Credibility of simulation models: a brick-by-brick approach

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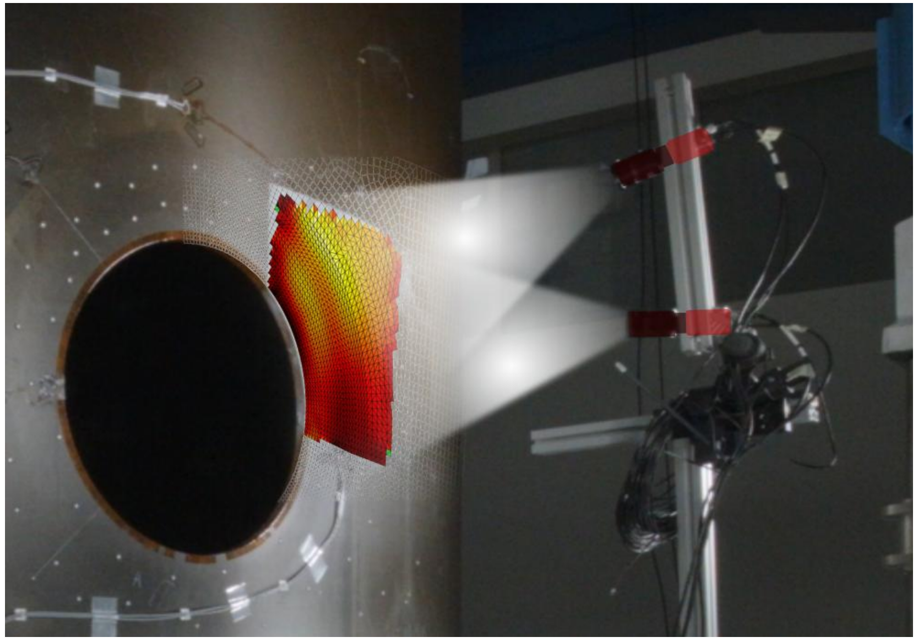
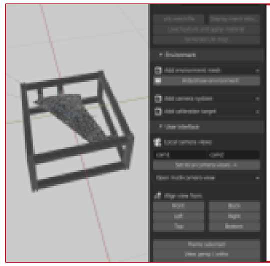
EikoSim

A word about EikoSim

EikoSim

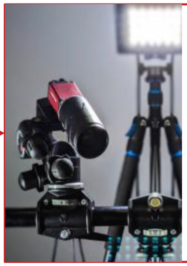
- Mission: Bridges the gap between physical testing and numerical simulation in structural mechanics.
- Technology: Utilizes Digital Image Correlation (DIC) to align simulation models with real-world experimental data.
- Value: Reduces costly physical tests and optimizes designs through accurate simulations.
- Industries: Aerospace, defense, automotive, energy, civil engineering.





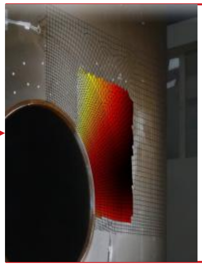
EIKOTWIN VIRTUAL

Synthetic image generation
- Planning
- Anticipating test difficulties



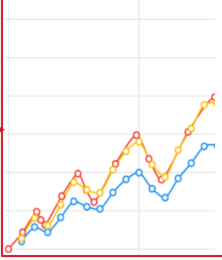
EIKOTWIN VISION

Image acquisition
- Set up cameras
- Acquire images



EIKOTWIN DIC

Image processing
- Calibration
- DIC measurement
- Test/simulation comparison



EIKOTWIN DIGITAL TWIN

Model calibration
- Boundary conditions control
- Sensitivity study
- Parameter identification

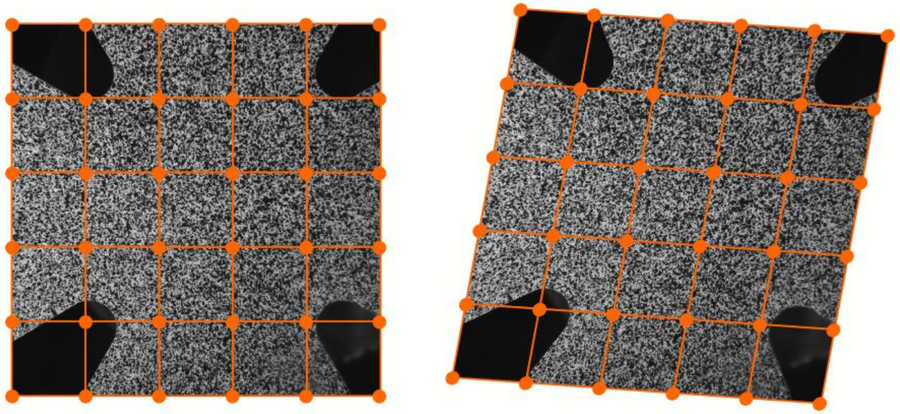
INTEGRATION PARTNERS

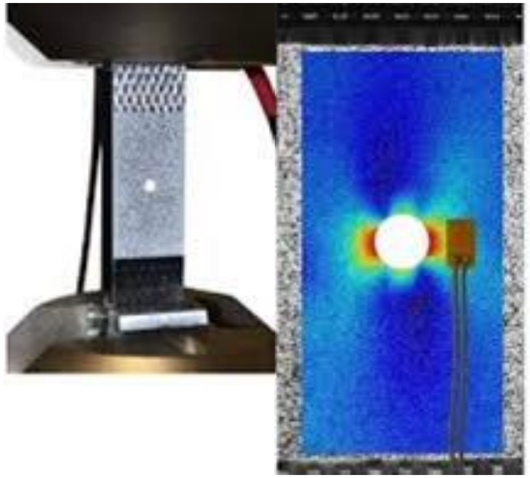
ALTAIR · POWERED BY ALTAIR UNITS · DASSAULT SYSTEMES · Ansys

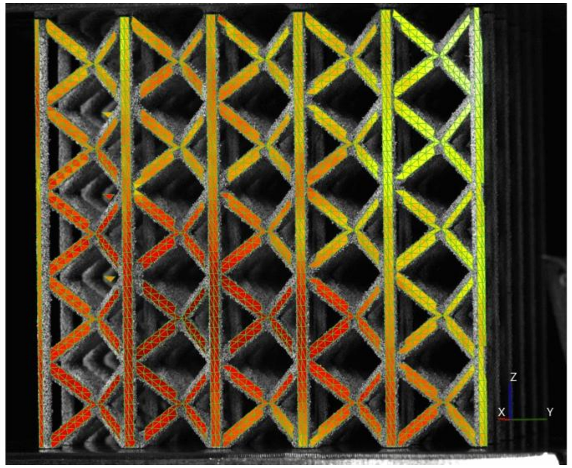
2

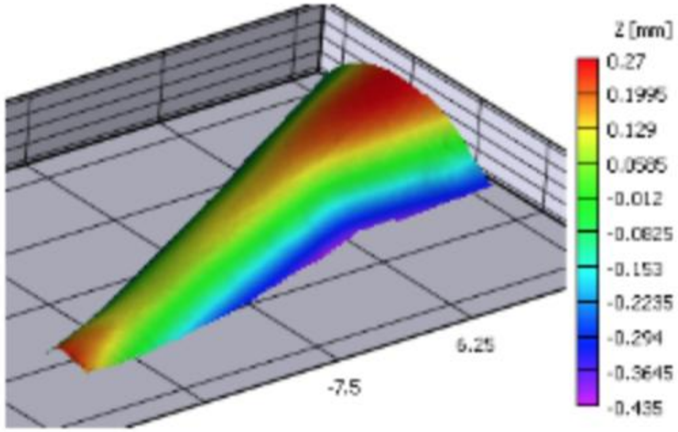
What is Digital Image Correlation?

DIC is an optical measurement technique that measures displacement and strain fields by following a pattern in a series of images







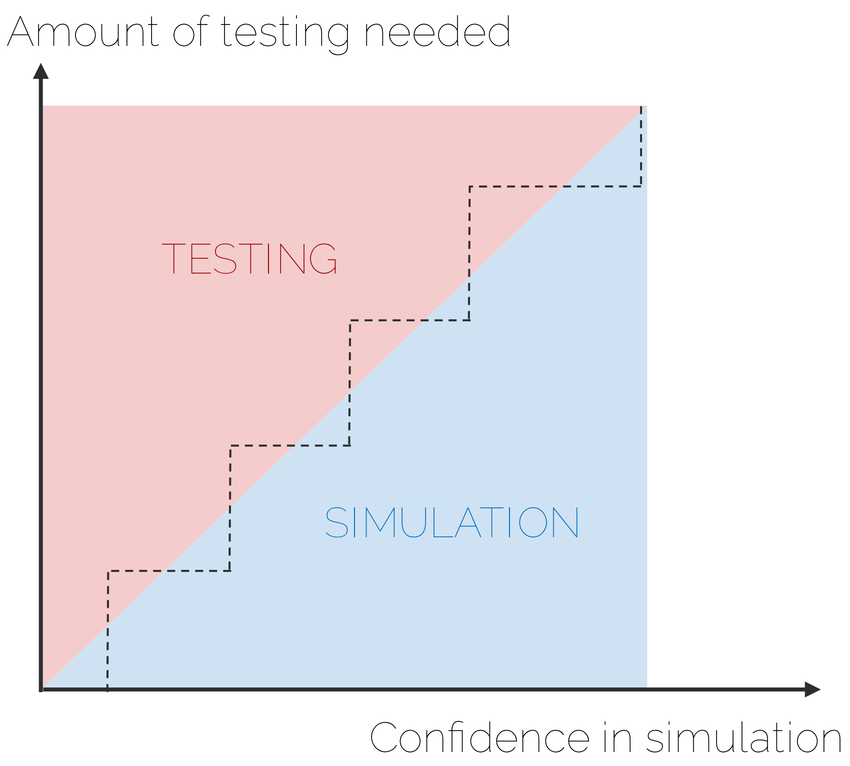


3

Assessing model credibility to develop faster

New generations of products are being developed with less and less testing, but this is not a straightforward journey

1. What does it mean to have a credible model?
2. What are necessary tools/scales to build model credibility?



Building model credibility : using a scale to set common goals

- Predictive Capability Maturity Model for Computational Modeling and Simulation, William L. Oberkampf, Martin Pilch, and Timothy G. Trucano, 2007
- *"The Predictive Capability Maturity Model (PCMM) is a new model that can be used to assess the level of maturity of computational modeling and simulation (M&S) efforts."*

Table 4: Example of PCMM Table Assessment and Project Maturity Requirements

MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity		Assessed	Required	
Physics and Material Model Fidelity			Assessed Required	
Code Verification		Assessed Required		
Solution Verification	Assessed		Required	
Model Validation		Assessed	Required	
Uncertainty Quantification and Sensitivity Analysis	Assessed			Required

Estimating model maturity

- makes evidence-based decision making easier when deciding on a testing policy
- allows to decide for necessary improvements in the modeling process

PCMM table

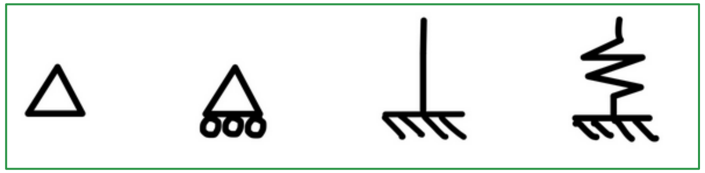
MATURITY / ELEMENT	Maturity Level 0 Low Consequence, Minimal M&S Impact, e.g. Scoping Studies	Maturity Level 1 Moderate Consequence, Some M&S Impact, e.g. Design Support	Maturity Level 2 High-Consequence, High M&S Impact, e.g. Qualification Support	Maturity Level 3 High-Consequence, Decision-Making Based on M&S, e.g. Qualification or Certification
Representation and Geometric Fidelity What features are neglected because of simplifications or stylizations?	• Judgment only • Little or no representational or geometric fidelity for the system and BCs	• Significant simplification or stylization of the system and BCs • Geometry or representation of major components is defined	• Limited simplification or stylization of major components and BCs • Geometry or representation is well defined for major components and some minor components • Some peer review conducted	• Essentially no simplification or stylization of components in the system and BCs • Geometry or representation of all components is at the detail of "as built", e.g., gaps, material interfaces, fasteners • Independent peer review conducted
Physics and Material Model Fidelity How fundamental are the physics and material models and what is the level of model calibration?	• Judgment only • Model forms are either unknown or fully empirical • Few, if any, physics-informed models • No coupling of models	• Some models are physics based and are calibrated using data from related systems • Minimal or ad hoc coupling of models	• Physics-based models for all important processes • Significant calibration needed using separate effects tests (SETs) and integral effects tests (IETs) • One-way coupling of models • Some peer review conducted	• All models are physics based • Minimal need for calibration using SETs and IETs • Sound physical basis for extrapolation and coupling of models • Full, two-way coupling of models • Independent peer review conducted
Code Verification Are algorithm deficiencies, software errors, and poor SQE practices corrupting the simulation results?	• Judgment only • Minimal testing of any software elements • Little or no SQE procedures specified or followed	• Code is managed by SQE procedures • Unit and regression testing conducted • Some comparisons made with benchmarks	• Some algorithms are tested to determine the observed order of numerical convergence • Some features & capabilities (F&C) are tested with benchmark solutions • Some peer review conducted	• All important algorithms are tested to determine the observed order of numerical convergence • All important F&Cs are tested with rigorous benchmark solutions • Independent peer review conducted
Solution Verification Are numerical solution errors and human procedural errors corrupting the simulation results?	• Judgment only • Numerical errors have an unknown or large effect on simulation results	• Numerical effects on relevant SRQs are qualitatively estimated • Input/output (I/O) verified only by the analysts	• Numerical effects are quantitatively estimated to be small on some SRQs • I/O independently verified • Some peer review conducted	• Numerical effects are determined to be small on all important SRQs • Important simulations are independently reproduced • Independent peer review conducted
Model Validation How carefully is the accuracy of the simulation and experimental results assessed at various tiers in a validation hierarchy?	• Judgment only • Few, if any, comparisons with measurements from similar systems or applications	• Quantitative assessment of accuracy of SRQs not directly relevant to the application of interest • Large or unknown experimental uncertainties	• Quantitative assessment of predictive accuracy for some key SRQs from IETs and SETs • Experimental uncertainties are well characterized for most SETs, but poorly known for IETs • Some peer review conducted	• Quantitative assessment of predictive accuracy for all important SRQs from IETs and SETs at conditions/geometries directly relevant to the application • Experimental uncertainties are well characterized for all IETs and SETs • Independent peer review conducted
Uncertainty Quantification and Sensitivity Analysis How thoroughly are uncertainties and sensitivities characterized and propagated?	• Judgment only • Only deterministic analyses are conducted • Uncertainties and sensitivities are not addressed	• Aleatory and epistemic (A&E) uncertainties propagated, but without distinction • Informal sensitivity studies conducted • Many strong UQ/SA assumptions made	• A&E uncertainties segregated, propagated and identified in SRQs • Quantitative sensitivity analyses conducted for most parameters • Numerical propagation errors are estimated and their effect known • Some strong assumptions made • Some peer review conducted	• A&E uncertainties comprehensively treated and properly interpreted • Comprehensive sensitivity analyses conducted for parameters and models • Numerical propagation errors are demonstrated to be small • No significant UQ/SA assumptions made • Independent peer review conducted

Predictive Capability Maturity Model for Computational Modeling and Simulation, William L. Oberkampf, Martin Pilch, and Timothy G. Trucano, 2007

6

Brick 1 – Representation and geometric fidelity

MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

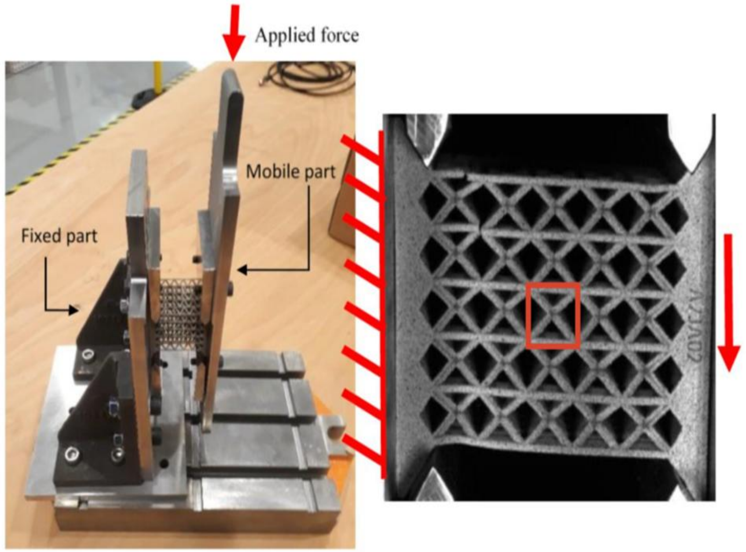


7

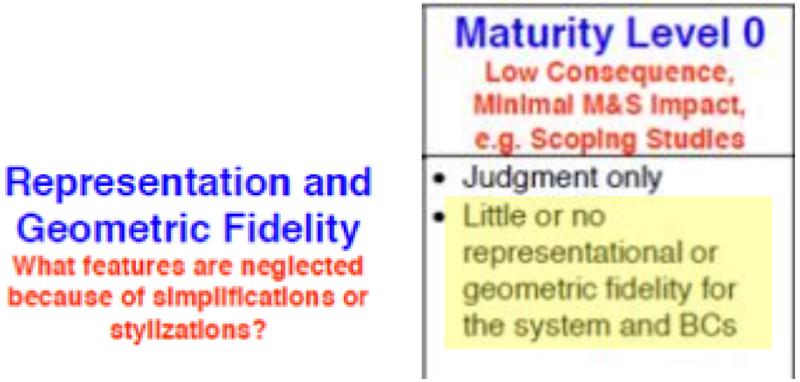
Lattice specimen @ IRT Saint-Exupéry

Context & objectives:

- Lattice structure
- Complex structural testing: impossible to use strain gauges
- Complex boundary conditions : make

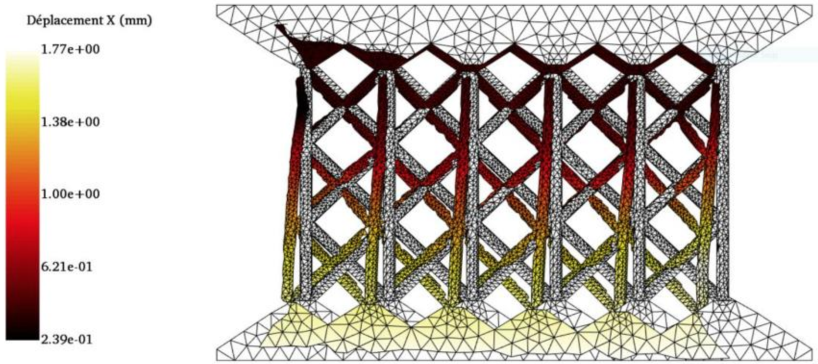


MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity	X			
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				



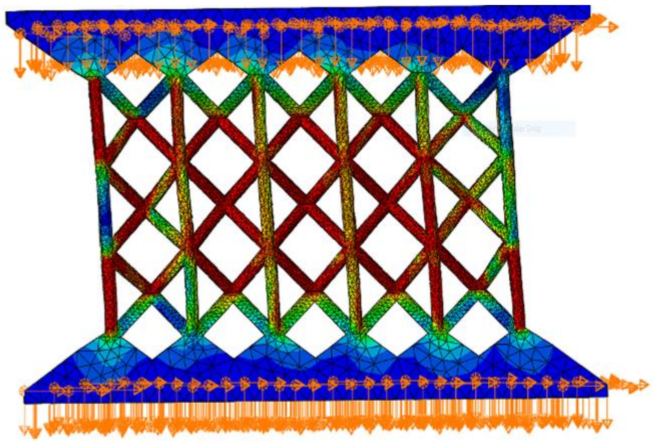
8

Lattice specimen @ IRT Saint-Exupéry



Procedure

- Measurement on a complex FE mesh
- Boundary conditions management from the displacement field via a 6dof RBM



MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity	X	→	X	
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

Representation and Geometric Fidelity
What features are neglected because of simplifications or stylizations?

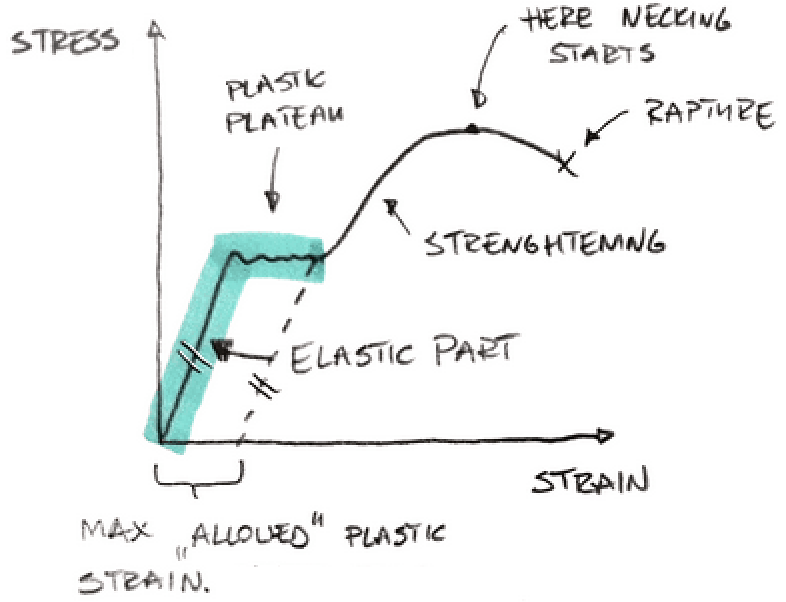
Maturity Level 2
High-Consequence, High M&S Impact, e.g. Qualification Support

- Limited simplification or stylization of major components and BCs
- Geometry or representation is well defined for major components and some minor components
- Some peer review conducted

9

Brick 2 – Physics and material model fidelity

MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

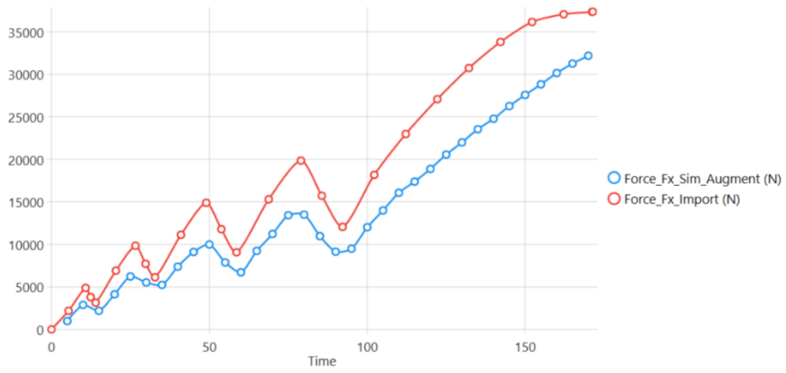


10

Lattice specimen @ IRT Saint-Exupéry

Context & objectives:

- Boundary conditions creation from the displacement field
- Homogenized parameters identification



MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity		X		
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

Physics and Material Model Fidelity

How fundamental are the physics and material models and what is the level of model calibration?

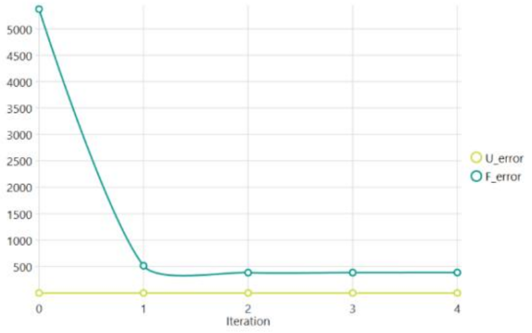
Maturity Level 1

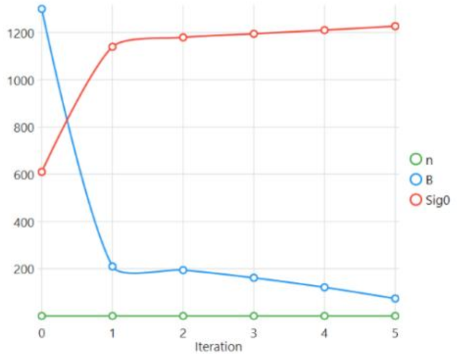
Moderate Consequence, Some M&S Impact, e.g. Design Support

- Some models are physics based and are calibrated using data from related systems
- Minimal or ad hoc coupling of models

11

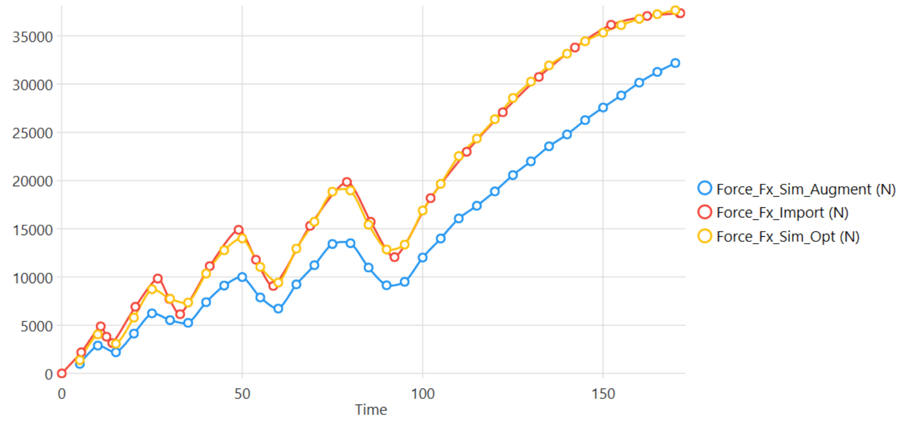
Lattice specimen @ IRT Saint-Exupéry





Procedure

- Material model calibration on U+F thanks to inverse method (Finite Element Model Updating)
- One-test identification of 3 parameters



MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity		X →		X
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

Maturity Level 3

High-Consequence, Decision-Making Based on M&S, e.g. Qualification or Certification

Physics and Material Model Fidelity

How fundamental are the physics and material models and what is the level of model calibration?

- All models are physics based
- Minimal need for calibration using SETs and IETs
- Sound physical basis for extrapolation and coupling of models
- Full, two-way coupling of models
- Independent peer review conducted

12

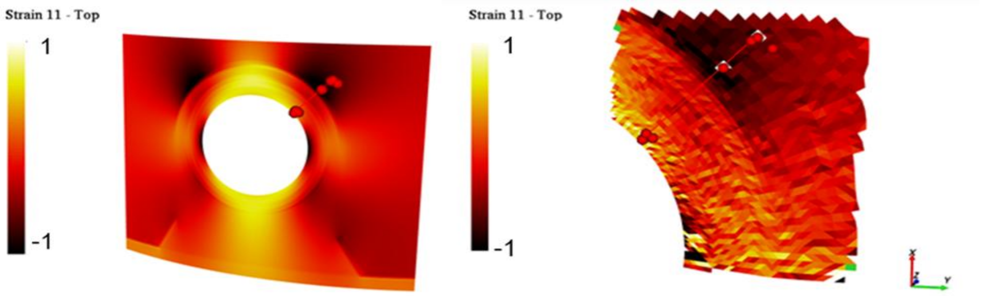
Brick 5 – Model validation

MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation				
Uncertainty Quantification and Sensitivity Analysis				

Structural validation test with ArianeGroup

Context & objectives:
- Size 1 Dual Launch Structure
- Compression test
- Goal : validation of the simulation

Procedure:
- Instrumentation : Multi-camera DIC systems (6), strain gauges, fiber optics, photogrammetry
- Global test/simulation comparison
- Uncertainty quantification for all measurement sources



MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity				
Physics and Material Model Fidelity				
Code Verification				
Solution Verification				
Model Validation		X	→	X
Uncertainty Quantification and Sensitivity Analysis				

Model Validation
How carefully is the accuracy of the simulation and experimental results assessed at various tiers in a validation hierarchy?

Maturity Level 1
Moderate Consequence, Some M&S Impact, e.g. Design Support
- Quantitative assessment of accuracy of SRQs not directly relevant to the application of interest
- Large or unknown experimental uncertainties

Maturity Level 3
High-Consequence, Decision-Making Based on M&S, e.g. Qualification or Certification
- Quantitative assessment of predictive accuracy for all important SRQs from IETs and SETs at conditions/geometries directly relevant to the application
- Experimental uncertainties are well characterized for all IETs and SETs
- Independent peer review conducted

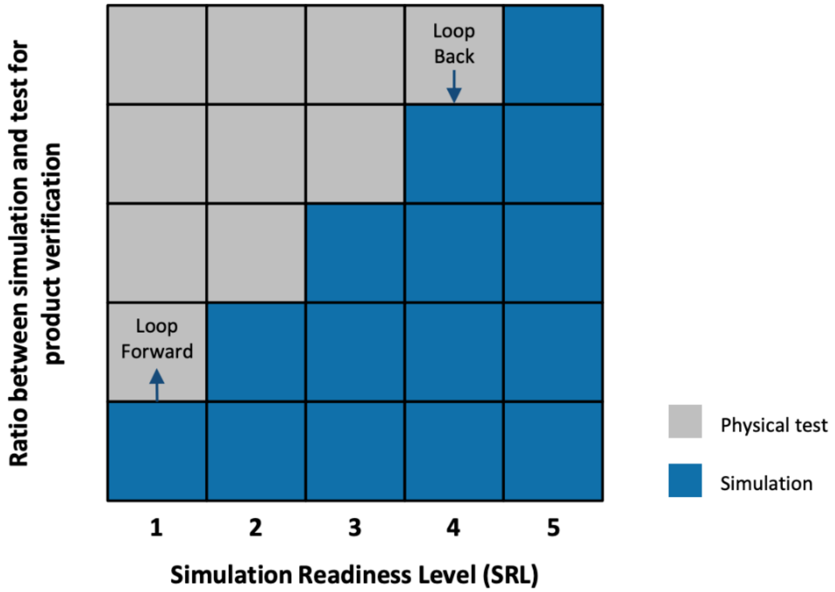
14

Conclusion

Main points

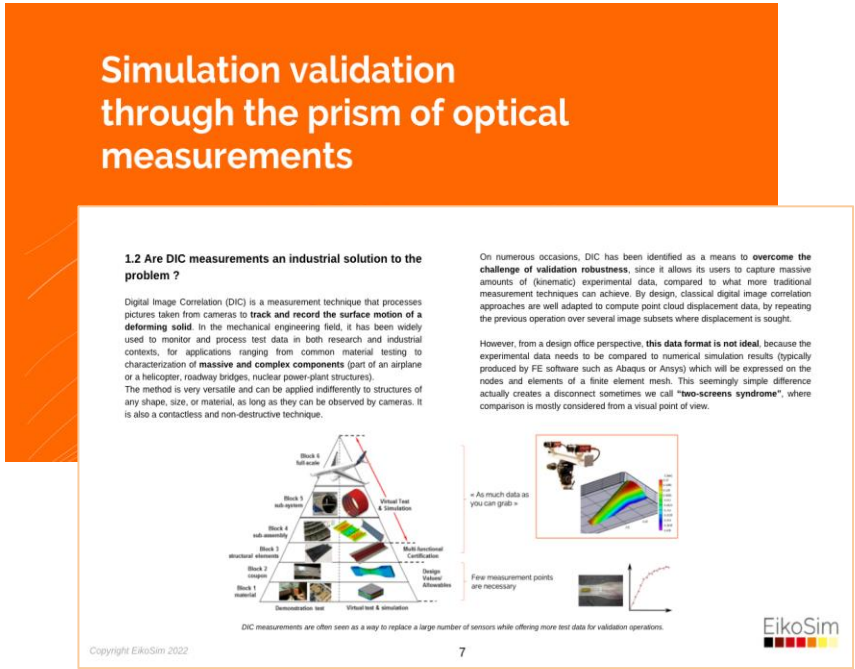
- Each category of the PCMM (or CAS, …) scale helps rationalize maturity objectives,
- Combined efforts by simulation and test teams allow to reach higher levels of maturity for each category,
- In all examples, the customer didn't use the PCMM scale, we did internally. Adopting such a system can lead to clarify expectations and define a set of internal rules on how much testing should be conducted.

Industrial Implementation of a Simulation Maturity Scale, Anders Bøge Jensen (Grundfos)
NAFEMS seminar on V&V, 2021



Questions?

Download our White Paper !



Simulation validation through the prism of optical measurements

1.2 Are DIC measurements an industrial solution to the problem ?

Digital Image Correlation (DIC) is a measurement technique that processes pictures taken from cameras to **track and record the surface motion of a deforming solid**. In the mechanical engineering field, it has been widely used to monitor and process test data in both research and industrial contexts, for applications ranging from common material testing to characterization of **massive and complex components** (part of an airplane or a helicopter, roadway bridges, nuclear power-plant structures).
The method is very versatile and can be applied indifferently to structures of any shape, size, or material, as long as they can be observed by cameras. It is also a contactless and non-destructive technique.

On numerous occasions, DIC has been identified as a means to **overcome the challenge of validation robustness**, since it allows its users to capture massive amounts of (kinematic) experimental data, compared to what more traditional measurement techniques can achieve. By design, classical digital image correlation approaches are well adapted to compute point cloud displacement data, by repeating the previous operation over several image subsets where displacement is sought.

However, from a design office perspective, **this data format is not ideal**, because the experimental data needs to be compared to numerical simulation results (typically produced by FE software such as Abaqus or Ansys) which will be expressed on the nodes and elements of a finite element mesh. This seemingly simple difference actually creates a disconnect sometimes we call **"two-screens syndrome"**, where comparison is mostly considered from a visual point of view.

DIC measurements are often seen as a way to replace a large number of sensors while offering more test data for validation operations.

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7

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