EASA
European Aviation Safety Agency

"Certification by Analysis", or: Modelling & Simulation

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Workshop on Modelling & Simulation
Cologne, 29/30 August 2019

Contents

Terminology

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

“No more testing…?”

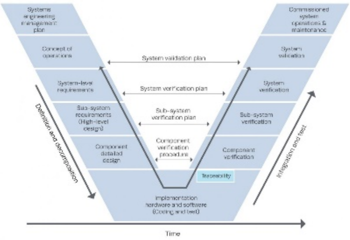
“Test data needed to validate analysis…!”

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

More Terminology

- Simulation may have different meanings:
  - Flight Simulator (pilot in the loop), or (flight) desktop simulation
  - Simulation of system behaviour
  - Finite Element Analysis
  - …….
- Similarly, Verification & Validation (V&V) may have different meanings:
  - Systems Engineering ("V-Model")
    - Procedures that are used together for checking that a product, service, or system meets requirements and specifications and that it fulfils its intended purpose
  - As defined in this presentation
  - …..



The Bigger Picture

- "The Virtual or Digital Aircraft"
  - Cover the complete lifespan of an aircraft, from conception to retirement from service
  - Design & Development
    - Virtual Prototyping (Computer Aided Design, Computer Aided Engineering)
    - Virtual Manufacturing
    - Systems and Software Development
  - Certification & Qualification by Analysis
    - Virtual Ground Testing and Computational Flight Testing
      - Structures: Computational Solid Mechanics, Computational Fluid Dynamics
      - Systems (Avionics, Flight Control Systems, Hydromechanical, Electrical, ECS,….)
      - Flight Test: Computational Flight Mechanics
    - Virtual / Augmented Reality (maintenance, flight simulators,…)
  - In-service operations
    - Digital Twin (maintenance, overhaul, health monitoring,…)

Background to M&S (1/5)

- "Certification by Analysis" already recognized in EASA Certification Specifications, for example:
  - CS 25.21 Proof of Compliance:

    (a) Each requirement of this Subpart must be met at each appropriate combination of weight and centre of gravity within the range of loading conditions for which certification is requested. This must be shown –

    (1) By tests upon an aeroplane of the type for which certification is requested, or by calculations based on, and equal in accuracy to, the results of testing; and

  - CS 25.307 Proof of Structure:

    Structural analysis may be used only if the structure conforms to that for which experience has shown this method to be reliable. In other cases, substantiating tests must be made to load levels that are sufficient to verify structural behaviour up to loads specified in CS 25.305.

  - CS 25.683 Operation Tests:

    (b) It must be shown by analysis and, where necessary, by tests that in the presence of deflections of the aeroplane structure due to the separate application of pitch, roll and yaw limit manoeuvre loads, the control system, when loaded to obtain these limit loads and operated within its operational range of deflections can be exercised about all control axes and remain free from-

    (1) Jamming;

    (2) Excessive friction;

    (3) Disconnection, and

    (4) Any form of permanent damage.

Background to M&S (2/5)

- Overall increase in use of M&S techniques to support the showing of compliance with airworthiness and environmental requirements

- 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 (3/5)

- Some on-going activities
  - AIAA WG on CQbA
    - Flight Test and Simulation
  - Dynamic Seat Testing
    - Boeing, Airbus, seat suppliers
  - CS2 MISSION
    - Modelling and Simulation Tools for Systems Integration on Aircraft
  - H2020 RoCS
    - Rotorcraft Certification by Simulation

Background to M&S (4/5)

- 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)
  - SAE AIR 6326 (M&S for Electrical Power Systems)
  - SAE ARP 5903 (Droplet Impingement and Ice Accretion Computer Codes)
  - CS/AMC-FSTD(A) (H) (Validation of Flight Simulation Training Devices)

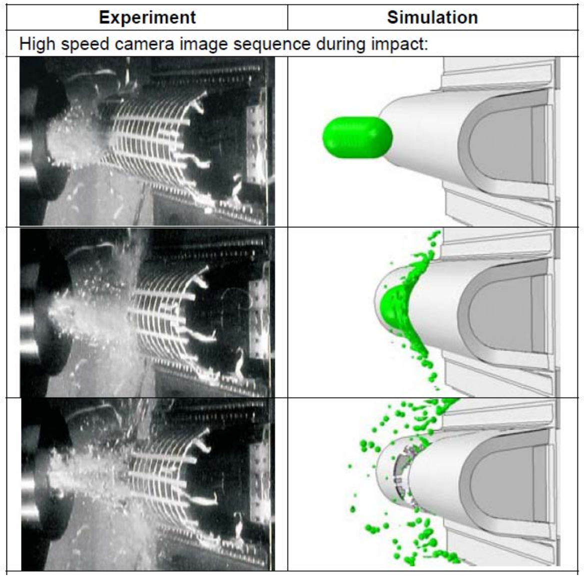
Background to M&S (5/5)

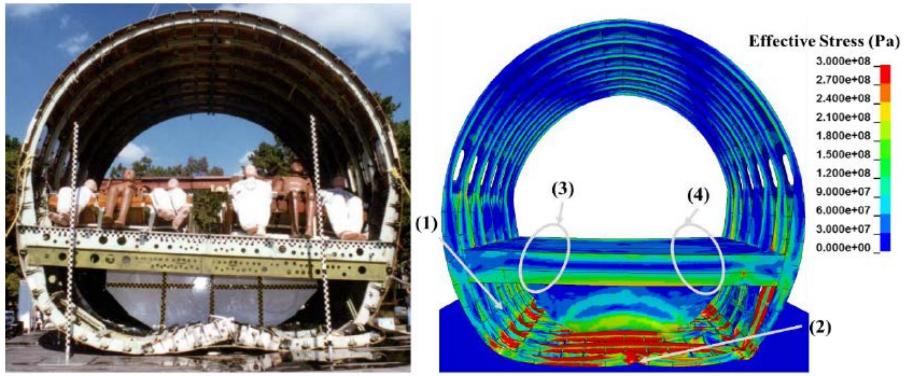
- Lack of standardisation and “analysis scepticism” drives detailed reviews of M&S applications

- 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 (heat transfer) analysis
  - Engine failure conditions
  - Fatigue & damage tolerance



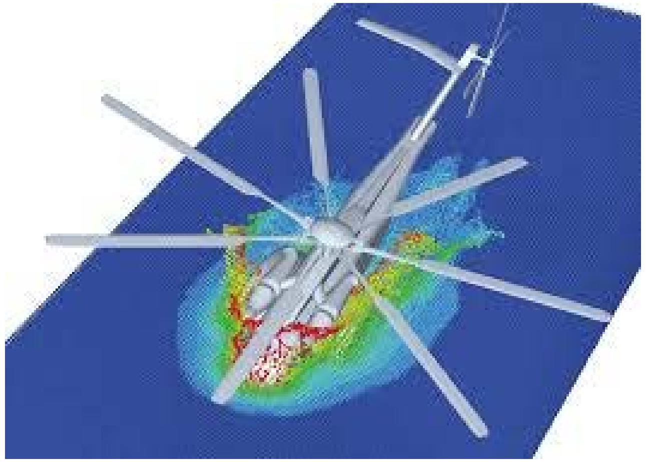


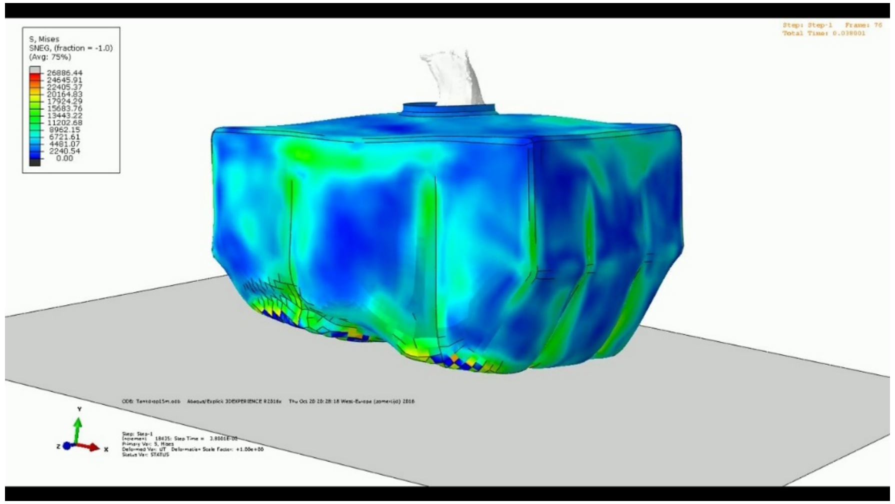
(a) Post-impact picture of section drop experiment

(b) Section drop test simulation result

M&S for Structures (2/2)

- Different types of M&S techniques for Structures:
  - 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 for M&S

Verification

Validation

Errors & Uncertainties

Extrapolation

Documentation

Experience

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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
  - Software vendor should perform Software Qualification Assurance and Numerical Algorithm Verification
  - Applicant should 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**

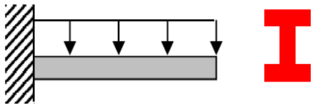
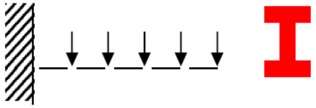
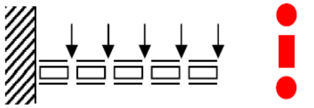
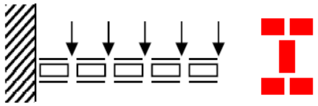
- Requires methodical approach to building analytical model (step by step, from simple to more complex modelling) and critical assessment of input and output data

- 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,…

Verification (4/5)

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

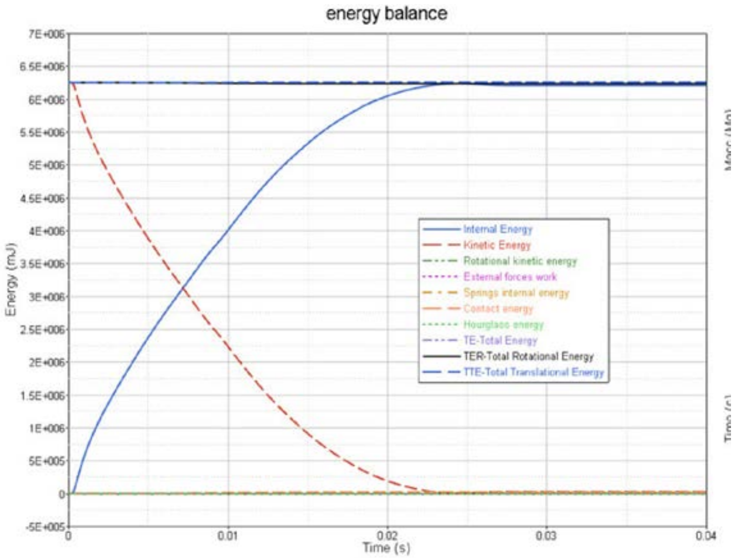
Choice of Elements: Cantilever Beam Summary

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

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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?")

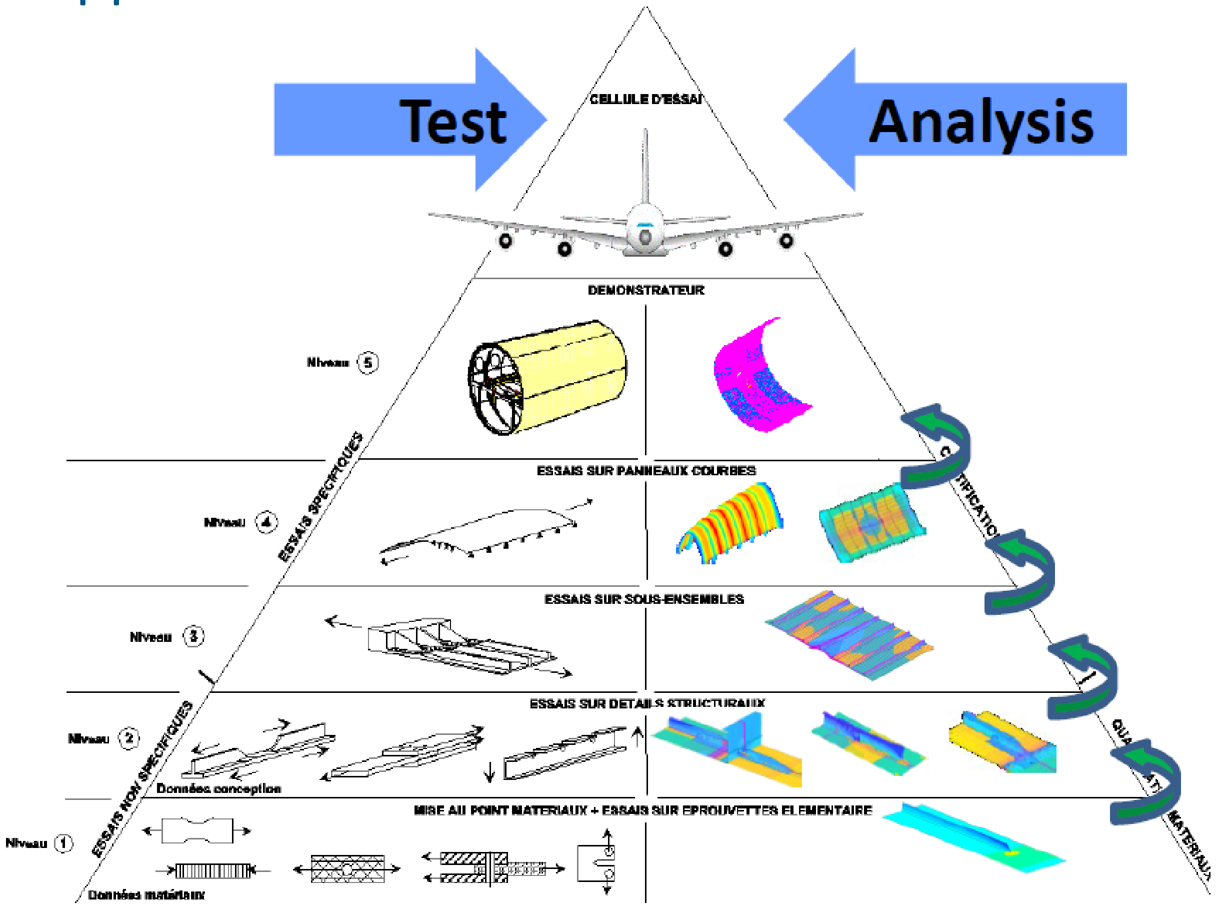
- Validation is typically based on comparison of analysis results with test data

- 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

- Calibration is not validation

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

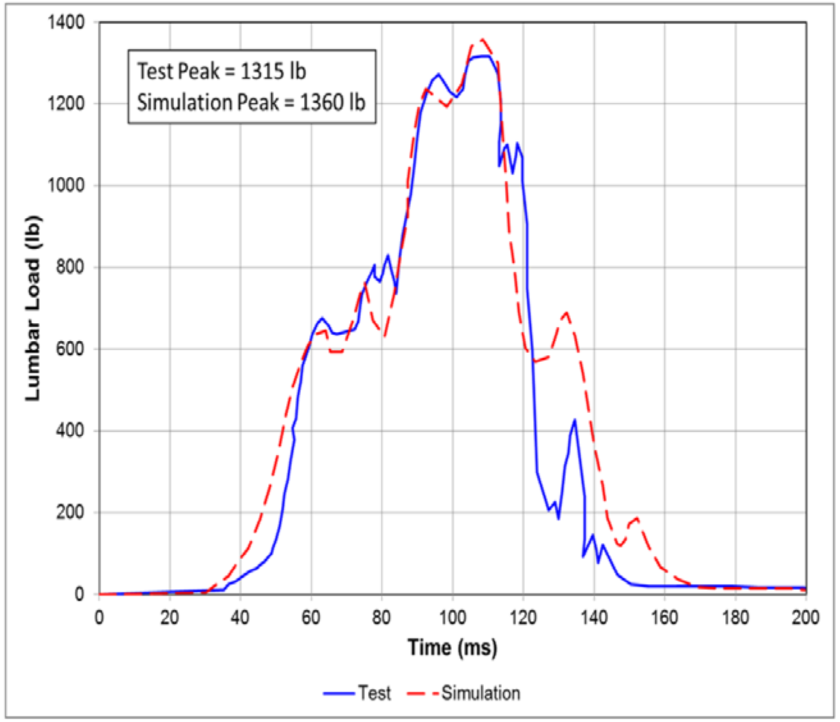
Validation (3/6)

- 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

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



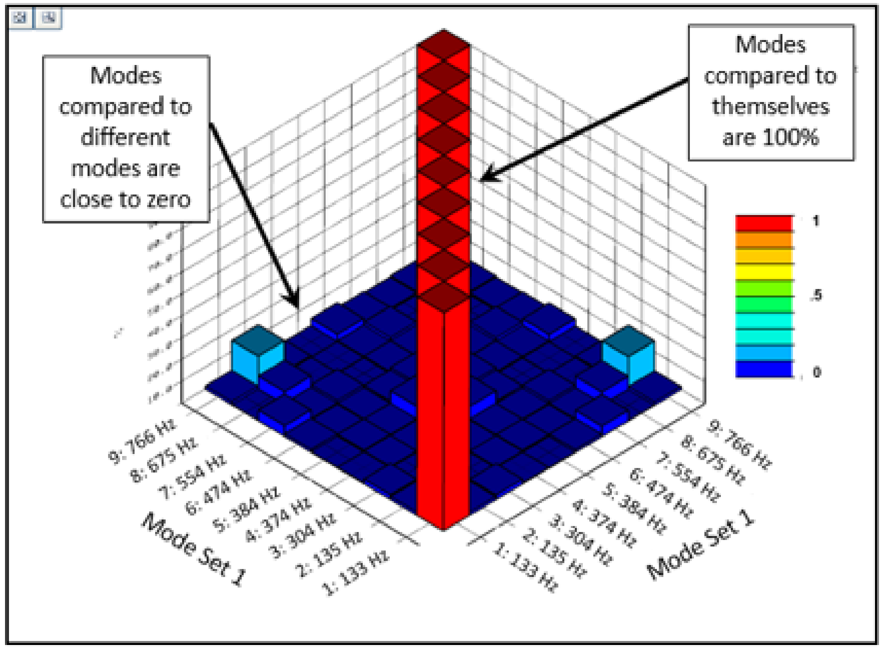
- Magnitude (peak) error= 3.4%
- SGCE = 7.2%

Ref. AC 20-146A

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)

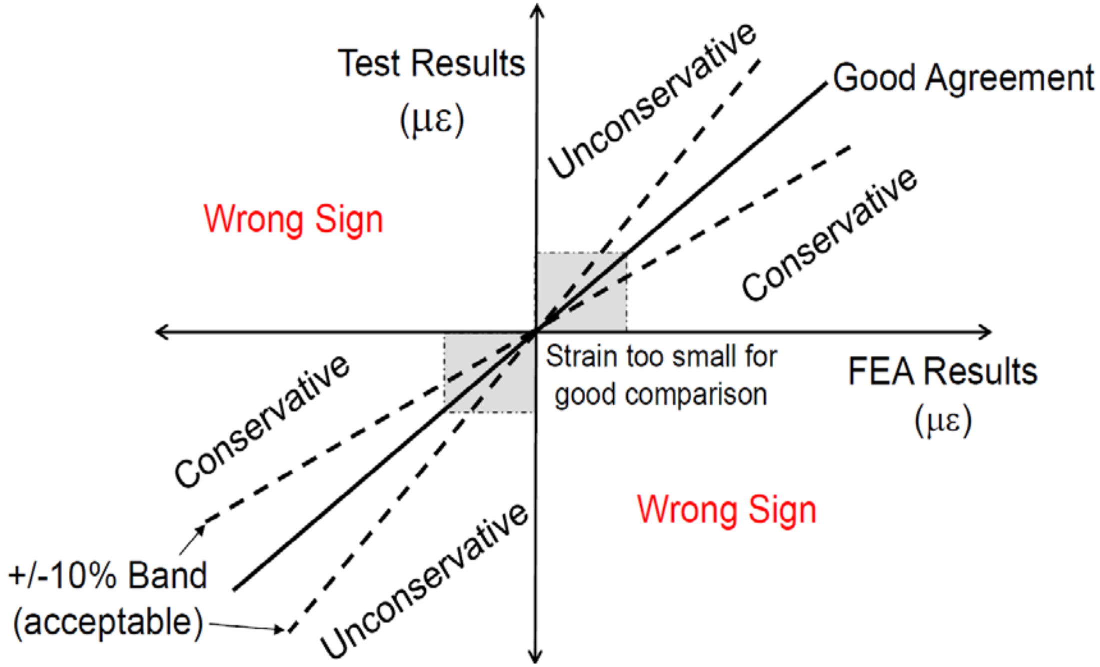
$$MAC(\{\varphi_r\},\{\varphi_s\}) = \frac{|\{\varphi_r\}^{*t}\{\varphi_s\}|^2}{(\{\varphi_r\}^{*t}\{\varphi_r\})(\{\varphi_s\}^{*t}\{\varphi_s\})}$$



Ref. Siemens PLM website

Validation (6/6)

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



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

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Errors & Uncertainties (1/10)

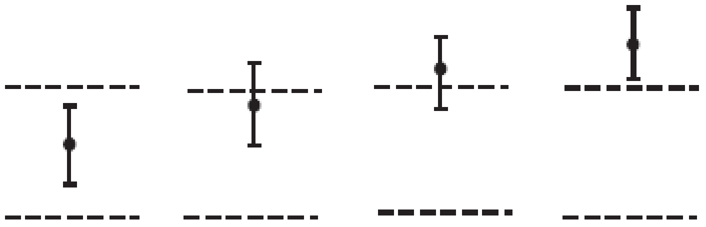
(Ref. AIAA G-077-1998)

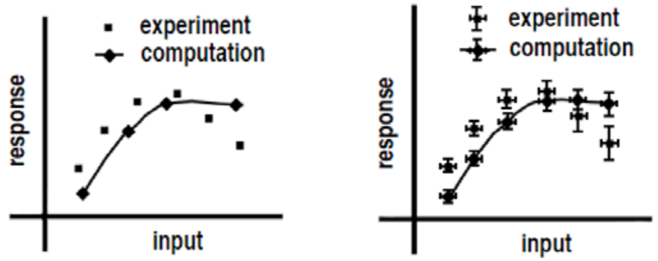
- **Error**
  - A recognizable deficiency in any phase or activity of modelling and simulation that is <u>not</u> due to lack of knowledge
- **Uncertainty**
  - A potential deficiency in any phase or activity of the modelling process that is due to the lack of knowledge

- "Lack of knowledge" has primarily to do with lack of knowledge about the physical processes that go into building the model

Errors & Uncertainties (2/10)

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





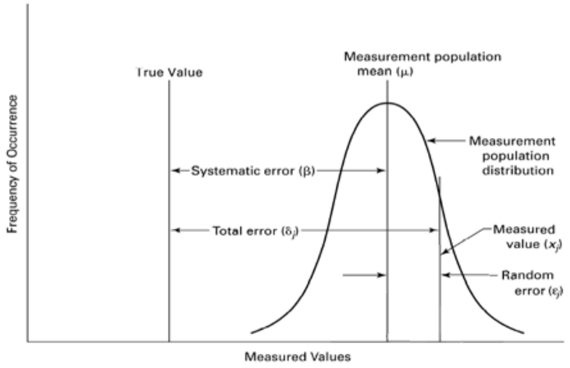
Test Errors & Uncertainties	
Analysis Errors - Acknowledged - Unacknowledged	Analysis Uncertainty - Deterministic - Probabilistic

Computational Simulation,
W. Oberkampf, 2004

Errors & Uncertainties (3/10)

- Test Errors & Uncertainties

- 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)
- Internationally recognized references available
  - ISO/GUM or ASME PTC 19.1



Ref. ASME PTC 19.1-2005

- Final goal: X ± Y with Z confidence
  - For example, length measured: 250 cm ± 5 cm with 95% confidence

Errors & Uncertainties (4/10)

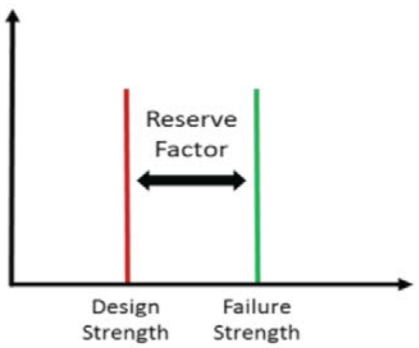
- Analysis Errors are either *acknowledged* or *unacknowledged:*
  - Acknowledged Error
    - Physical approximation error
      - Physical modelling error
      - Geometry modelling error
    - Computer round-off error
    - Iterative convergence error
    - Discretization error
      - Spatial discretization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

Errors & Uncertainties (5/10)

- 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 & Uncertainties (6/10)

- Analysis uncertainty
  - “Deterministic”
  - “Probabilistic” – sampling methods like Monte Carlo simulation
- “Deterministic”: application of safety factor

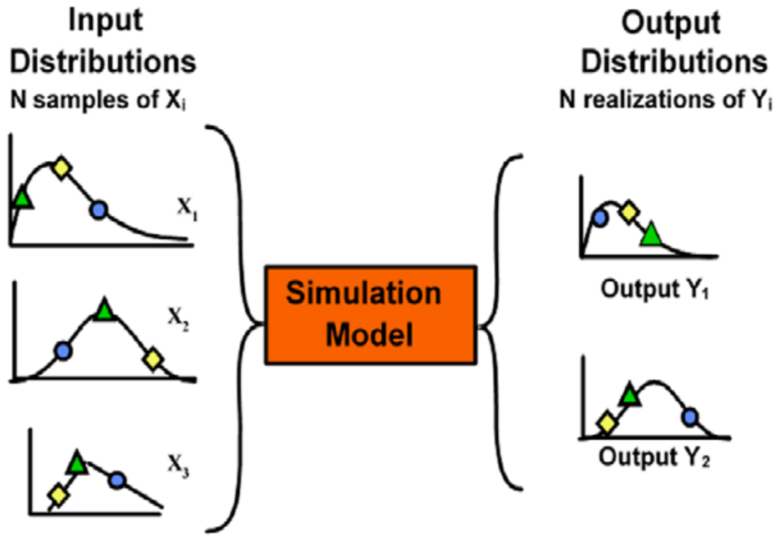


Ref. NAFEMS publication: What is UQ?

- 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 & Uncertainties (7/10)

- 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 & Uncertainties (8/10)

- *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 & Uncertainties (9/10)

- 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: with “probabilistic” approach, one may need to perform multiple full scale tests, and perform many simulations, which is not (yet) very practical within the scope of a certification programme

Errors & Uncertainties (10/10)

- Practical Approach
  - 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 for M&S

Verification

Validation

Errors & Uncertainties

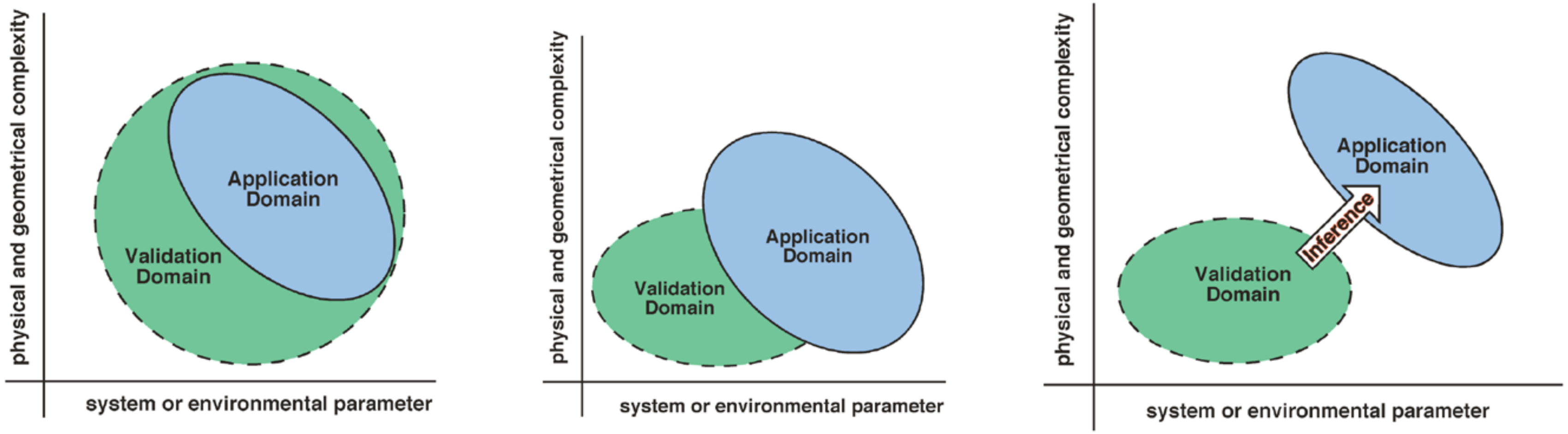
Extrapolation

Documentation

Experience

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 for M&S

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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 for M&S

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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
  - Apply proper configuration management of models
- 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

Main Attention Items for M&S

- Example Case
  - Bird Strike (CS 25.631)
  - EASA “Checklist“

Microsoft Word Document

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 – additional Workshop?)
- Need to identify best practices & develop guidance material to facilitate application of M&S (level playing field) and streamline certification process

Q & A