EASA
European Aviation Safety Agency

"Certification by Analysis", or: Modelling & Simulation

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Terminology

- Certification by Analysis (CbA)…
- Certification & Qualification by Analysis (CQbA)…
- Certification by Analysis Supported by Test (CAST)…
- Virtual Certification…
- Digital Certification…
- Certification by Simulation…

"No more testing…?"

"Test data needed to validate analysis…!"

Modelling and Simulation (M&S)

- **M&S** is a complement or substitute for physical experimentation, in which computers are used to compute the results of some physical phenomenon
- **Modelling** is the act of constructing a model
- **Simulation** is the execution of a model

The Bigger Picture

- "The Virtual or Digital Aircraft"
  - To cover the complete life cycle of an aircraft, from initial design to retirement from service:
    - Design & Development
      - Virtual Manufacturing, Virtual Prototyping,…
    - Certification & Qualification by Analysis
      - Structures, Systems, Flight Mechanics,…
    - In-service operations
      - Digital Twin

Background to M&S (1/3)

- Increase in use of M&S techniques to support the showing of compliance with airworthiness and environmental requirements
  - (CS 29.631) “Compliance must be shown by tests, or by analysis based on tests carried out on sufficiently representative structures of similar design.”
- Opportunities & Benefits
  - Allows investigations by analysis where testing would be impractical or impossible
  - Reduce or eliminate need for testing
- Risks & Challenges
  - Establish credibility of M&S results

Background to M&S (2/3)

- Currently there is a lack of coherent regulatory guidance material or Industry standards for M&S

- For some subjects useful references or standards exist, e.g.:
  - AC 20-146A / SAE ARP 5765A (Dynamic Seat Certification)
  - ASME V&V 10-2006 (V&V for Computational Solid Mechanics)
  - AIAA G-077-1998 (V&V for Computational Fluid Dynamics)
  - ED-79A / SAE ARP 4754A (Development of Systems)
  - SAE AIR 6326 (M&S for Electrical Power Systems)
  - CS/AMC-FSTD(A) (H) (Validation of Flight Simulation Training Devices)

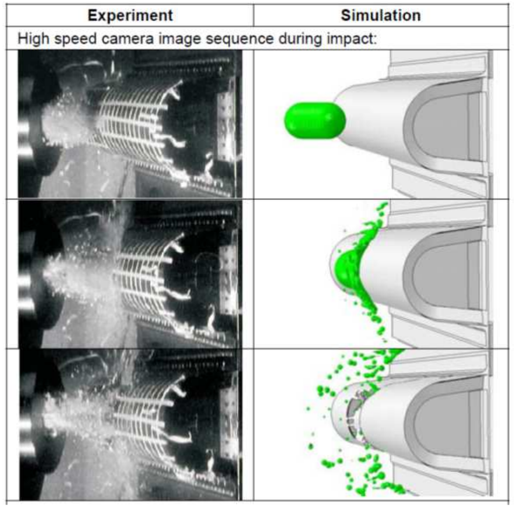
Background to M&S (3/3)

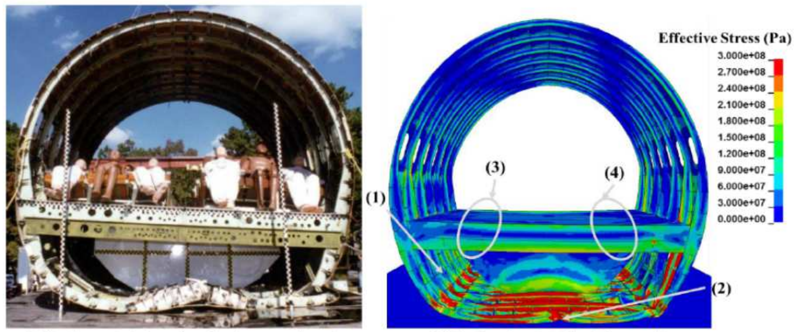
- Lack of standardisation and "analysis scepticism" drives detailed reviews of M&S applications

- Better to rely on process rather than detailed review of every M&S case
  - Based on best practices and processes
  - Documented in regulatory guidance material and/or Industry standards
  - Incorporated in design approval holders' manuals and procedures
  - Spot-checked during design approval process

M&S for Structures (1/2)

- Main Structures subjects where M&S is applied:
  - Static strength
  - Impact conditions
    - Crashworthiness including Ditching
    - Bird strike
    - Dynamic seat certification
    - Fuel system crash resistance
    - Uncontained engine failures
    - Wheel & tyre debris
  - Loads and aeroelasticity / vibration & buffeting
  - Thermal analysis
  - Engine failure conditions
  - Fatigue & damage tolerance

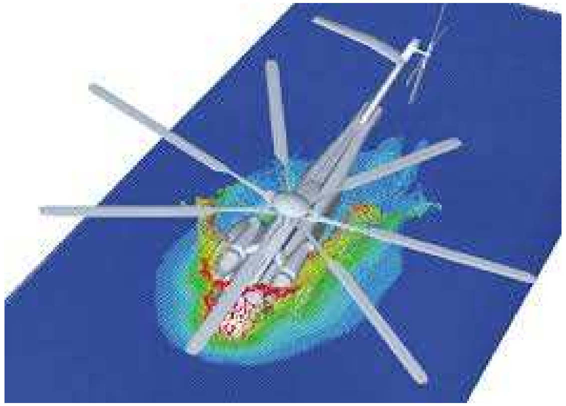


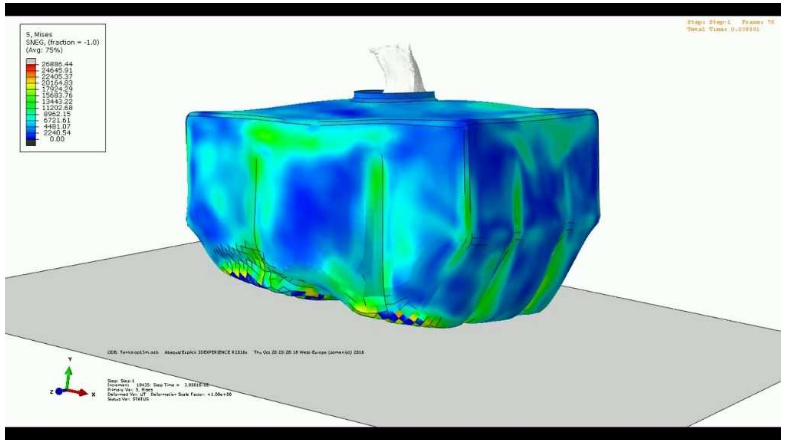


(a) Post-impact picture of section drop experiment
(b) Section drop test simulation result

M&S for Structures (2/2)

- Different types of M&S techniques:
  - Finite (Element, Difference, Volume) Methods
    - Computational Solid or Structural Mechanics (CSM)
    - Computational Fluid Dynamics (CFD)
  - Static and dynamic, linear and non-linear
  - Implicit and explicit analysis
  - Eulerian, Lagrangian, Arbitrary Lagrangian-Eulerian (ALE), Combined Eulerian-Lagrangian (CEL), Smoothed Particle Hydrodynamics (SPH)





Main Attention Items

Verification

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Validation

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Errors & Uncertainties

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Extrapolation

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Experience

↓

Documentation

Verification (1/5)

(ref. ASME V&V 10-2006)

- **Verification**: the process of determining that a computational model accurately represents the underlying mathematical model and its solution ("Are the equations being solved correctly?")

- **Code Verification**
  - Are the mathematical model and solution algorithms working correctly?

- **Calculation (or Solution) Verification**
  - Is the discrete solution of the mathematical model accurate?

Verification (2/5)

- **Code Verification**

- EASA does not approve software tools, only compliance data

- Most applicants use established and commercially available software tools
  - Code verification less of an issue for EASA
  - Establish that software tool is suitable for the type of analysis, run benchmark cases, check new releases for consistency with previous results,…

- When applicants develop their own software tools to perform M&S, code verification needs to be performed and discussed with EASA

Verification (3/5)

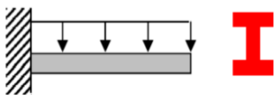
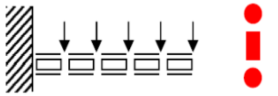
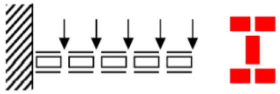
- **Calculation Verification**

- Requires methodical approach to building analytical model (step by step, from simple to more complex modelling) and critical assessment of input and output data

- Includes checks during both pre-processing and post-processing steps in M&S process:
  - Checks on material properties, units, dimensions, boundary conditions, elements/cells, orientation, mass,….
  - Checks on energy balance, hourglass effects, negative volumes, singularities, reaction forces, deformation, spatial and temporal convergence,…

- Example of pre-processing step (choice of elements)

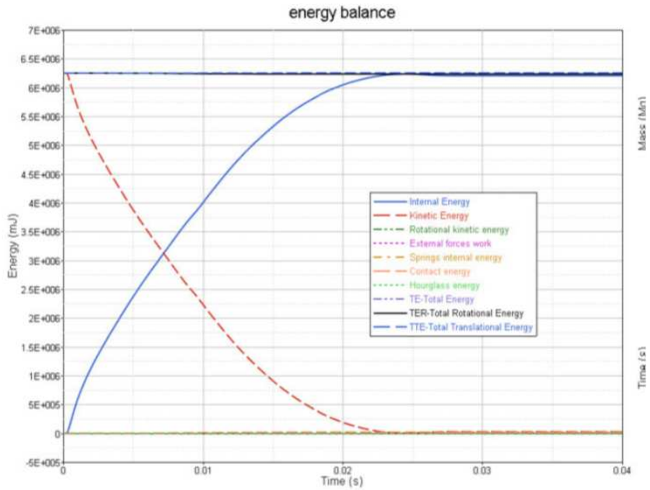
Choice of Elements: Cantilever Beam Summary

Model		Deflection (inches)	Max. Stress (Ksi)	Stress % Diff
Theoretical Solution		0.2837	15.2	--
Beam Elements		0.2837	15.2	0
Rod-Plate-Rod		0.4013	18.1	+19
Plate Elements		0.2843	14.1	-7

Ref. Finite Element Modelling and Analysis Validation Requirements and Methods, P. Safarian, November 2017

Verification (5/5)

- Example of post-processing step (energy balance)



- Total Energy = Internal Energy + Kinematic Energy + Hourglass Energy + Contact Energy - External Work ……
  - Total Energy should remain constant
  - Hourglass Energy < 10% of Total Energy
  - Hourglass energy + Contact Energy < 15% of Total Energy

    Ref. Crash Analysis with RADIOSS – Study Guide

Main Attention Items

Verification

Validation

Errors & Uncertainties

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Validation (1/6)

(ref. ASME V&V 10- 2006)

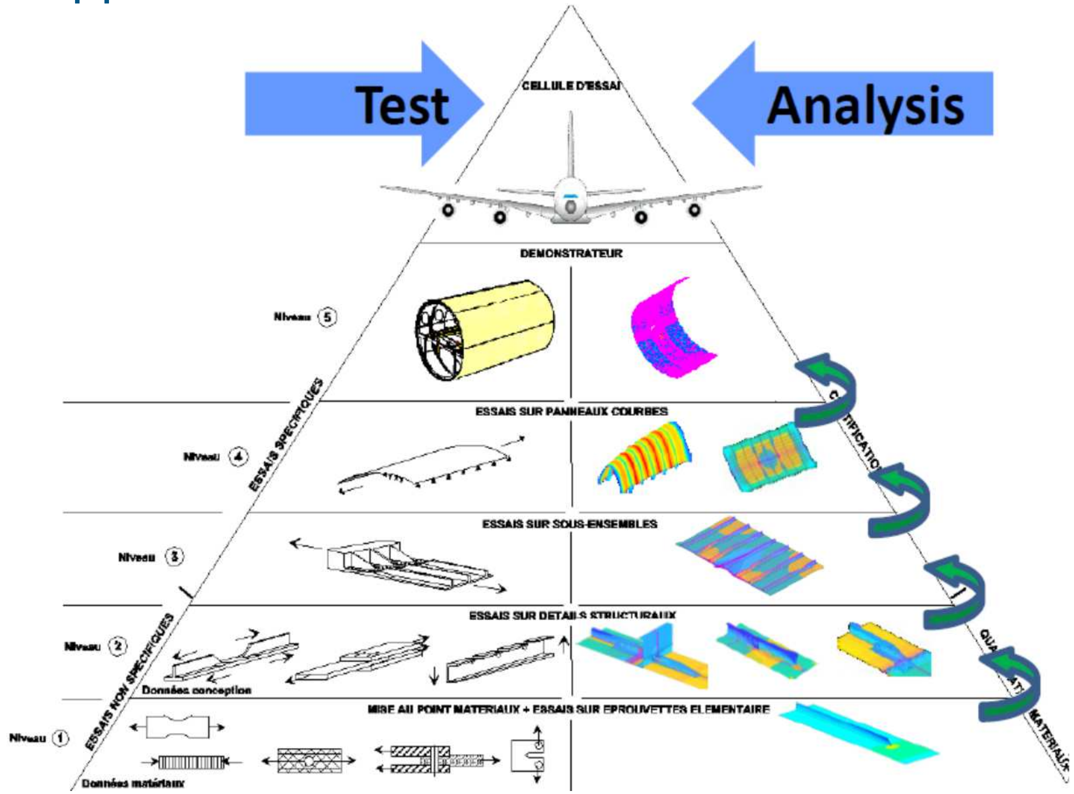
- **Validation**: the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model ("Are the correct equations being solved?")

- Validation is typically based on comparison of analysis results with test data

- Validation should apply principles of building block approach (see next slide)
  - Test and analysis pyramid with (from bottom to top) increasing complexity and reducing number of test specimens

Validation (2/6)

- Building Block Approach



Ref. Verification and Validation of Models and Analyses: a must for the aeronautical industry, Jean-François Imbert, October 2012

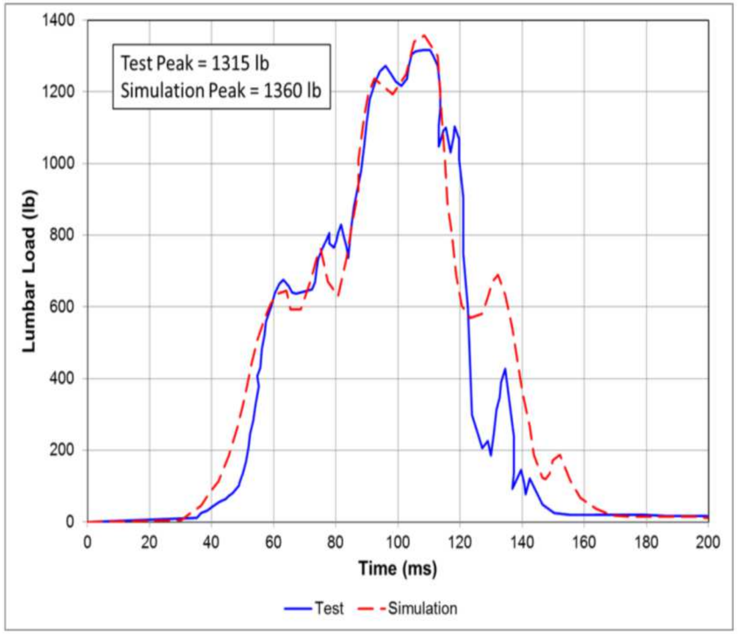
Validation (3/6)

- Some of the issues to be considered:
  - High quality test data are required for comparison with analysis results
  - As many test data as possible should be collected
  - Test variability
  - Appropriate techniques to be applied for comparison of test data with analysis results (next slides)

Validation (4/6)

- Test data vs. analysis results, example 1
  - Sprague and Geers Comprehensive Error
  - Considers both magnitude and curve shape
  - Used in dynamic seat and crashworthiness evaluations

$$C_{SG} = \sqrt{M_{SG}^2 + P_{SG}^2}$$



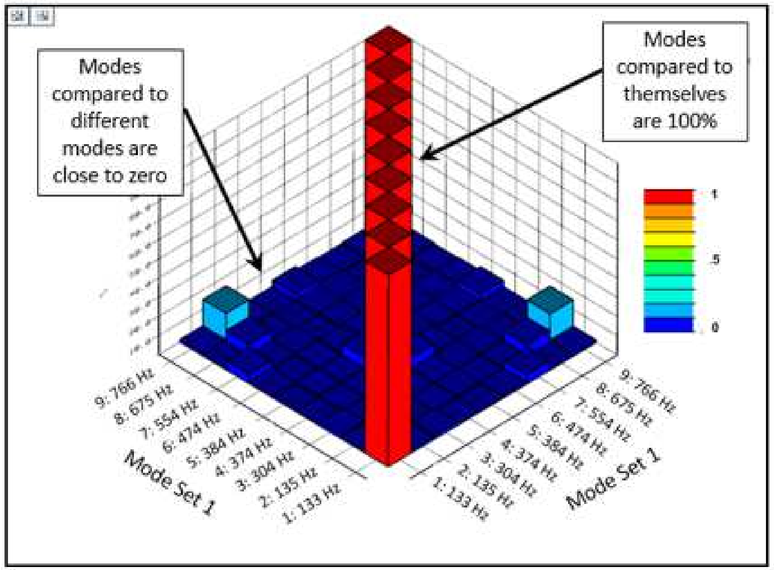
Ref. AC 20-146A

  - Magnitude (peak) error= 3.4%
  - SGCE = 7.2%

Validation (5/6)

- Test data vs. analysis results, example 2
  - Modal Assurance Criteria
  - Comparison of analytical and experimental mode shapes
  - Used for compliance with aeroelastic stability requirements (GVT data vs. FEA analysis)

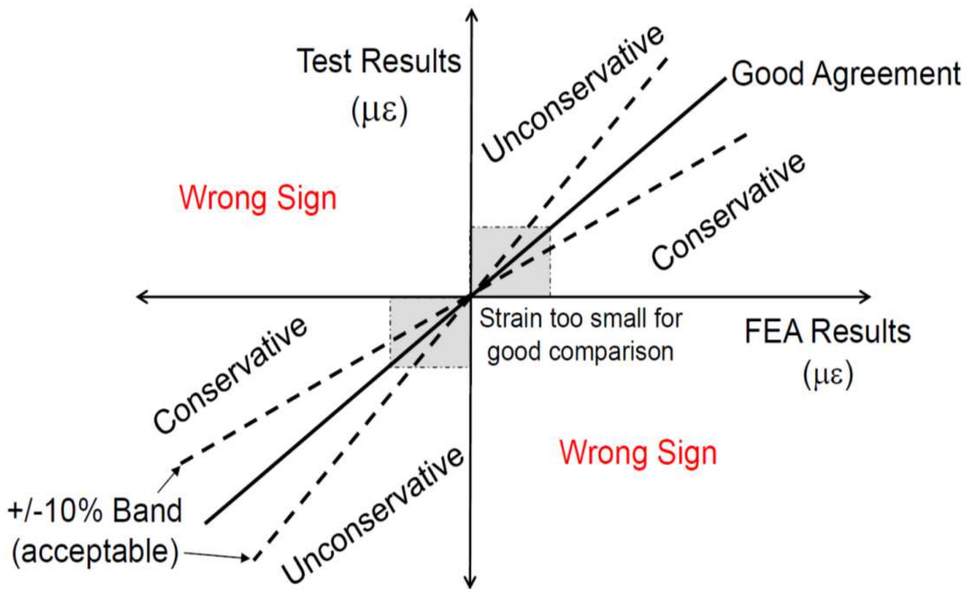
$$MAC(\{\varphi_r\},\{\varphi_s\}) = \frac{|\{\varphi_r\}^{*t}\{\varphi_s\}|^2}{(\{\varphi_r\}^{*t}\{\varphi_r\})(\{\varphi_s\}^{*t}\{\varphi_s\})}$$



Ref. Siemens PLM website

Validation (6/6)

- Acceptability criteria also need to be established
  - Maximum acceptable amount of mismatch between test data and analysis results
  - Typically 5% (deflection), 10% (strain/stress) or 0.90/0.95 (MAC) or….



Ref. Finite Element Modeling and Analysis Validation Requirements and Methods, P. Safarian, November 2017)

Main Attention Items

Verification

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Validation

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Errors & Uncertainties

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Extrapolation

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Experience

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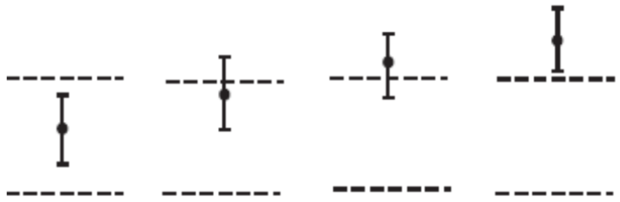
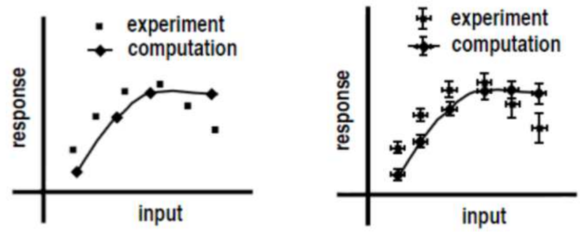
Documentation

Errors & Uncertainty Quantification (1/13)

- Issue to be addressed: both test data and analysis results contain errors and uncertainties



Test Errors & Uncertainties	
Analysis Errors - Acknowledged - Unacknowledged	Analysis Uncertainty - Aleatoric - Epistemic



Computational Simulation, W. Oberkampf, 2004

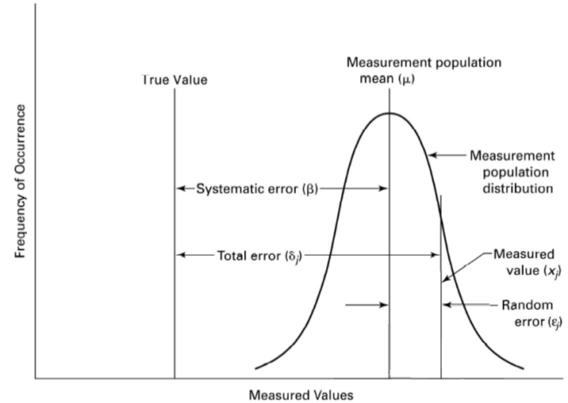
- Previously mentioned techniques to compare test data with analysis results did not consider errors and uncertainties…

Errors & Uncertainty Quantification (2/13)

- Test Errors

- Total test error consists of systematic and random errors
  - Systematic errors remain constant throughout repeated measurements (e.g. due to imperfect calibration techniques)
  - Random errors vary randomly throughout repeated measurements (e.g. due to uncontrolled test conditions)

Ref. ASME PTC 19.1-2005



Errors & Uncertainty Quantification (3/13)

- Test errors and uncertainty can be determined:
  - Data driven – statistical assessment of repeated measurements (“Type A”)
    - Normal (Gaussian) distribution
  - By previous measurements, experience, engineering judgement (“Type B”)
    - Assumed distribution: normal (Gaussian), rectangular, triangular,…
- Internationally recognized references available
  - ISO/GUM or ASME PTC 19.1
- Methods available for single or multiple measurements
- Optimum case: X ± Y with Z confidence
  - For example, deflection measured = 250 cm ± 5 cm with 95% confidence

Errors & Uncertainty Quantification (4/13)

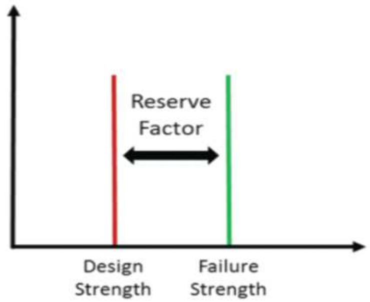
- Analysis Errors are either *acknowledged* or *unacknowledged:*
  - Acknowledged Error
    - Physical approximation error
      - Physical modelling error
      - Geometry modelling error
    - Computer round-off error
    - Iterative convergence error
    - Discretization error
      - Spatial discretization error
      - Temporal discretization error
  - Unacknowledged Error
    - Computer programming error
    - Usage error

Errors & Uncertainty Quantification (5/13)

- How to address *acknowledged* or *unacknowledged errors?*
  - Acknowledged Error
    - Physical approximation error <= check on assumptions & simplifications
      - Physical modelling error
      - Geometry modelling error
    - Computer round-off error <= usually known and typically small
    - Iterative convergence error <= usually known and typically small
    - Discretization error
      - Spatial discretization error <= check convergence through mesh refinement (Grid Convergence Index)
      - Temporal discretization error <= check convergence through smaller time steps
  - Unacknowledged Error
    - Computer programming error <= code verification
    - Usage error <= calculation (or solution) verification

Errors & Uncertainty Quantification (6/13)

- *How to address (quantify) analysis uncertainty?*
  - Deterministic
  - Probabilistic – sampling methods like Monte Carlo simulation
- Deterministic: application of safety factor

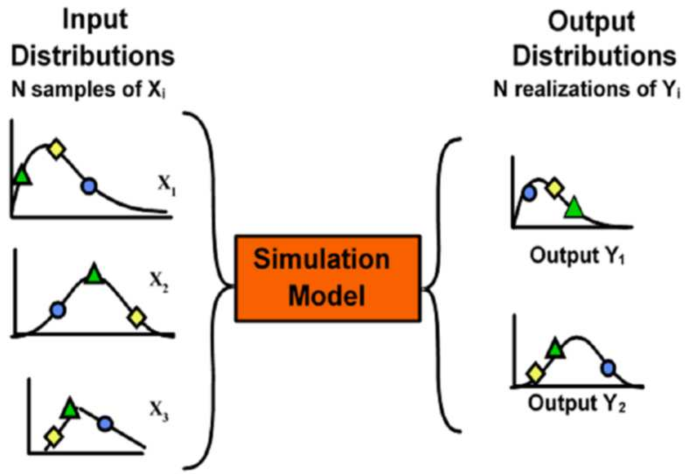


Ref. NAFEMS publication: What is UQ?

- Examples:
  - Factor of safety (2X.303) of 1.5 between LL and UL plus “A” & “B” design values
  - Special factors (2X.619): fitting factor, casting factor, bearing factor,...

Errors & Uncertainty Quantification (7/13)

- *How to address (quantify) analysis uncertainty?*
  - Probabilistic



Ref. Uncertainty Quantification and Validation Assessment, B. Thacker, 2016

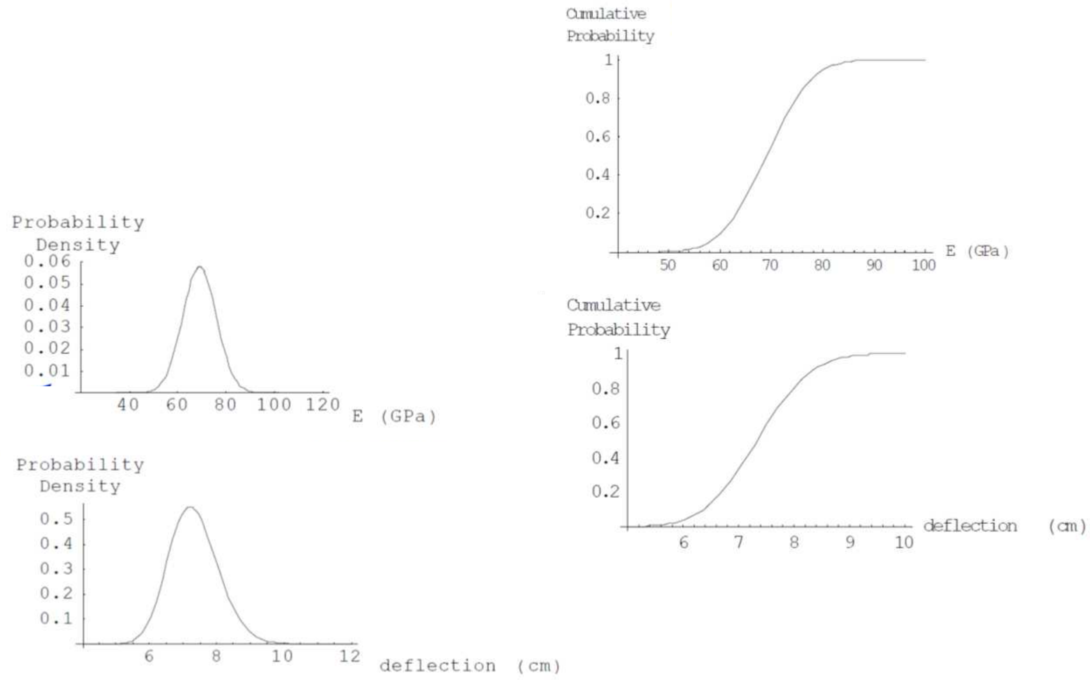
  - Propagate input uncertainties (distributions) through model to determine output distributions, that can be statistically assessed
    - Mean input ≠ mean output…..

Errors & Uncertainty Quantification (8/13)

Example of probabilistic approach

- **Deflection = PL^3/(3EI)** = 7.2 cm

- **Length = 1 m**
- **Width = 1 cm, Height = 2 cm**
- **P = load = 100 N**
- **Material = Aluminum 6061-T6:**
- **E = Elastic Modulus**
  - **Mean = μ = 69 GPa**
  - **Std Deviation = σ = 6.9 GPa**



Ref. Validation and Uncertainty Quantification Methods in the DAKOTA Software Toolkit, A. Giunta, 2006

Errors & Uncertainty Quantification (9/13)

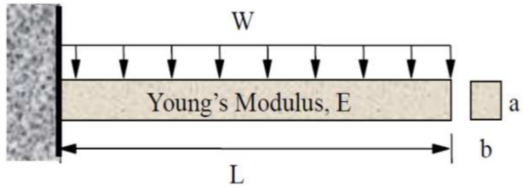
- *Sensitivity analysis* is important part of uncertainty quantification
- To help determine which parameters contribute most to the analysis uncertainty

- Deterministic example: AMC 25.629 (Aeroelastic Stability Requirements)
  - "The sensitivity of most critical parameters may be determined analytically by **varying the parameters** from nominal."

=> Variation in mass, stiffness, flight control systems,…

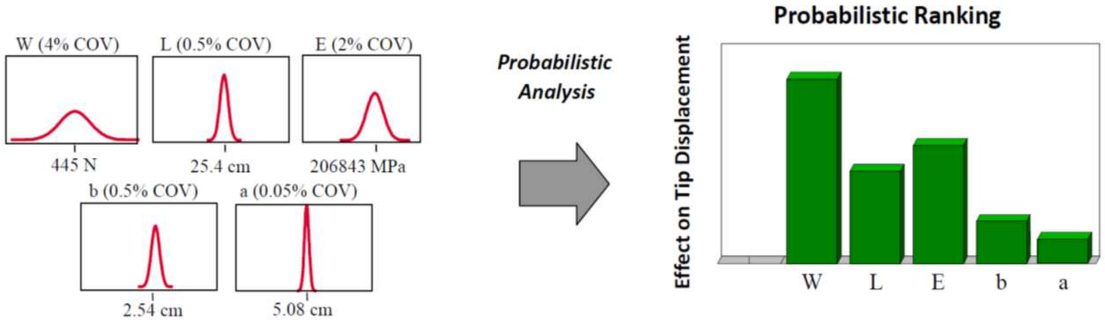
Errors & Uncertainty Quantification (10/13)

- *Sensitivity analysis*
- Probabilistic example:



$$\delta = \frac{3WL^3}{2Eba^3}$$

W=445 N, L=25.4 cm, E=207 GPa, b=2.54 cm, a=5.08 cm



Pareto Chart

Ref. Uncertainty Quantification and Validation Assessment, B. Thacker, 2016

Errors & Uncertainty Quantification (11/13)

- Identification of errors and quantification of uncertainty is fundamental to establishing credibility of M&S process
- As the use of M&S becomes more widespread, and the amount of testing reduces, the need to consider and quantify errors and uncertainty increases
  - In both test and analysis results
- Problem/challenge: running multiple full scale tests, and perform 1000 + simulations is not very practical within the scope of a certification programme

Errors & Uncertainty Quantification (12/13)

- Solutions…?
  - Simplified (meta- or surrogate or reduced order) model, that can be run in a shorter time frame (but may lead to loss of information and accuracy)
  - Different statistical approach (e.g. Polynomial Chaos Expansion)
  - Sensitivity analysis to focus on important parameters
    - Perform probabilistic approach with only those parameters
    - Reduced variability in those parameters as much as possible

Errors & Uncertainty Quantification (13/13)

- Solutions…?
  - Application of safety factors like AC 20-146A:
    - One method to add conservatism to the process is to incorporate test uncertainty as a factor of safety in validation and model use. Assuming a typical data spread of ±200 HIC units, the 95 percent confidence HIC value is 890 HIC units. Therefore, the FAA recommends that only seat configurations with dynamic test data that produce a HIC value below 890 HIC units should be used for validation. Likewise, for model use, the FAA recommends that only models that produce a HIC value below 890 HIC units be used.
  - Similarly, a cap (e.g. 80% of critical value) could be put on analysis results, beyond which additional testing (validation) would be needed

Main Attention Items

Verification

↓

Validation

↓

Errors & Uncertainties

↓

Extrapolation

↓

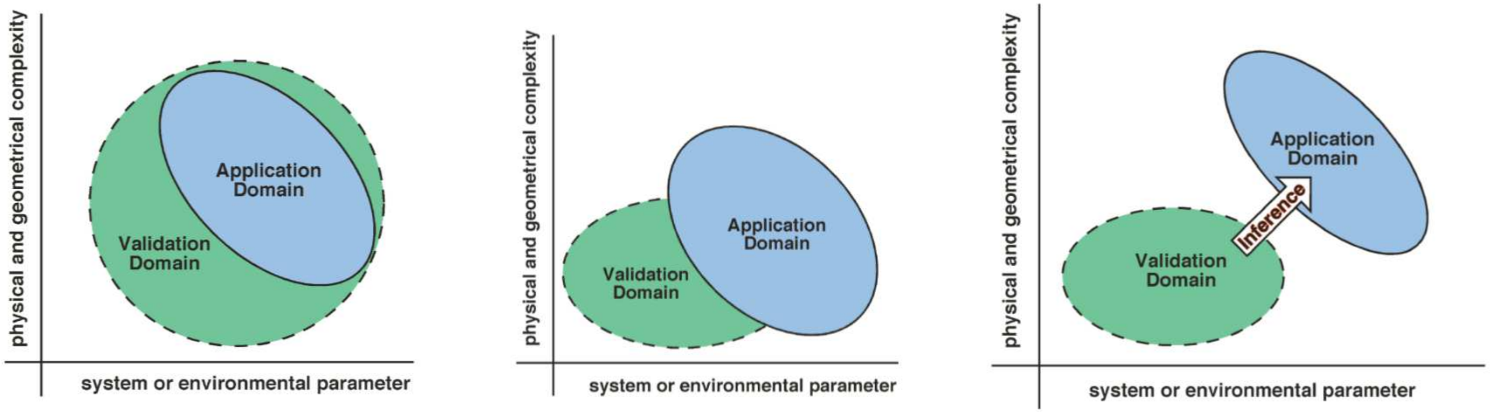
Experience

↓

Documentation

Extrapolation (1/2)

- Once analysis has been properly validated, it may be used for different cases / conditions => extrapolation (based on similarity)



Ref. Verification and Validation in Computational Simulation, W. Oberkampf, 2004

- Where to draw the line…? When is additional validation (test data) needed?

Extrapolation (2/2)

- Analysis must stay within bounds of established validity
  - If not, additional validation (test data) is required

- Requires careful evaluation and comparison between cases of:
  - Software tools used (including different releases)
  - Modelling techniques (implicit, explicit, ALE, SPH,…)
  - Experience of staff (including subcontractors)
  - Structural design features (geometry, load paths,….see e.g. AMC 25.307)
  - Design conditions (impact, loads,..)
  - Response of structure (failure modes, damage propagation,…)
  - ………..

- May require significant amount of discussion and engineering judgement

Main Attention Items

Verification

↓

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Experience

↓

Documentation

Experience

- Experience base of company and its staff are very important in M&S process
  - Also recognized in Part 21A.245 “The staff in all technical departments are of sufficient numbers and experience…”
- Although current software tools are deceivingly easy to use, nothing replaces experience to assess the process and results
  - Includes peer review and oversight by senior staff
- No generally accepted standards seem to exist on this subject
  - NAFEMS/ISO 9001 previously proposed some guidelines, but these have been withdrawn
- EASA is reviewing need for more guidance & standardization on this subject

Main Attention Items

Verification

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Documentation / Record Keeping

- Applicants are expected to:
  - Document and specify (release, issue, platform,…) software tools they use
  - Have procedures how to use these tools (Best Practices)
  - Define qualifications of analysts, identify staff, training,…
  - Have procedures for peer review and quality checks

- Certification Programme (Part 21), V&V Plan (SAE ARP 5765A), Validation Analysis Report (AC 20-146A), Validation Test Plan(s), Validation Test Report(s),…

- Need to store all input and output analysis data, until the product is no longer in service
  - Or be able to re-create the output data whenever necessary

Summary

- Modelling & Simulation plays an important role in the life cycle of an aircraft, from conceptual design to retirement from service
- Software tools are becoming more advanced, more capable, more widespread….and more difficult to comprehend /assess
- Trend is to perform more analysis and less testing
- Requires more attention to issues such as verification & validation aspects, errors and uncertainty quantification, extrapolation/similarity, experience and record keeping
- Overall lack of guidance material – more standardization is needed, as much as possible (Structures CM is being prepared)
- Need to identify best practices & develop guidance material to facilitate application of M&S (level playing field) and streamline certification process

Q & A