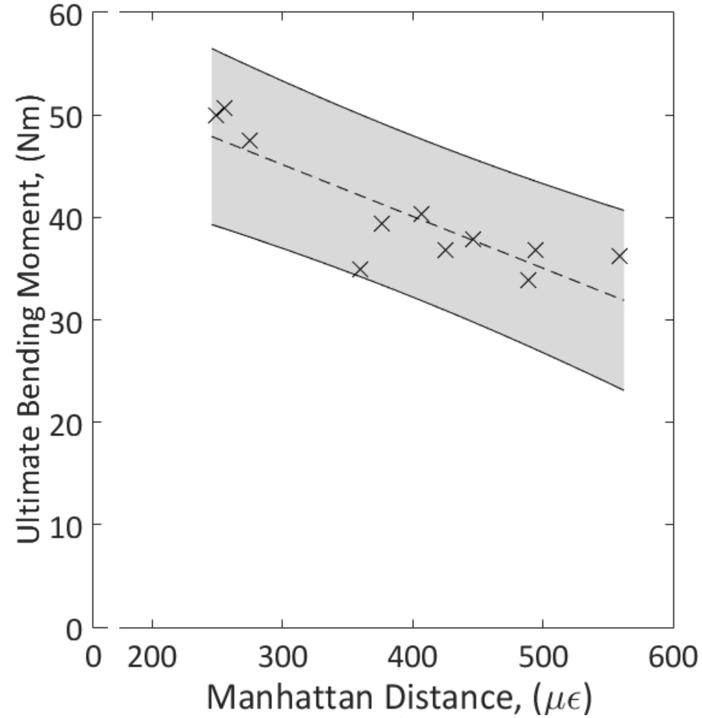
Ultrasound evaluation of fibre waviness in CFRP

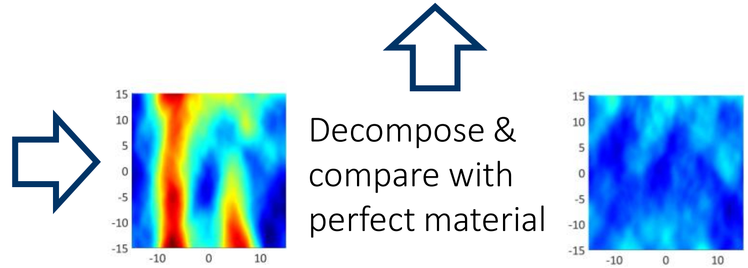


Strain[DIC]-based evaluation of fibre waviness

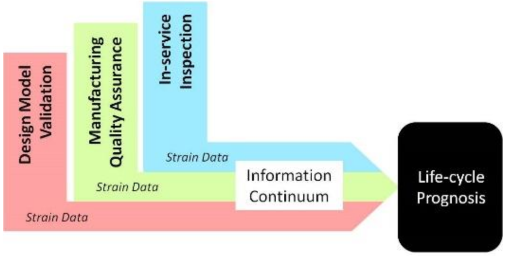


Residual strength prediction using DIC evaluation of fibre waviness





Concluding remarks



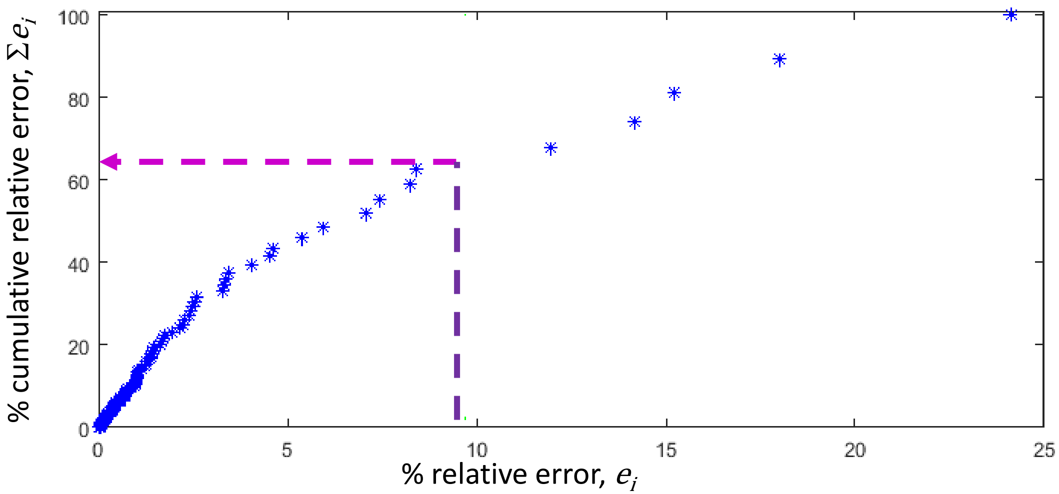
- **Opportunity to unite design validation, manufacturing assurance & in-service inspection in digital twins**
- **Model validation is about quantifying the strength of evidence**
  – Uncertainty quantification is an essential step in validation
  – Aim to use 'observational evidence' of maximum quantity & quality
- **Manufacturing quality assurance viable in composites**
  – Strain data indicate likely structural performance relative to design model
- **In-service inspection viable for composites laminates**
  – Strain data provide input to more reliable residual life assessments
- **All enabled by proper orthogonal decomposition**
  – low-dimensional descriptions that capture the features of interest in large quantities of high dimensional data

Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016

www.RealizeEngineering.WordPress.com

Current work: frequentist approch

- **Relative error for each data pair,** $e_i = \left| \frac{S_{M,i} - S_{E,i}}{max|S_{E,i}|} \right|$



64% probability of model being valid + ***when simulating specific parameter & conditions*** + ***given 9% relative uncertainty in experimental data***

Dvurecenska K, Patterson EA, Patelli E & Graham SJ, Preliminary evaluation of validation metrics for computational mechanics models, *Proc. 10th Int. Conf. on Advances in Exptl. Mech.*, September 1-3, 2015.