What is V&V?

December 3rd, 2009

Agenda

What is V&V

December 3rd, 2009
8am PST (Seattle) / 11am EST (New York) / 4pm GMT (London)

- Welcome & Introduction (Overview of NAFEMS Activities)
    - Matthew Ladzinski, NAFEMS North America
- What is V&V
    - Len Schwer, Independent Consultant
- Q&A Session
    - Panel
- Closing


Ladzinski


Schwer

THE INTERNATIONAL ASSOCIATION
FOR THE ENGINEERING ANALYSIS
COMMUNITY

An Overview of NAFEMS Activities

Matthew Ladzinski
NAFEMS North America

Planned Activities

- Webinars
  - New topic each month!
    - Visualization – January 2010
    - Product Performance Simulation in the Year 2020 – February 2010
  - Recent webinars:
    - What is V&V
    - How to Ensure that CFD for Industrial Applications is Fit for Purpose
    - Practical CFD
    - Composite FE Analysis
    - 10 Ways to Increase Your Professional Value in the Engineering Industry
    - Dynamic FE Analysis
    - Modal Analysis in Virtual Prototyping and Product Validation
    - Pathways to Future CAE Technologies and their Role in Ambient Intelligent Environments
    - Computational Structural Acoustics: Technology, Trends and Challenges
    - FAM: Advances in Research and Industrial Application of Experimental Mechanics
    - CCOPPS: Power Generation: Engineering Challenges of a Low Carbon Future
    - Practical CFD Analysis
    - Complexity Management
    - CCOPPS: Creep Loading of Pressurized Components – Phenomena and Evaluation
    - Multiphysics Simulation using Implicit Sequential Coupling
    - CCOPPS: Fatigue of Welded Pressure Vessels
    - Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures
    - A Common Sense Approach to Stress Analysis and Finite Element Modeling
    - The Interfacing of FEA with Pressure Vessel Design Codes (CCOPPS Project)
    - Multiphysics Simulation using Directly Coupled-Field Element Technology
    - Methods and Technology for the Analysis of Composite Materials
    - Simulation Process Management
    - Simulation-supported Decision Making (Stochastics)
    - Simulation Driven Design (SDD) Findings

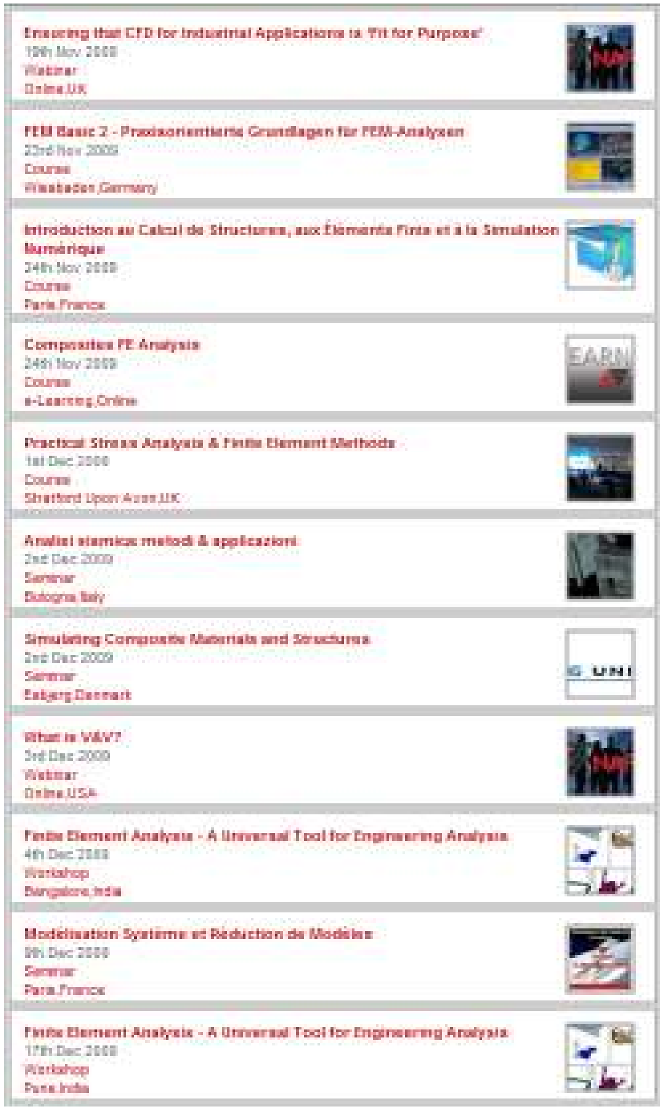
To register for upcoming webinars, or to view a past webinar, please visit: www.nafems.org/events/webinars

e-LEARNING NAFEMS

- Established in 2009
- Next courses:
  - Dynamic FE Analysis – January 12th, 2010 (*six-week course*)
  - Non-Linear Analysis – March 2nd, 2010 (*four-week course*)
  - Composite FE Analysis – April 13th, 2010 (*four-week course*)
- Proposed course offerings:
  - Optimization – Summer 2010 (*four-week course*)
- For more information, visit: www.nafems.org/e-learning

NAFEMS Events

- Multiple opportunities to attend conferences, seminars/workshops and training courses



Ensuring that CFD for Industrial Applications is 'Fit for Purpose'
19th Nov 2009
Webinar
Online,UK

FEM Basic 2 - Praxisorientierte Grundlagen für FEM-Analysen
23rd Nov 2009
Course
Wiesbaden,Germany

Introduction au Calcul de Structures, aux Éléments Finis et à la Simulation Numérique
24th Nov 2009
Course
Paris,France

Composites FE Analysis
24th Nov 2009
Course
e-Learning,Online

Practical Stress Analysis & Finite Element Methods
1st Dec 2009
Course
Stratford Upon Avon,UK

Analisi sismica: metodi & applicazioni
2nd Dec 2009
Seminar
Bologna,Italy

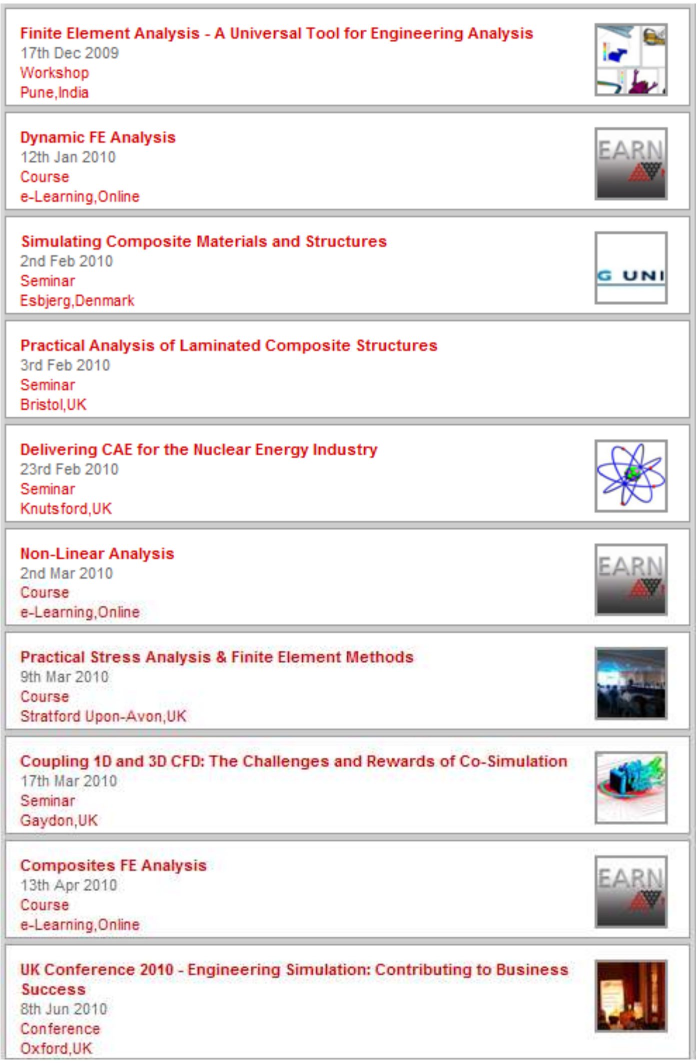
Simulating Composite Materials and Structures
2nd Dec 2009
Seminar
Esbjerg,Denmark

What is V&V?
3rd Dec 2009
Webinar
Online,USA

Finite Element Analysis - A Universal Tool for Engineering Analysis
4th Dec 2009
Workshop
Bangalore,India

Modélisation Système et Réduction de Modèles
9th Dec 2009
Seminar
Paris,France

Finite Element Analysis - A Universal Tool for Engineering Analysis
17th Dec 2009
Workshop
Pune,India



Finite Element Analysis - A Universal Tool for Engineering Analysis
17th Dec 2009
Workshop
Pune,India

Dynamic FE Analysis
12th Jan 2010
Course
e-Learning,Online

Simulating Composite Materials and Structures
2nd Feb 2010
Seminar
Esbjerg,Denmark

Practical Analysis of Laminated Composite Structures
3rd Feb 2010
Seminar
Bristol,UK

Delivering CAE for the Nuclear Energy Industry
23rd Feb 2010
Seminar
Knutsford,UK

Non-Linear Analysis
2nd Mar 2010
Course
e-Learning,Online

Practical Stress Analysis & Finite Element Methods
9th Mar 2010
Course
Stratford Upon-Avon,UK

Coupling 1D and 3D CFD: The Challenges and Rewards of Co-Simulation
17th Mar 2010
Seminar
Gaydon,UK

Composites FE Analysis
13th Apr 2010
Course
e-Learning,Online

UK Conference 2010 - Engineering Simulation: Contributing to Business Success
8th Jun 2010
Conference
Oxford,UK

- Let us know if you would like to schedule an on-site training course

NAFEMS

Overview of
END TO END EXAMPLE:
AN ILLUSTRATION OF THE CONCEPTS OF VERIFICATION AND VALIDATION

ASME V&V-10 Standards Committee on
Verification & Validation in Computational Solid Mechanics

Len Schwer
Schwer Engineering & Consulting Services
Windsor CA USA
Len@Schwer.net

SETTING THE STANDARD

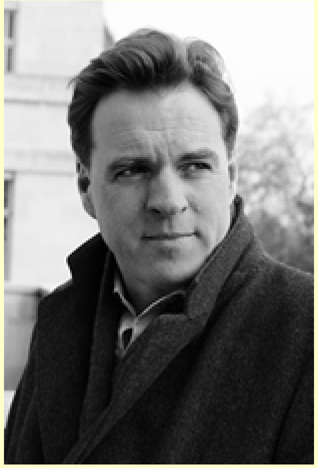
COMPUTATIONAL MECHANICS

The use of numerical *approximations* to solve *mathematics* based *models* of physics of interest.

Wikipedia - Computational mechanics is the discipline concerned with the use of computational methods to study phenomena governed by the principles of mechanics.

MATHEMATICS

"Those whom the gods want to destroy they first teach math."



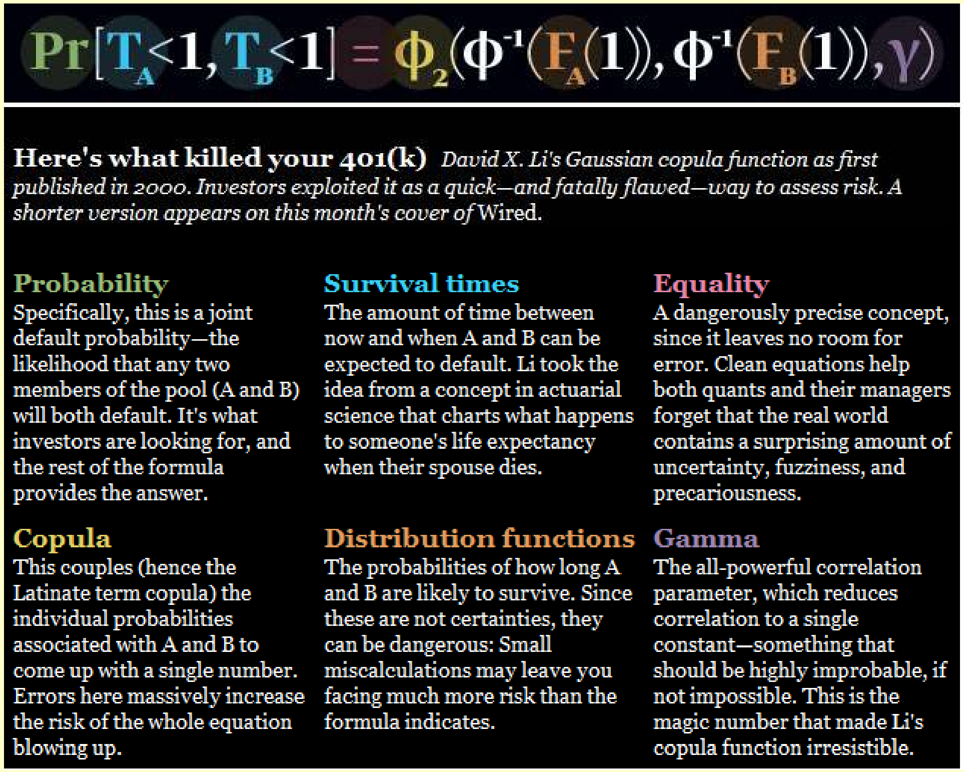
Niall Ferguson (born April 18, 1964, in Glasgow) is a British historian and author of *The Ascent of Money: A Financial History of the World.*

SETTING THE STANDARD

MODELS

$$C_\rho(u,v) = \Phi_\rho\left(\Phi^{-1}(u), \Phi^{-1}(v)\right)$$

Gaussian copula function - One example of a copula often used for modeling in finance, e.g. model for the pricing of collateralized debt obligations by David X. Li



$$\Pr[T_A<1, T_B<1] = \phi_2(\phi^{-1}(F_A(1)), \phi^{-1}(F_B(1)), \gamma)$$

Here's what killed your 401(k) *David X. Li's Gaussian copula function as first published in 2000. Investors exploited it as a quick—and fatally flawed—way to assess risk. A shorter version appears on this month's cover of* Wired.

Probability
Specifically, this is a joint default probability—the likelihood that any two members of the pool (A and B) will both default. It's what investors are looking for, and the rest of the formula provides the answer.

Copula
This couples (hence the Latinate term copula) the individual probabilities associated with A and B to come up with a single number. Errors here massively increase the risk of the whole equation blowing up.

Survival times
The amount of time between now and when A and B can be expected to default. Li took the idea from a concept in actuarial science that charts what happens to someone's life expectancy when their spouse dies.

Distribution functions
The probabilities of how long A and B are likely to survive. Since these are not certainties, they can be dangerous: Small miscalculations may leave you facing much more risk than the formula indicates.

Equality
A dangerously precise concept, since it leaves no room for error. Clean equations help both quants and their managers forget that the real world contains a surprising amount of uncertainty, fuzziness, and precariousness.

Gamma
The all-powerful correlation parameter, which reduces correlation to a single constant—something that should be highly improbable, if not impossible. This is the magic number that made Li's copula function irresistible.

David X. Li (born in the 1960s, China)

“Recipe for Disaster: The Formula That Killed Wall Street” by Felix Salmon
02.23.09 *Wired Magazine*

THE ESSENCE OF V&V

George E.P. Box
Department of Industrial Engineering
University of Wisconsin-Madison

**"All models are wrong,
but some are still useful."**

THE ESSENCE OF V&V

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"All models are wrong, but some are still useful."

DETERMINING WHICH MODELS ARE USEFUL

WHAT IS V&V?

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.

VERIFICATION IS IMPORTANT

Lockheed's F-22 Raptor Gets Zapped by International Date Line

“The U.S. Air Force's mighty Raptor was felled by the International Date Line (IDL).

When the group of Raptors crossed over the IDL, multiple computer systems crashed on the planes. Everything from fuel subsystems, to navigation and partial communications were completely taken offline. Numerous attempts were made to "reboot" the systems to no avail.”

Daily Tech Brandon Hill (Blog) - February 26, 2007 10:28 AM
http://www.dailytech.com/Article.aspx?newsid=6225

WILLIAM TELL VALIDATION

The most common form of
"validation(?)"

WILLIAM TELL VALIDATION

EXPERIMENTAL RESULT

WILLIAM TELL VALIDATION

COMPUTED RESULTS

PRESENTATION OUTLINE

I. Brief History of V&V

II. ASME V&V Committee and Activities

III. The V&V Process and *Example* in outline

IV. Verification & Validation Plan

V. Model Development

VI. Verification

VII. Comparisons of Experiments and Predictions

- Requirement 1: Deterministic-Deterministic
- Requirement 2: Statistical-Deterministic
- Requirement 3: Probabilistic-Probabilistic

ASME
SETTING THE STANDARD

A BRIEF HISTORY OF V&V

1987 - American Nuclear Society

“Guidelines for the Verification and Validation of Scientific and Engineering Computer Programs for the Nuclear Industry”

1998 – Dr. Patrick Roache (first book length treatment)

“Verification and Validation in Computational Science and Engineering”

1998 - American Institute of Aeronautics and Astronautics/Computational Fluid Dynamics Committee on Standards, (first modern standards document)

“Guide for the Verification and Validation of Computational Fluid Dynamics Simulations” (AIAA G-077-1998)”

2003 - U.S. Department of Defense, DoD Instruction 5000.61, Defense Modeling and Simulation Office

“DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A)”

ASME SETTING THE STANDARD

No claim is made that this brief history is comprehensive, but rather that it is good enough for ‘engineering purposes.’

A BRIEF HISTORY OF V&V

2006 - American Society of Mechanics Engineers V&V Standards Committee V&V10

“Guide for Verification & Validation in Computational Solid Mechanics (ASME V&V-10-2006)”

2008 - National Aeronautics and Space Administration

“Standard for Models and Simulations (NASA-STD-7009)”

2009 - American Society of Mechanics Engineers V&V Standards Committee V&V-20

“Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer”

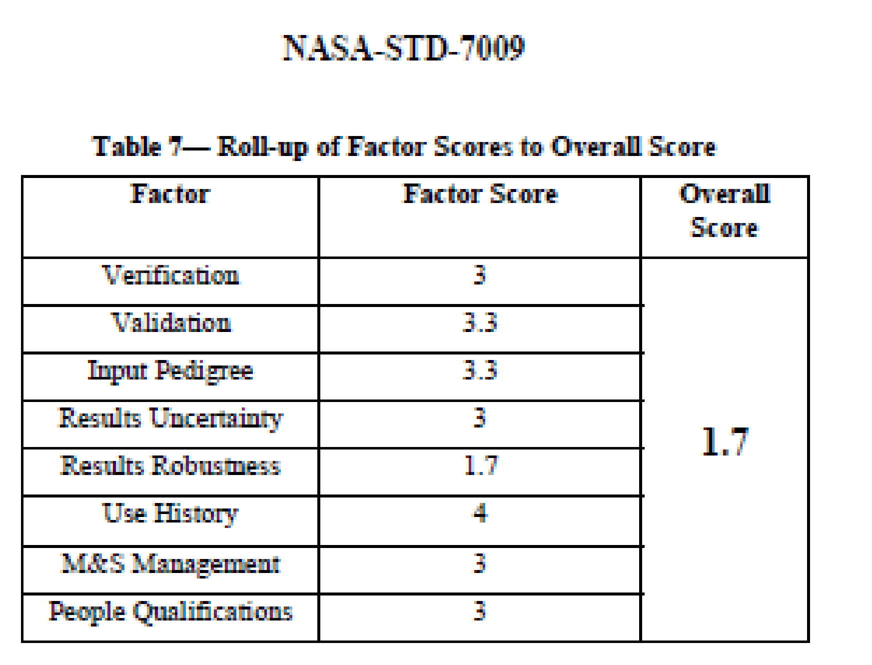
ASME
SETTING THE STANDARD

No claim is made that this brief history is comprehensive, but rather that it is good enough for ‘engineering purposes.’

NASA TECHNICAL STANDARD

Published July 2008

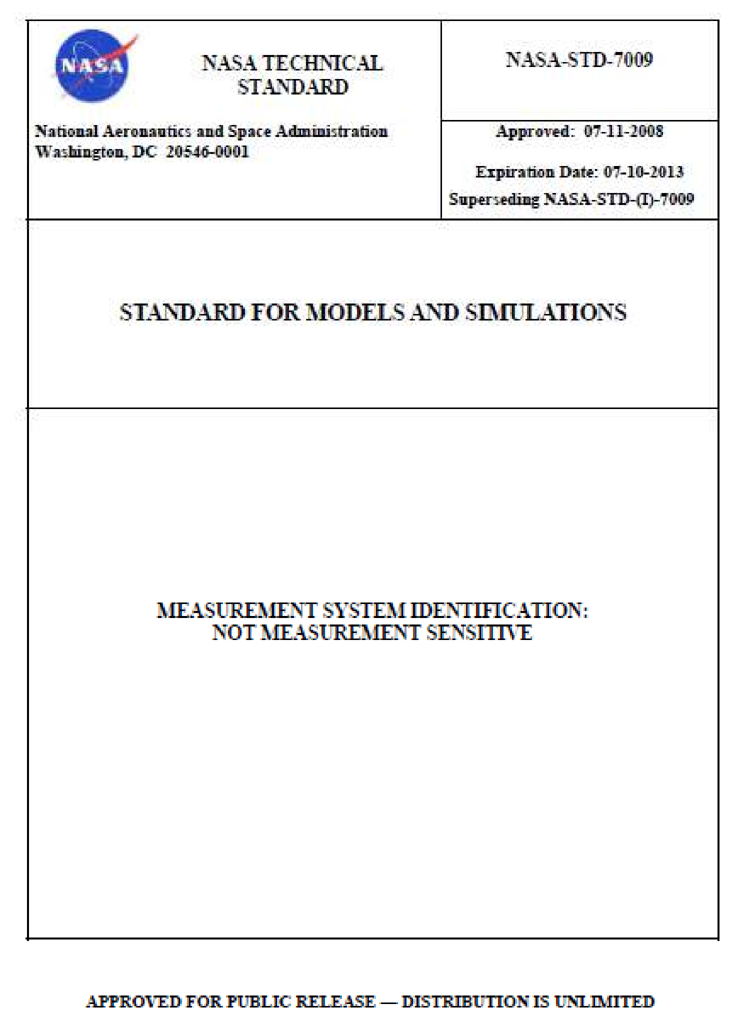
Provides a detailed numerical score for V&V effort.



NASA-STD-7009

Table 7— Roll-up of Factor Scores to Overall Score

Factor	Factor Score	Overall Score
Verification	3	1.7
Validation	3.3	
Input Pedigree	3.3	
Results Uncertainty	3	
Results Robustness	1.7	
Use History	4	
M&S Management	3	
People Qualifications	3	



NASA TECHNICAL STANDARD

National Aeronautics and Space Administration
Washington, DC 20546-0001

NASA-STD-7009

Approved: 07-11-2008

Expiration Date: 07-10-2013
Superseding NASA-STD-(I)-7009

STANDARD FOR MODELS AND SIMULATIONS

MEASUREMENT SYSTEM IDENTIFICATION:
NOT MEASUREMENT SENSITIVE

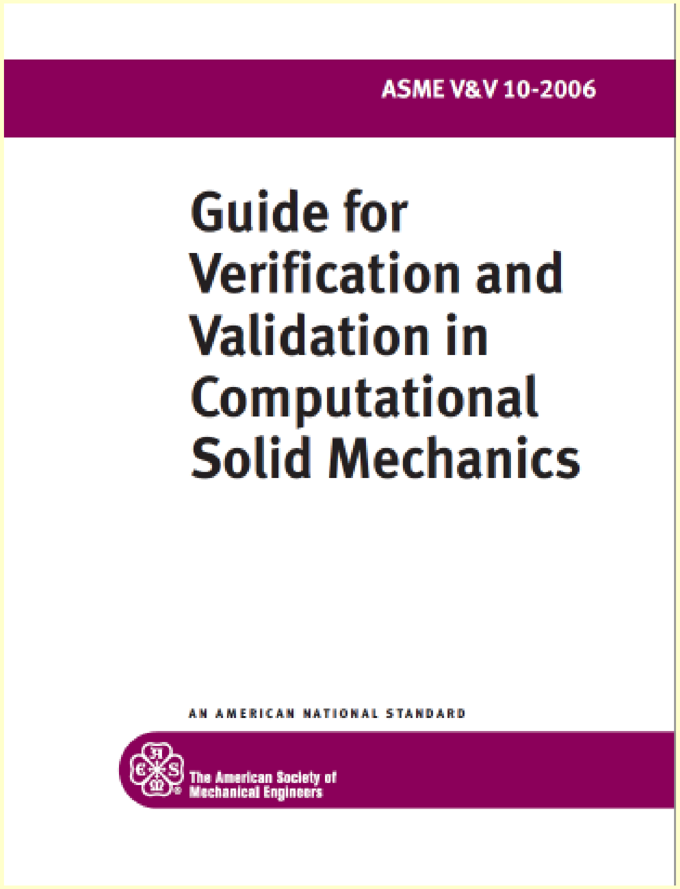
APPROVED FOR PUBLIC RELEASE — DISTRIBUTION IS UNLIMITED

NASA web site: **http://standards.nasa.gov/documents/nasa**

Guide for Verification and Validation in Computational Solid Mechanics

Published December 2006

Provides a high level description of the philosophy, procedures, and definition of terms for computational mechanics.



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 web site: **www.asme.org**

Publications > Codes & Standards > Electronic Editions (PDF)
Search on “verification” or “V&V 10”

ASME V&V-10 COMMITTEE

In 1999 an ad hoc Verification & Validation specialty committee was formed under the auspices of the United States Association for Computational Mechanics (USACM).

In 2001 the American Society of Mechanical Engineers (ASME) approved the committee's charter:

To develop standards for assessing the correctness and credibility of modeling and simulation in computational solid mechanics.

and the committee was assigned the title and designation of the ASME Committee for Verification & Validation in Computational Solid Mechanics V&V-10 (PTC-60 prior to 2009).

ASME
SETTING THE STANDARD

ASME V&V-10 ACTIVITIES

The Committee's objective is to fill-in the V&V outline presented in the *Guide* with topic specific documents that will lead to Recommended Practice documents.

- ☐ ***End-to-End Example*** –
  - ➢ Follows the *Guide* with application to a simple cantilever beam.
  - ➢ Objective is to walk analysts through the V&V steps with a simple example.
- ☐ ***Uncertainty Quantification in V&V*** –
  - ➢ Expands on the role of UQ in V&V.
  - ➢ How V&V analysts perform UQ and how they communicate their results, conclusions and recommendations to decision makers.
- ☐ ***Validation Metrics*** –
  - ➢ Provides a measure by which the experimental and simulation outcomes and can be compared.
  - ➢ Initial focus on waveform comparisons.

WHY AN END-TO-END EXAMPLE?

- The “End-to-End Example” document is an attempt to provide a step-by-step illustration of the *key concepts* of verification and validation.

- The intent is to provide a primer for those who are new to verification and validation and seek a single source document that illustrates, through a consistent example, the steps and methodology comprising verification and validation.

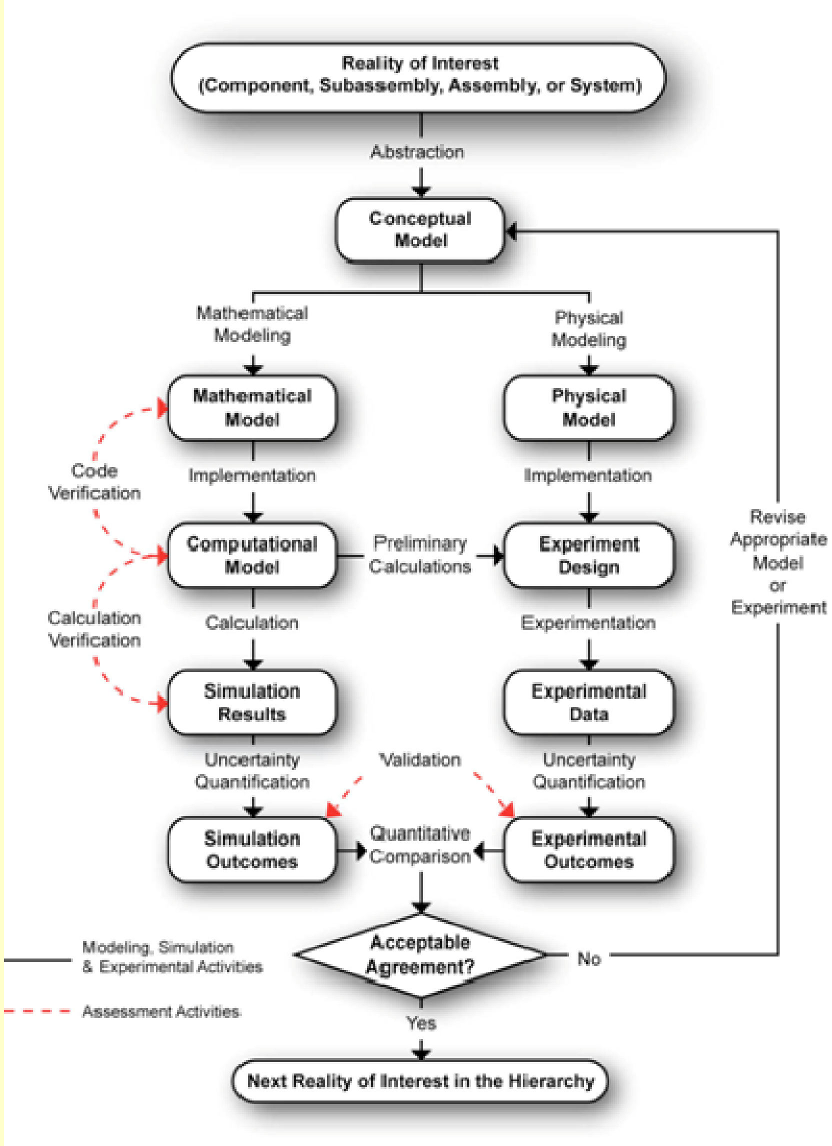
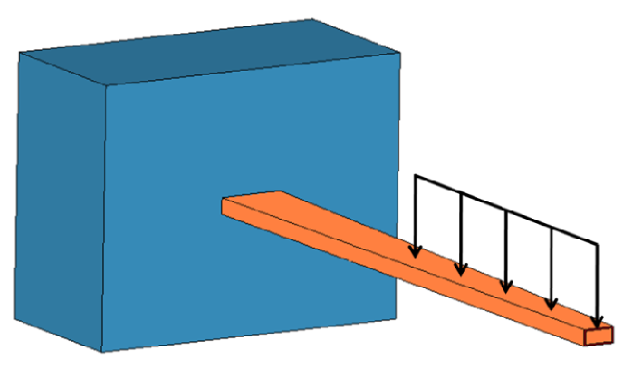


Figure 4 in ASME *Guide*

WHAT IS THE END-TO-END EXAMPLE?

Cantilever Beam Example



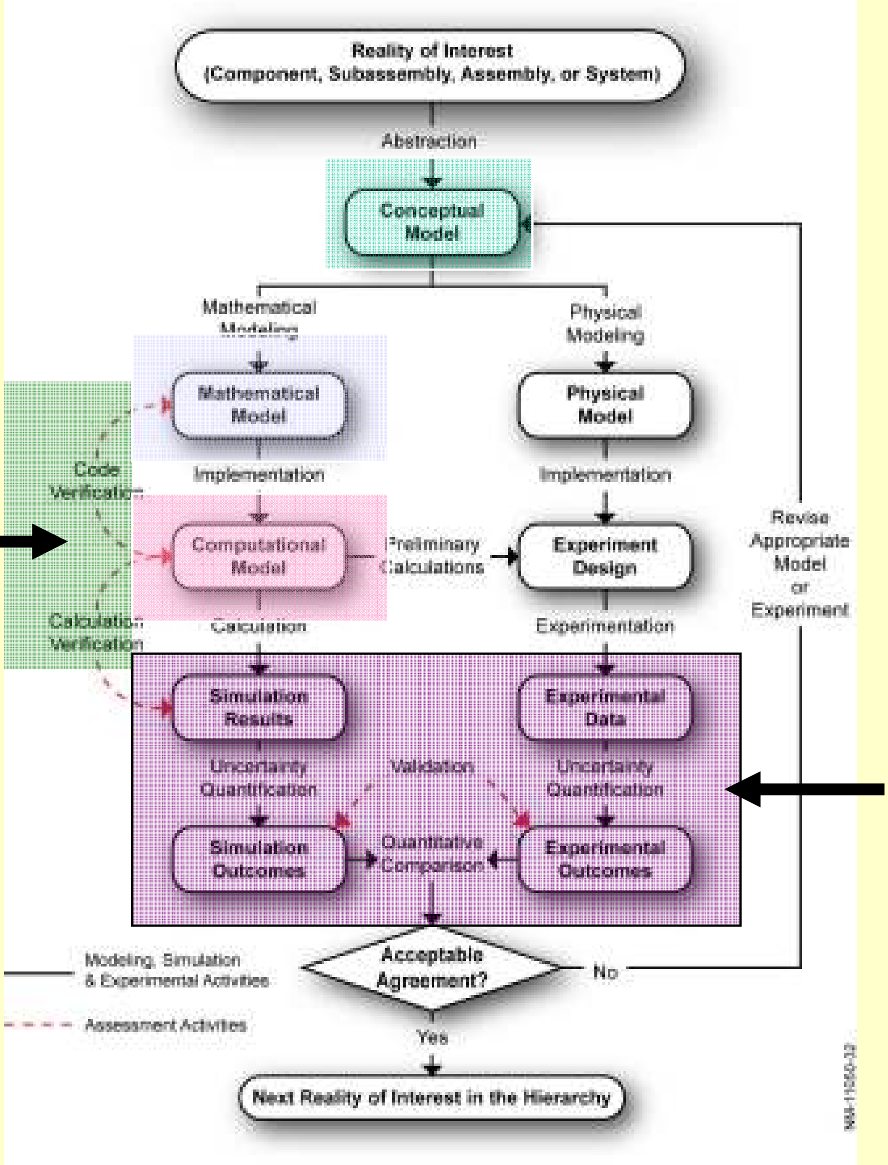
- The illustrative example selected is that of a tapered cantilever Bernoulli-Euler beam under a distributed load.

- The boundary condition at the cantilevered end of the beam is assumed to be non-ideal, with a torsional spring limiting the rotation of the beam.

- This formulation enables us to illustrate the treatment of a parameter unrelated to beam deformation while avoiding unnecessary theoretical complications that might detract from the presentation of basic verification and validation principles.

‘KISS’ Principle

V&V PROCESS



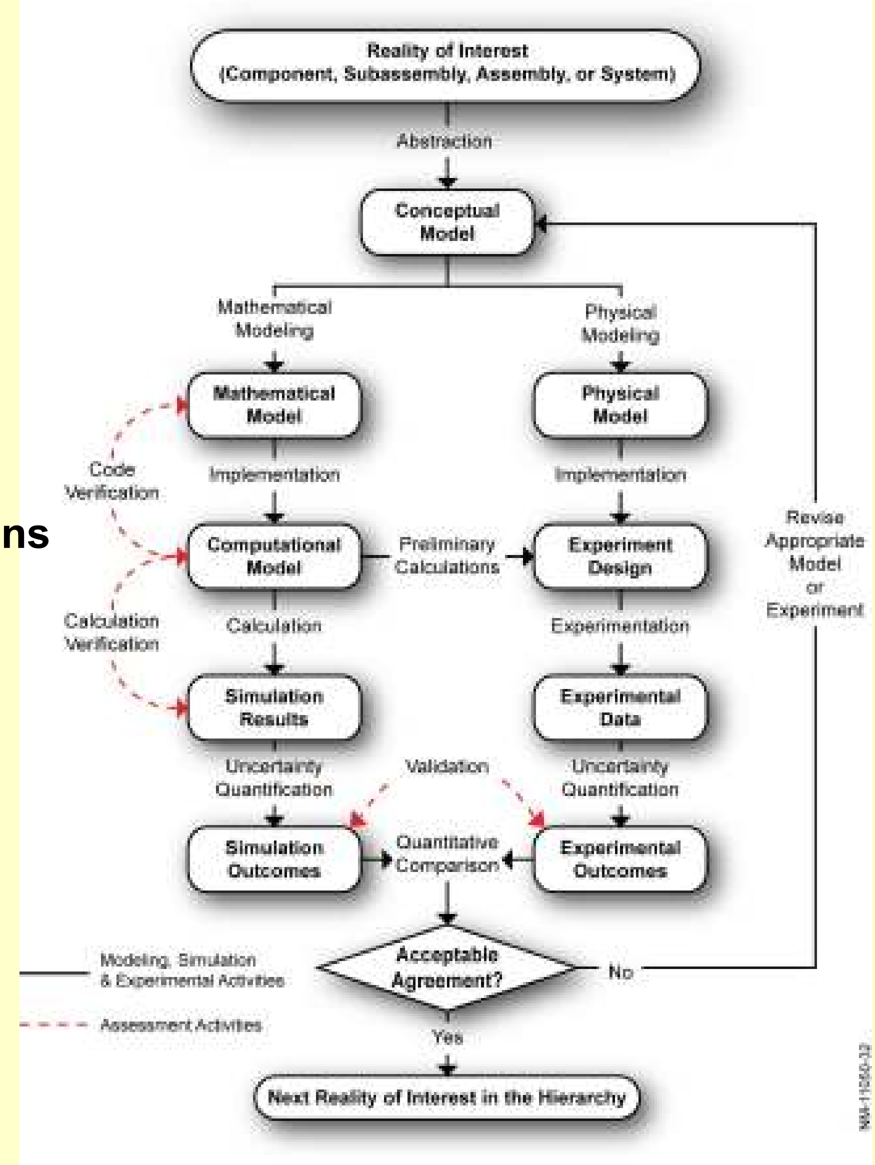
Verification

Validation

E2E EXAMPLE OUTLINE

E2E Major Sections:

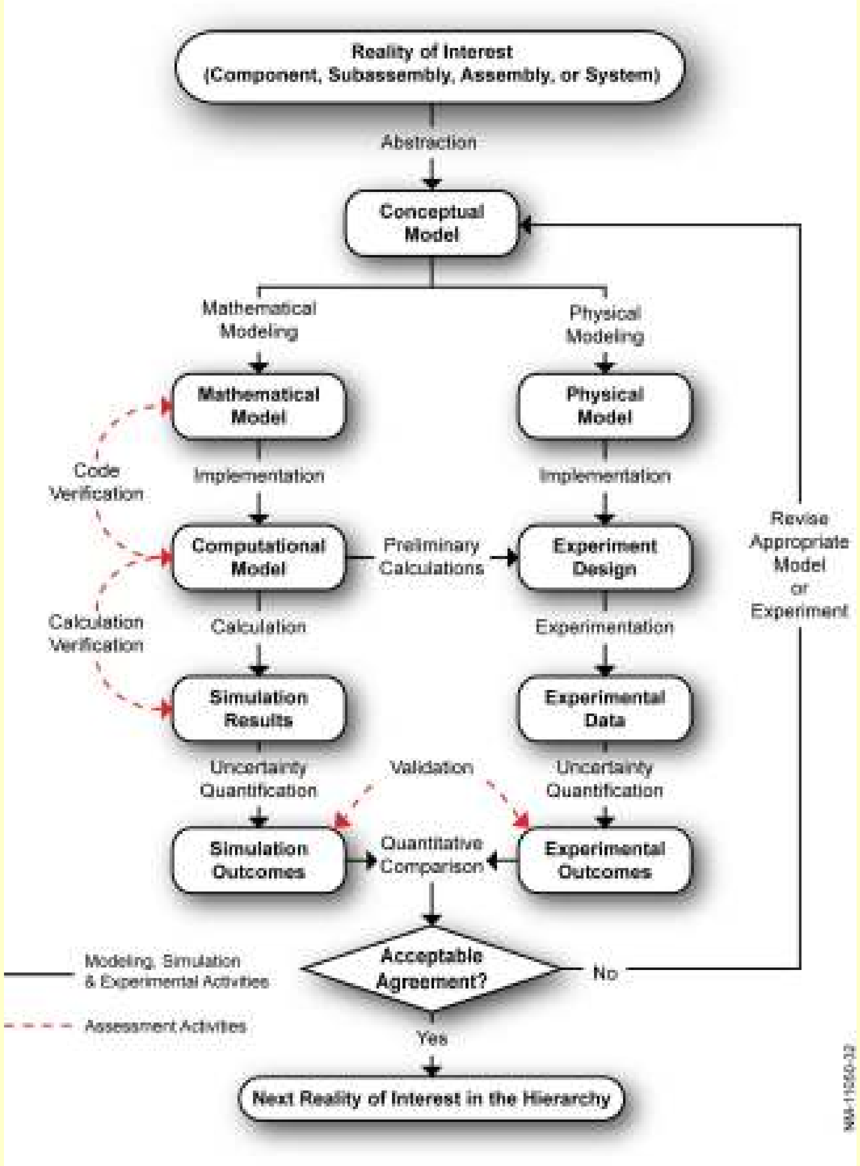
- **Verification & Validation Plan**
- **Model Development**
- **Verification**
- **Comparisons of Experiments and Predictions**
    - **Deterministic-Deterministic**
    - **Statistical-Deterministic**
    - **Probabilistic-Probabilistic**



E2E EXAMPLE OUTLINE

Verification & Validation Plan
Model Development
Verification
Comparisons of Experiments and Predictions

The ***Verification and Validation Plan*** is a document that defines certain key parameters, assumptions and expectations of the model to be developed, i.e. the Plan for navigating the V&V Process.



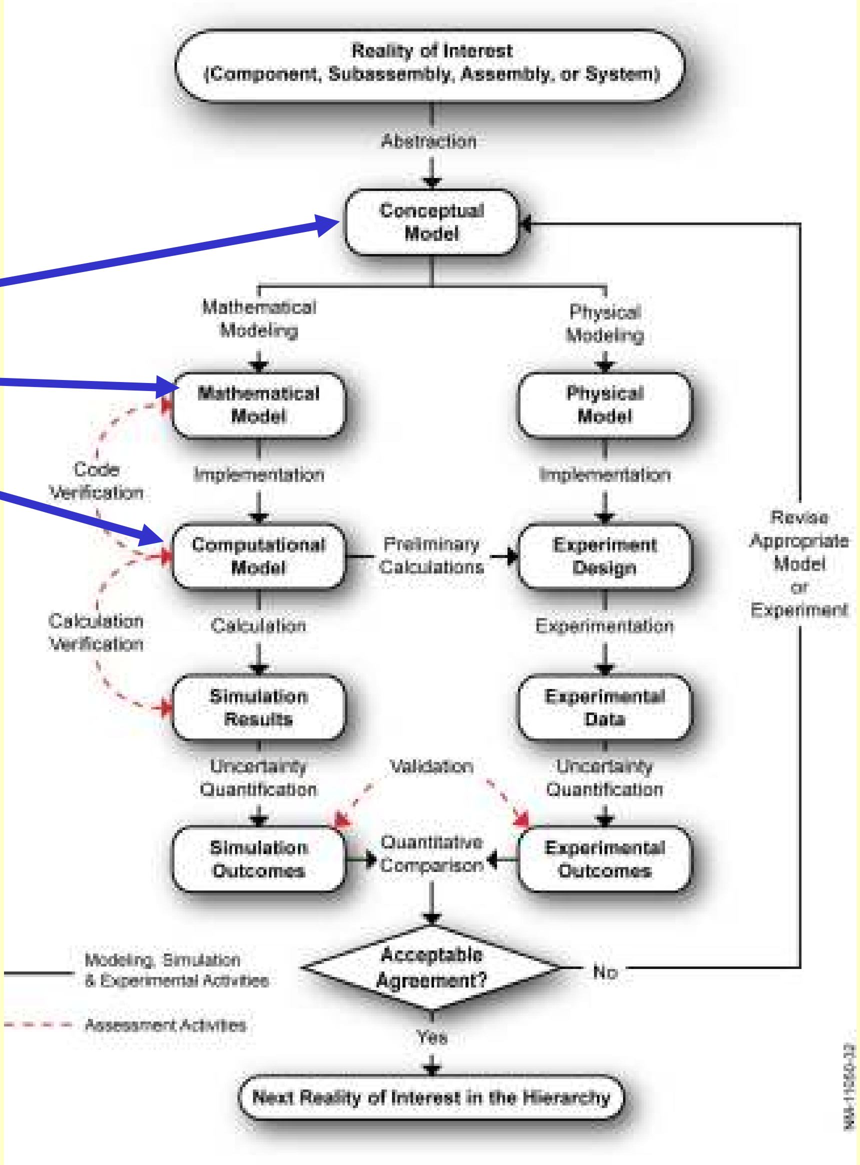
E2E EXAMPLE OUTLINE

Verification & Validation Plan

Model Development

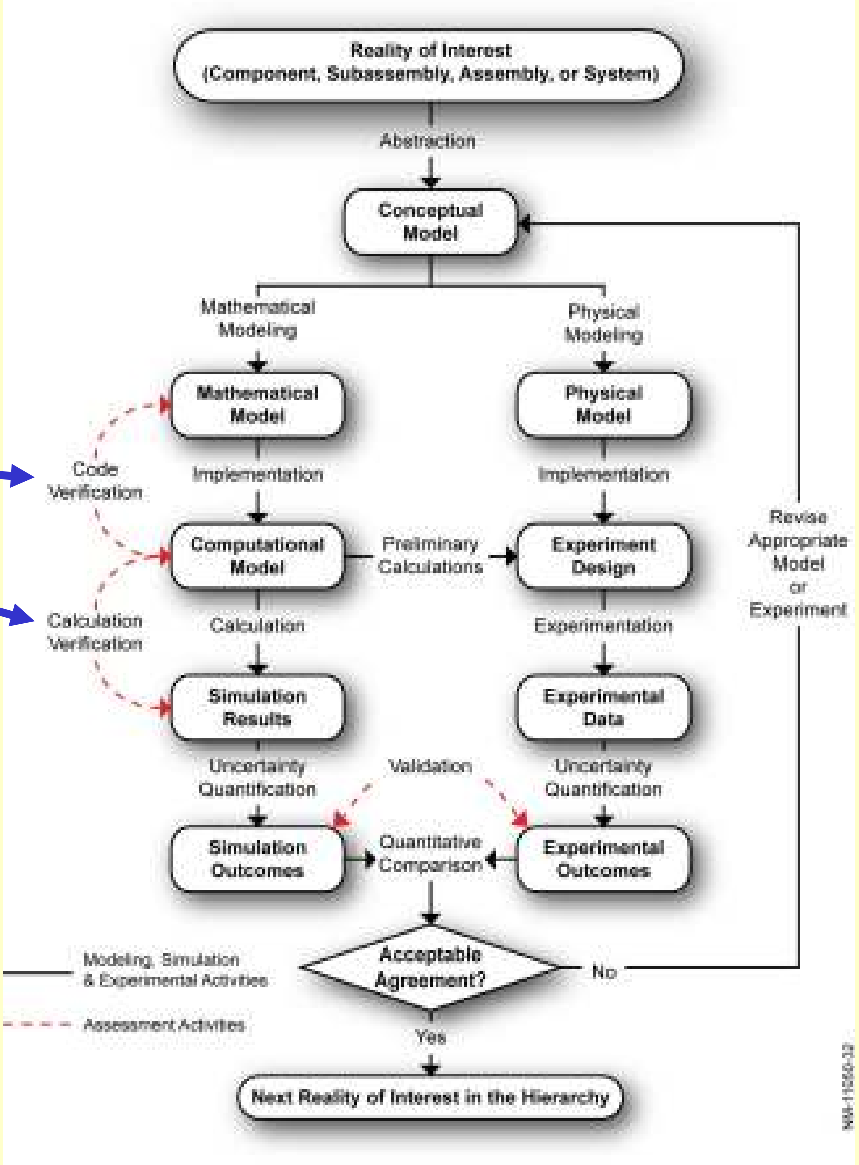
Verification

Comparisons of Experiments and Predictions



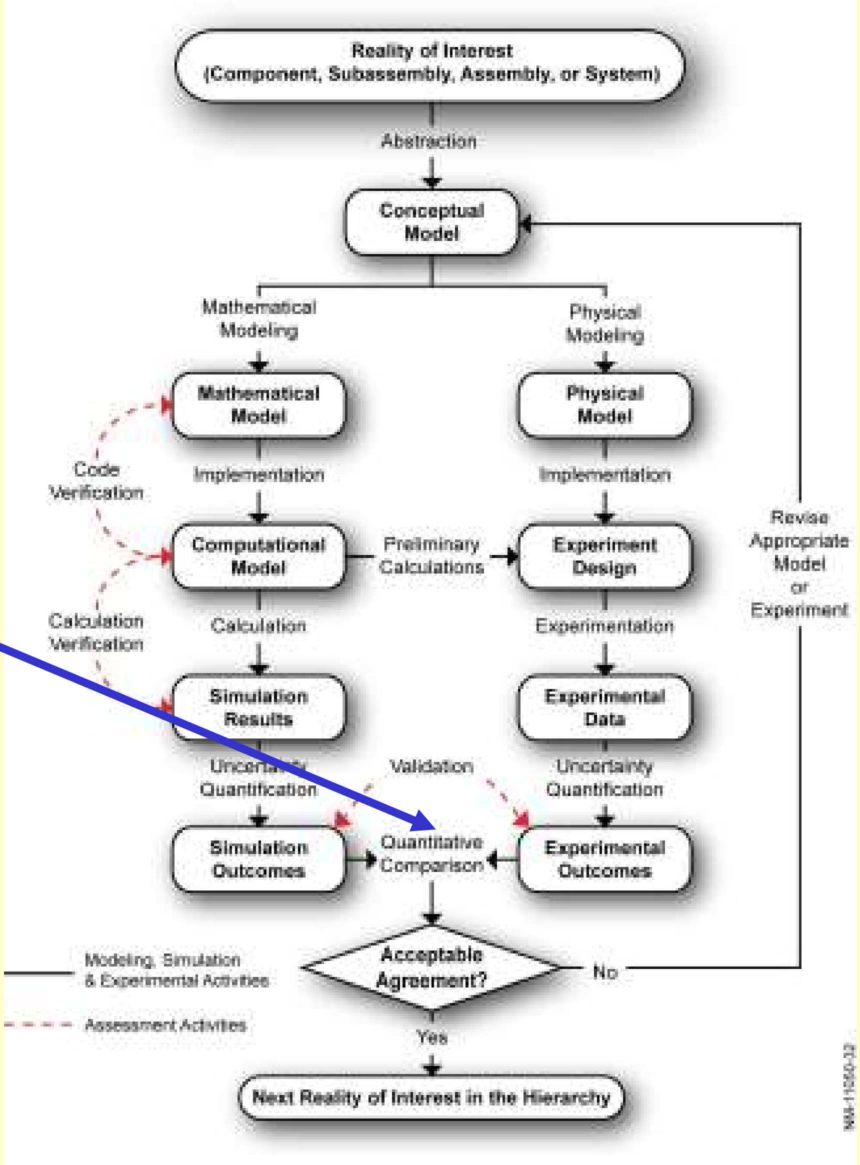
E2E EXAMPLE OUTLINE

Verification & Validation Plan
Model Development
Verification
Comparisons of Experiments and Predictions



E2E EXAMPLE OUTLINE

Verification & Validation Plan
Model Development
Verification
Comparisons of Experiments and Predictions



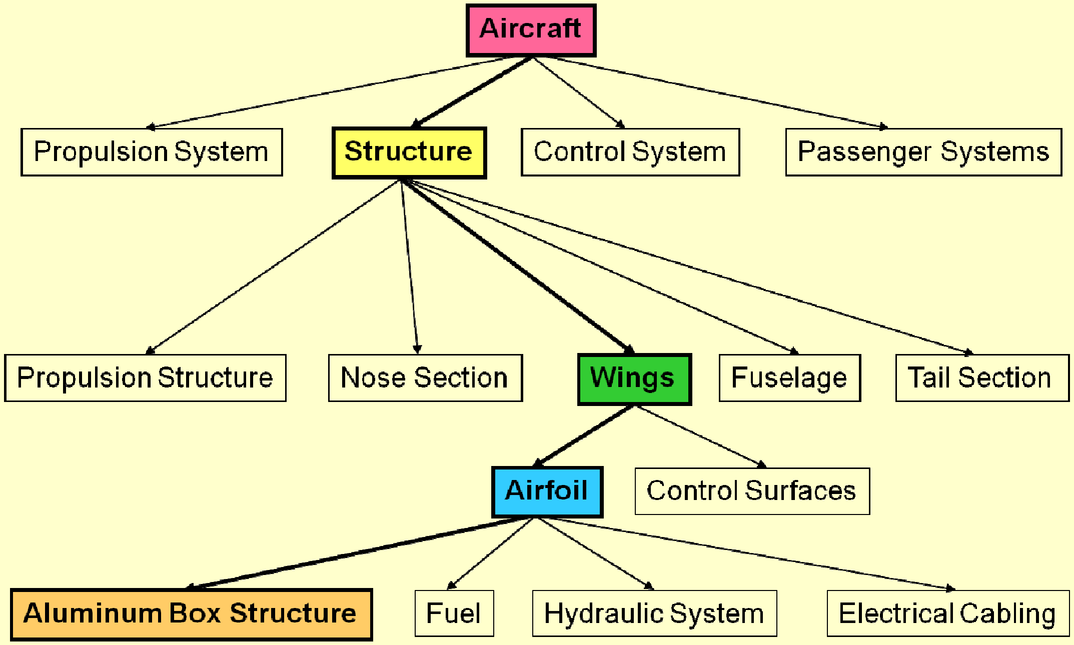
VERIFICATION & VALIDATION PLAN

MODEL HEIRARCHY
SYSTEM RESPONSE QUANITIES
VALIDATION REQUIREMENTS

HIERARCHICAL MODEL VALIDATION

Establishing Model Requirements

- Customer establishes intended use and top-level model requirement.
- Validation team constructs hierarchy, establishes sub-level metrics and validation requirements.
- Hierarchy adds confidence: Right answer for right reason.



SYSTEM RESPONSE QUANTITIES

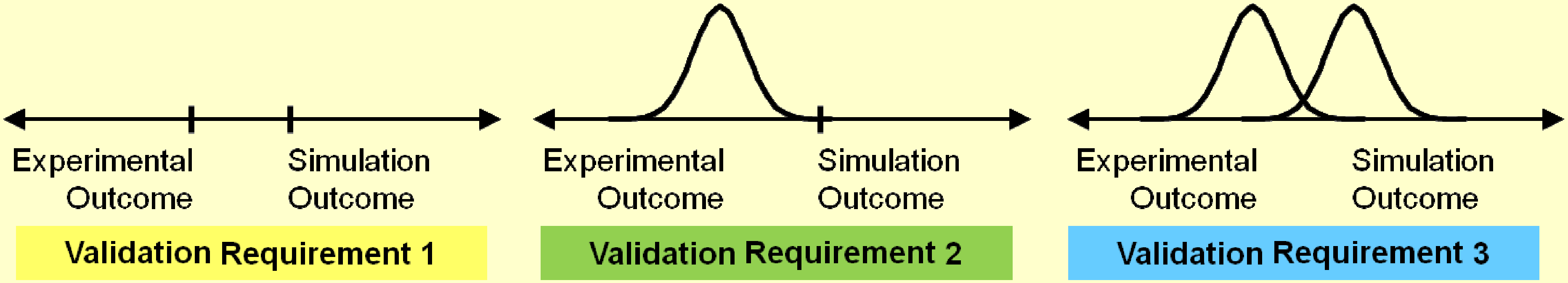
Beam ***end deflection*** and outer ***surface strain*** are to be measured & predicted.

Although *end deflection* is the primary System Response Quantity of interest, the surface strain will also be compared to provide some assurance that both the model and experiment provide the right answer for the right reason.

The problem definition *must* also contains the ***validation requirements***, i.e. metrics to be used and acceptable values, e.g. the predicted tip deflection should be within a 10% band of the experimental measurement.

The validation requirements also ***drive model development*** decisions, e.g. yielding versus no yielding can use simple elastic material models.

VALIDATION REQUIREMENTS



Experimental Outcome
Simulation Outcome
Validation Requirement 1

Experimental Outcome
Simulation Outcome
Validation Requirement 2

Experimental Outcome
Simulation Outcome
Validation Requirement 3

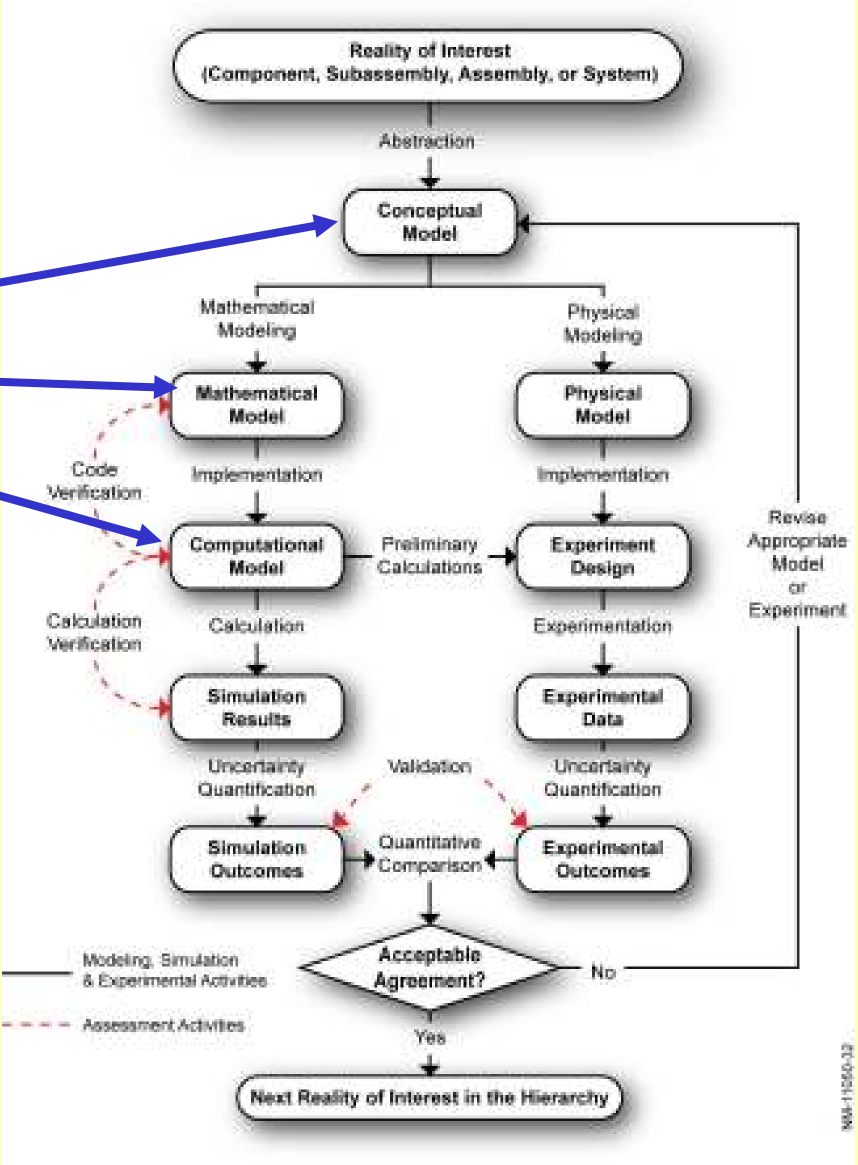
Requirement 1 - Deterministic Comparison of Experimental Measurement with Model Prediction.

Requirement 2 - A Comparison Based on Statistics of Several Experiments with a Deterministic Model Prediction.

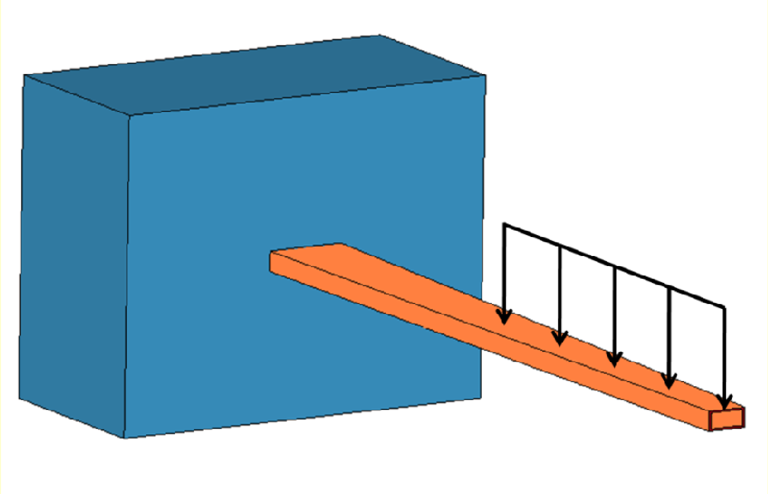
Requirement 3 - A Comparison Between Empirical CDF of Experimental Results and CDF from Model Predictions.

MODEL DEVELOPMENT

CONCEPTUAL
MATHEMATICAL
COMPUTATIONAL
PHYSICAL



CONCEPTUAL MODEL



Conceptual Model Summary:

- The beam material is homogeneous and linear elastic,
- The beam undergoes only small deflections,
- Beam deflections are governed by static Bernoulli-Euler beam theory,
- The beam and its boundary conditions are perfectly symmetric from side to side, and all loads are applied symmetrically; therefore, beam deflections occur in a plane,
- The beam boundary constraint is modeled as fixed translation with a linear rotational spring.

Photo Credit: 42-16687817| RF| © Randy Faris/Corbis http://pro.corbis.com

MATHEMATICAL & COMPUTATIONAL MODEL

Mathematical Model:
Bernoulli-Euler Beam Theory

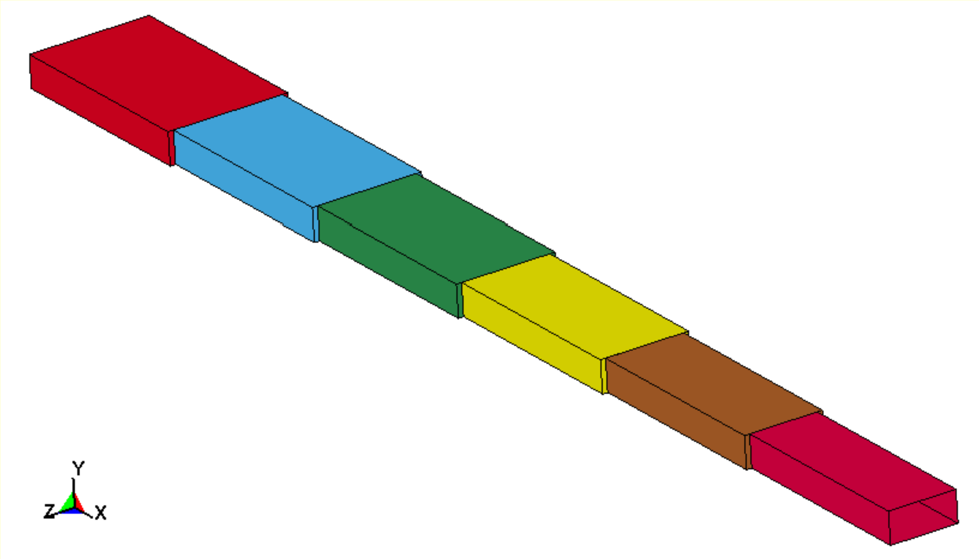
$$\frac{d^2}{dx^2}\left(EI(x)\frac{d^2}{dx^2}w(x)\right)=q(x)\;\;,\;\;0\le x\le L\;\;,$$

$$w(0)=0,\;\;\left.\frac{dw}{dx}\right|_{x=0}=f_r EI(0)\left.\frac{d^2w}{dx^2}\right|_{x=0},\;\;\left.\left[EI(x)\frac{d^2}{dx^2}w(x)\right]\right|_{x=L}=0,$$

$$\left.\frac{d}{dx}\left[EI(x)\frac{d^2}{dx^2}w(x)\right]\right|_{x=L}=0$$

f_r is the flexibility of the linear rotational spring restraining the beam at its constrained end.

Computational Model:
Bernoulli-Euler Beam Elements



The *mathematical model* (differential equations*)* are rarely written explicitly today. The *computational model* is constructed directly from the *conceptual model* via selection of element types. The *differential equations* are documented in the software user manual.

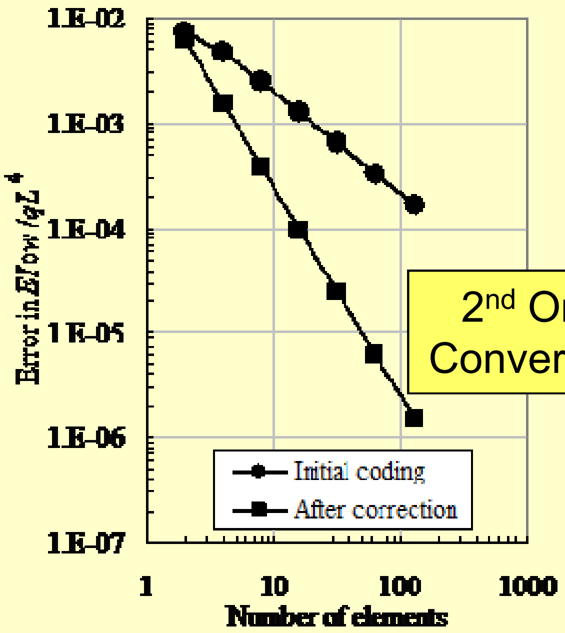
VERIFICATION

CODE VERIFICATION
CALCULATION VERIFICATION

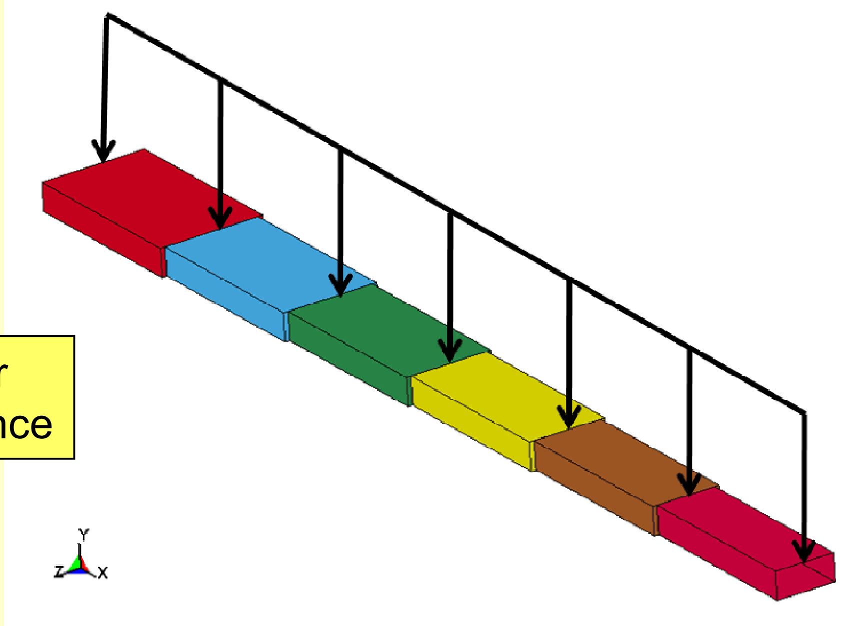
SETTING THE STANDARD

CODE VERIFICATION

- Bernoulli-Euler Beam Elements were used to construct a code, using MATLAB, for solving general beam problems.
- Used a slightly different problem, i.e. uniform load and no end spring.
- Analytical solution available.
- Tip deflection for various mesh refinements compared with analytical solution.
- Constructed observed order of accuracy and compared with theoretical order of accuracy.



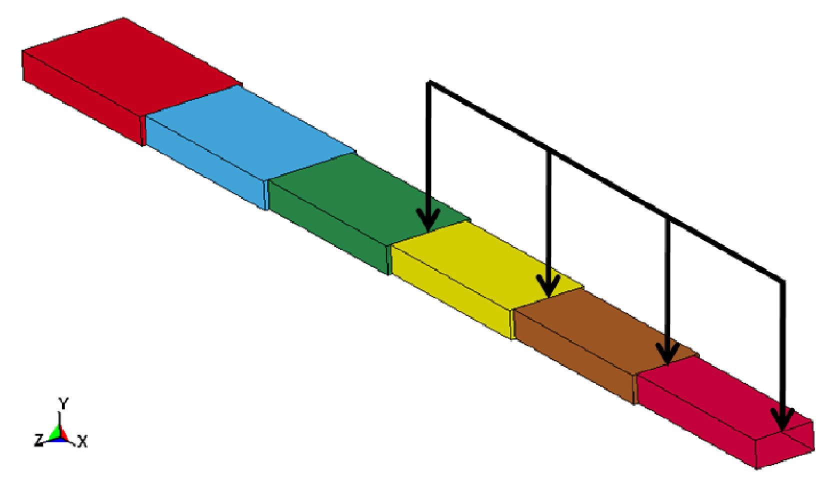
2nd Order Convergence



CALCULATION VERIFICATION

For the tapered beam model (without end spring) to be used for predictions, the **Grid Convergence Index** (GCI) method was used to estimate the discretization error of the tip deflection.

Grid number	Number of elements.	h, m	w, mm
3	4	0.5	13.09873938
2	8	0.25	13.00836675
1	12	0.16666667	12.99165677
	200	0.02	12.97834179



Using the three coarsest grids yields
GCI=0.1284%

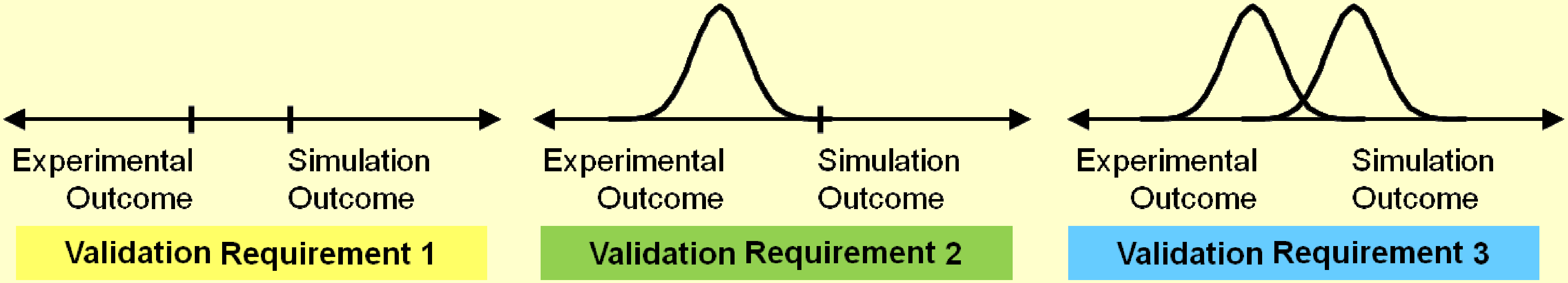
This discretization error should be least one or two orders of magnitude smaller than (a) the validation accuracy requirement, or (b) the anticipated measurement uncertainty; whichever is smaller.

Roache, P. J. (1998), *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque.

VALIDATION

COMPARISON OF RESULTS VIA THREE VALIDATION REQUIREMENTS

VALIDATION REQUIREMENTS



Requirement 3 - A Comparison Between Empirical CDF of Experimental Results and CDF from Model Predictions.

Requirement 2 - A Comparison Based on Statistics of Several Experiments with a Deterministic Model Prediction.

Requirement 1 - Deterministic Comparison of Experimental Measurement with Model Prediction.

VALIDATION REQUIREMENT 3
PROBABILISTIC-PROBABILISTIC

- Validation Experiments – **Experiments (10 beams)**

  Random Variables:
  - support spring *flexibility* (20 measurements)
  - *modulus of elasticity* of beam (10 measurements)

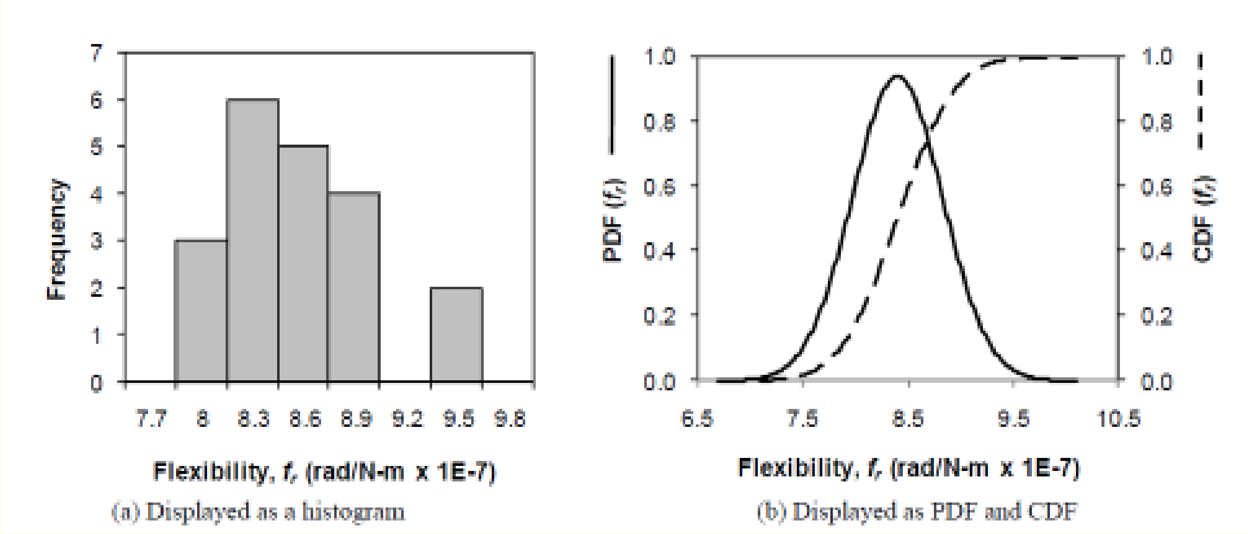
- Model Prediction – **Uncertainty Propagation**

- Validation Assessment – Metric: **Area Between CDFs**

VALIDATION REQUIREMENT 3
PROBABILISTIC-PROBABILISTIC

Characterize Random Variables:

Example: support spring *flexibility* (20 measurements)



(a) Displayed as a histogram

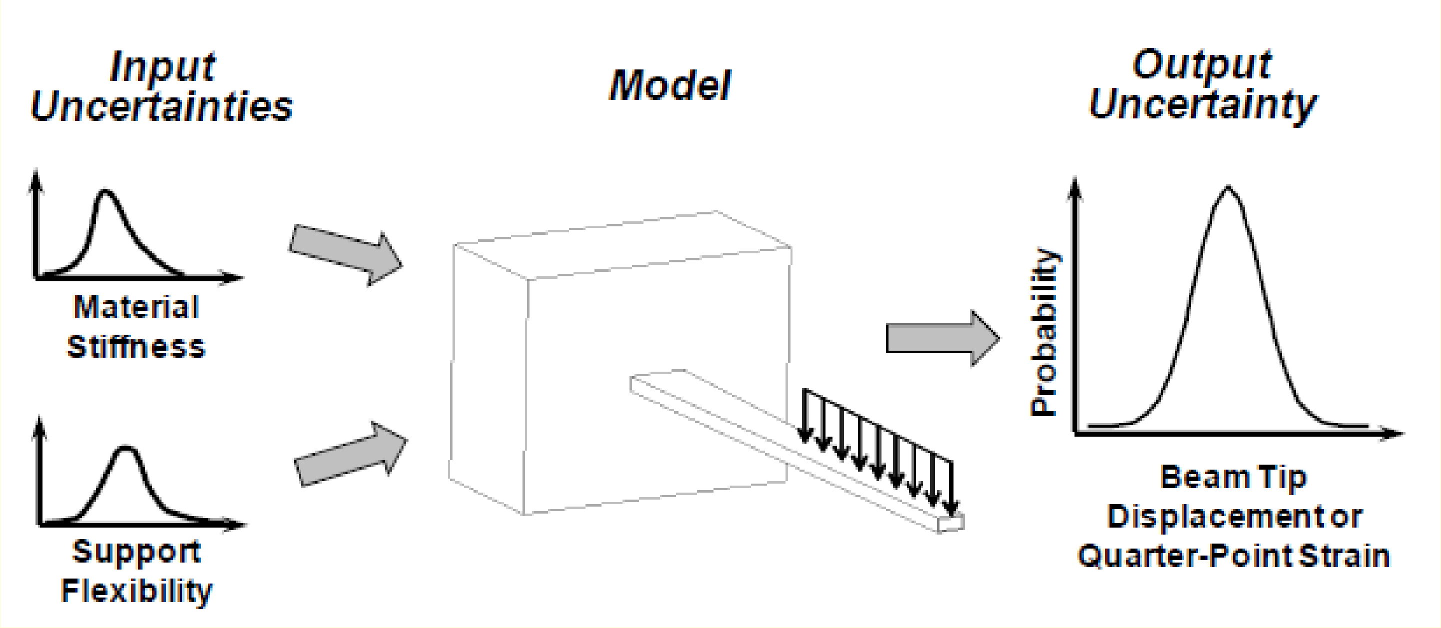
(b) Displayed as PDF and CDF

Histogram of 20 Samples

Probability Density Function (PDF) and its integral a Cumulative Distribution Function (CDF)

VALIDATION REQUIREMENT 3
PROBABILISTIC-PROBABILISTIC

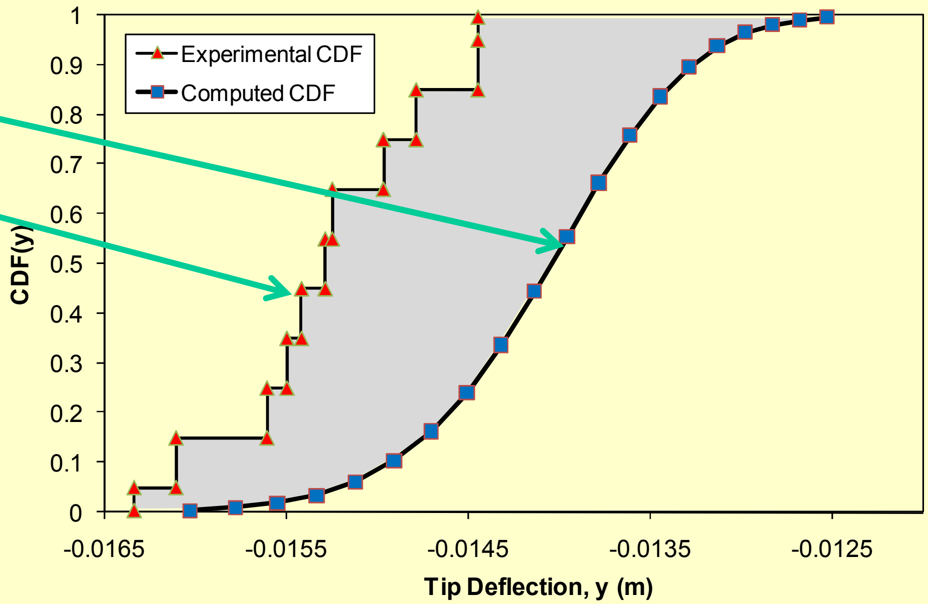
Model Prediction – Uncertainty Propagation



VALIDATION REQUIREMENT 3
PROBABILISTIC-PROBABILISTIC

- Model
- Experiment
- Comparison

Normalized Area Metric



$$M_3^{y} = \frac{1}{\left|\overline{y}^{\exp}\right|}\int_{-\infty}^{\infty}\left|F_y^{\mathrm{mod}}(y) - F_y^{\exp}(y)\right| dy$$

$$M_3^{y} < 0.1 \quad , \quad M_3^{\varepsilon} < 0.1$$

$$M_3^{y} = 1.1873 / 15.36 = 7.7\%$$

$$M_3^{\varepsilon} = 0.0107 / .2011 = 5.3\%$$

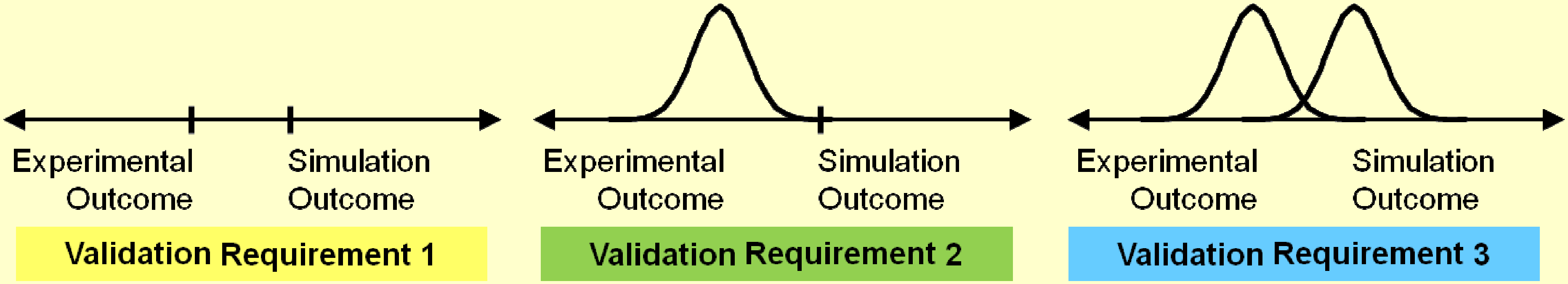
Judged to be adequate

[1] Ferson, Oberkampf and Ginzburg, Model validation and predictive capability for the thermal challenge problem, Comp Meth Appl Mech Eng, Vol. 197, 2008.

VALIDATION REQUIREMENT 3
PROBABILISTIC-PROBABILISTIC

- Normalized area metric satisfies all mathematical and recommended properties of a metric.
- Entire distribution (all statistics) represented.
- Challenging: Only zero if two CDFs are identical.
- If the two CDFs do not cross, the area metric is equal to the difference in the mean values.
- Area metric is the smallest possible expectation of the absolute value of the differences between random variables given by the two distributions.

VALIDATION REQUIREMENTS



Experimental Outcome

Simulation Outcome

Validation Requirement 1

Experimental Outcome

Simulation Outcome

Validation Requirement 2

Experimental Outcome

Simulation Outcome

Validation Requirement 3

Requirement 3 - A Comparison Between Empirical CDF of Experimental Results and CDF from Model Predictions.

Requirement 2 - A Comparison Based on Statistics of Several Experiments with a Deterministic Model Prediction.

Requirement 1 - Deterministic Comparison of Experimental Measurement with Model Prediction.

VALIDATION REQUIREMENT 2
STATISTICAL-DETERMINISTIC

- Parameter Estimation – support spring flexibility

$$f_r = 8.404 \times 10^{-7} \text{ radian/N-m}$$

- Model Prediction - Deterministic
- **Validation Experiments (10 beams) - Statistics**
- Validation Assessment – Metric: **Relative Error of Mean**

VALIDATION REQUIREMENT 2
STATISTICAL-DETERMINISTIC

- Model

$$y^{\text{mod}} = -14.24 \text{ mm} \;\; \text{Tip Deflection}$$

$$\varepsilon^{\text{mod}} = -0.1919 \text{ m}\varepsilon \;\; \text{Bottom Surface Strain}$$

- Experiment

$$\overline{y}^{\exp} = \frac{1}{10}\sum_{i=1}^{10} y_i^{\exp} = -15.36 \text{ mm}$$

$$\overline{\varepsilon}^{\exp} = \frac{1}{10}\sum_{i=1}^{10} \varepsilon_i^{\exp} = -0.2011 \text{ m}\varepsilon\,.$$

- Comparison

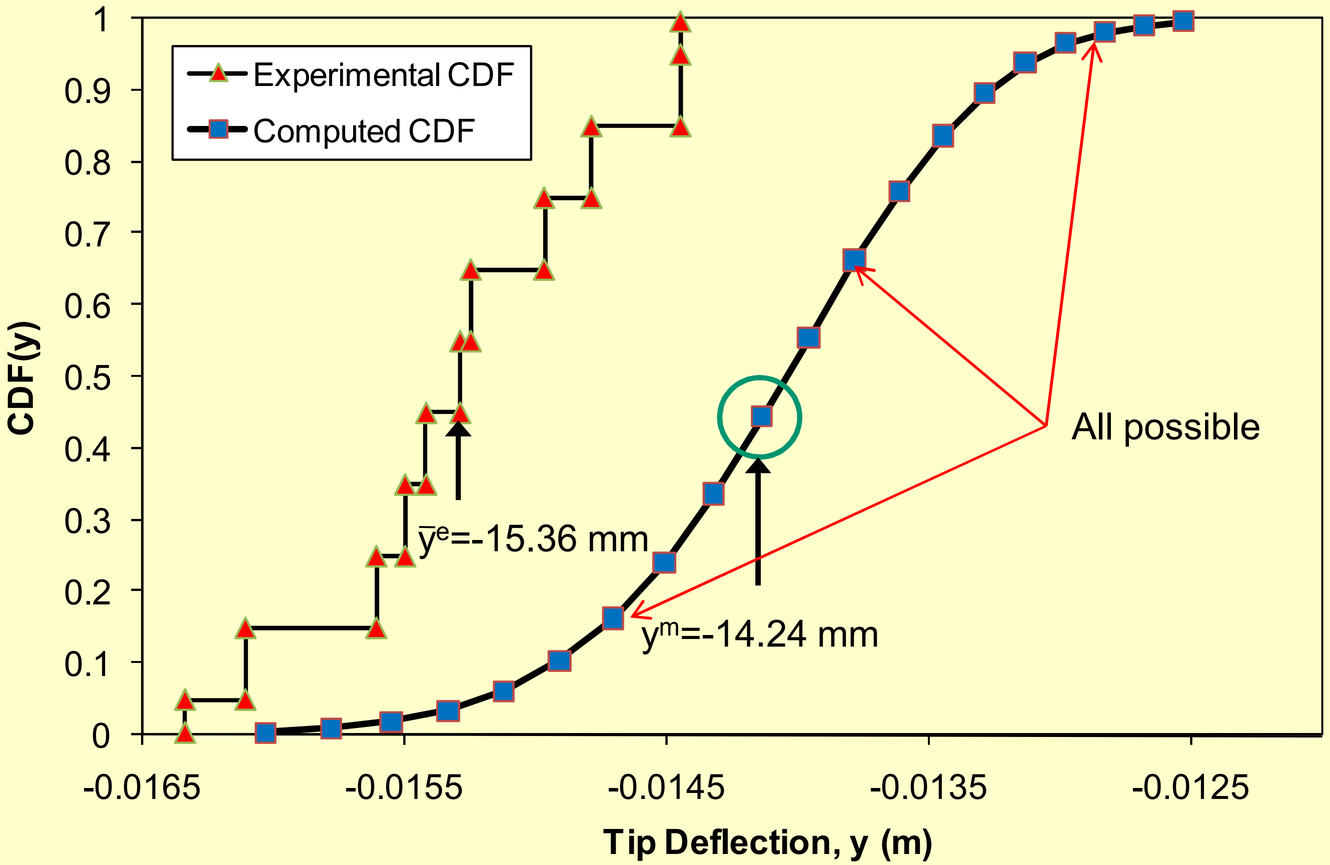
$$M_1^y = \left|\frac{y^{\text{mod}} - \overline{y}^{\exp}}{\overline{y}^{\exp}}\right| \le 10\% \quad \textit{and} \quad M_1^\varepsilon = \left|\frac{\varepsilon^{\text{mod}} - \overline{\varepsilon}^{\exp}}{\overline{\varepsilon}^{\exp}}\right| \le 10\%$$

$$M_2^y = 7.29\% \quad \text{and} \quad M_2^\varepsilon = 4.57\%$$

Judged to be adequate

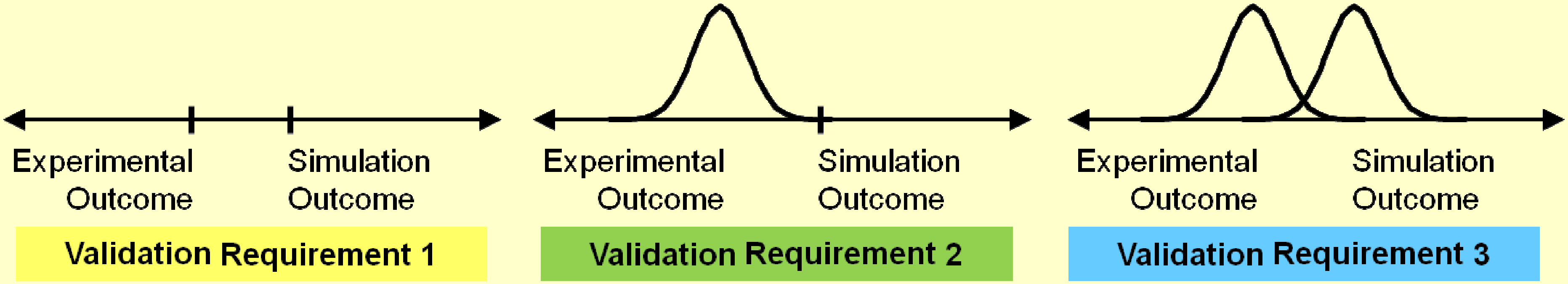
- **The Problems**
  - Only one “sample” from the model
  - Only the average used from the experiment
  - Variation from experiment ignored (will be updated)

VALIDATION REQUIREMENT 2
STATISTICAL-DETERMINISTIC



Within requirements: Just Lucky!

VALIDATION REQUIREMENTS



Experimental Outcome | Simulation Outcome

Validation Requirement 1

Experimental Outcome | Simulation Outcome

Validation Requirement 2

Experimental Outcome | Simulation Outcome

Validation Requirement 3

Requirement 3 - A Comparison Between Empirical CDF of Experimental Results and CDF from Model Predictions.

Requirement 2 - A Comparison Based on Statistics of Several Experiments with a Deterministic Model Prediction.

Requirement 1 - Deterministic Comparison of Experimental Measurement with Model Prediction.

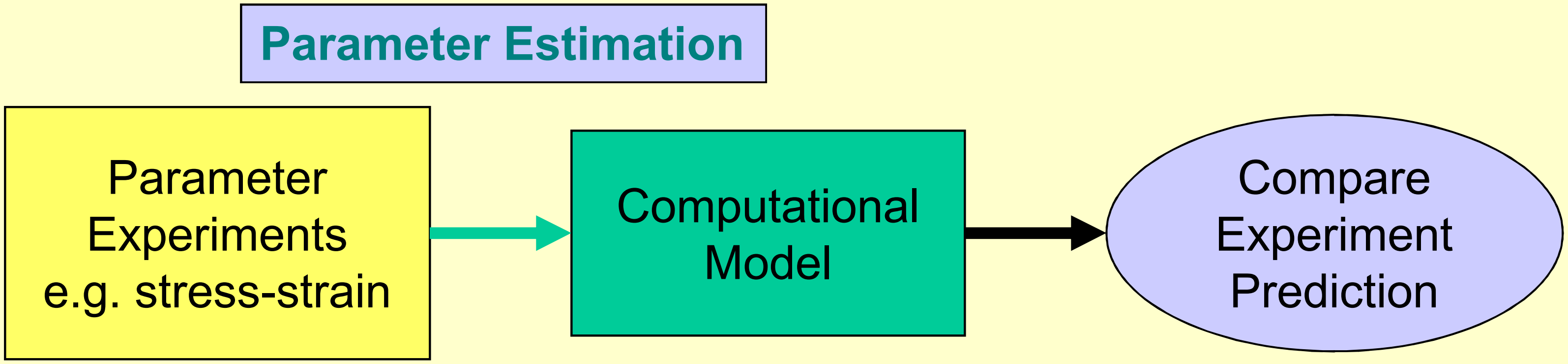
VALIDATION REQUIREMENT 1
DETERMINISTIC-DETERMINISTIC

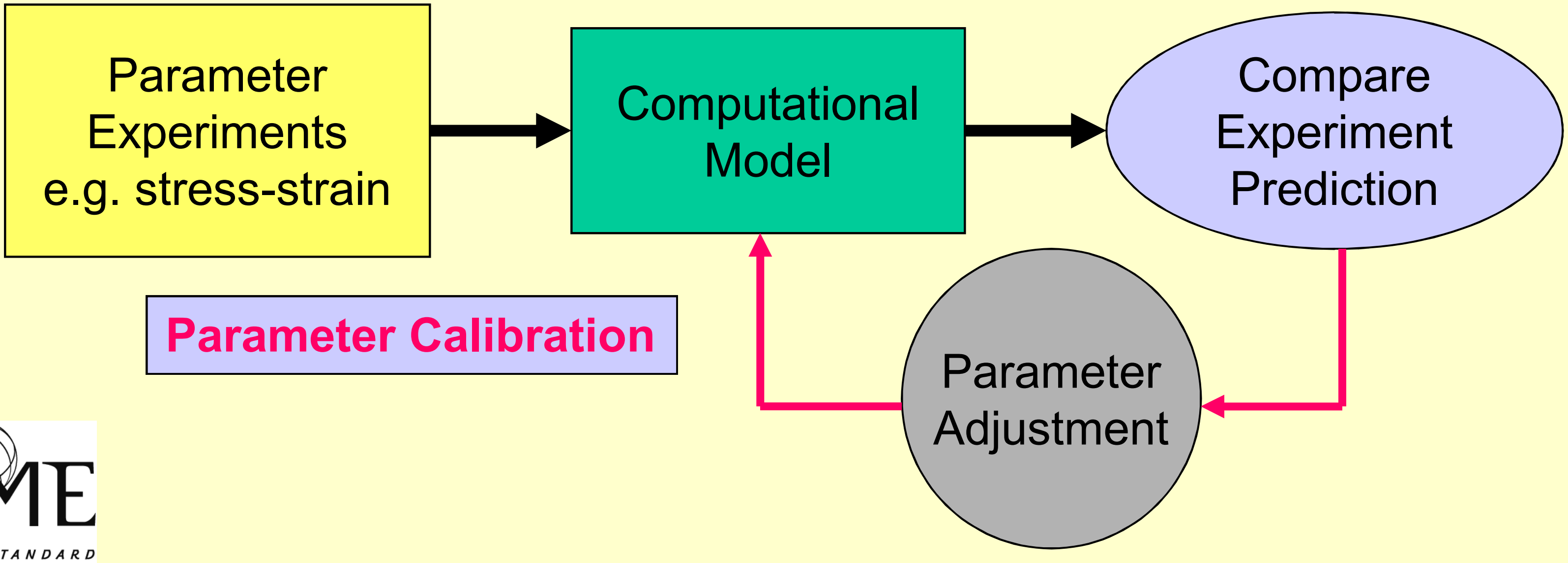
- **Parameter Estimation – support spring flexibility**

$$f_r = 8.404 \times 10^{-7} \text{ radian/N-m}$$

- Model Prediction - Deterministic
- Validation Experiment - Deterministic
- Validation Assessment – Metric: Relative Error

PARAMETER ESTIMATION





VALIDATION REQUIREMENT 1
DETERMINISTIC-DETERMINISTIC

- Model

$$y^{\text{mod}} = -14.24 \text{ mm} \;\; \text{Tip Deflection}$$

$$\varepsilon^{\text{mod}} = -0.1919 \text{ m}\varepsilon \;\; \text{Bottom Surface Strain}$$

- Experiment

$$y^{\text{exp}} = -14.44 \text{ mm} \;\; \text{Tip Deflection}$$

$$\varepsilon^{\text{exp}} = -0.2063 \text{ m}\varepsilon \;\; \text{Bottom Surface Strain}$$

- Comparison

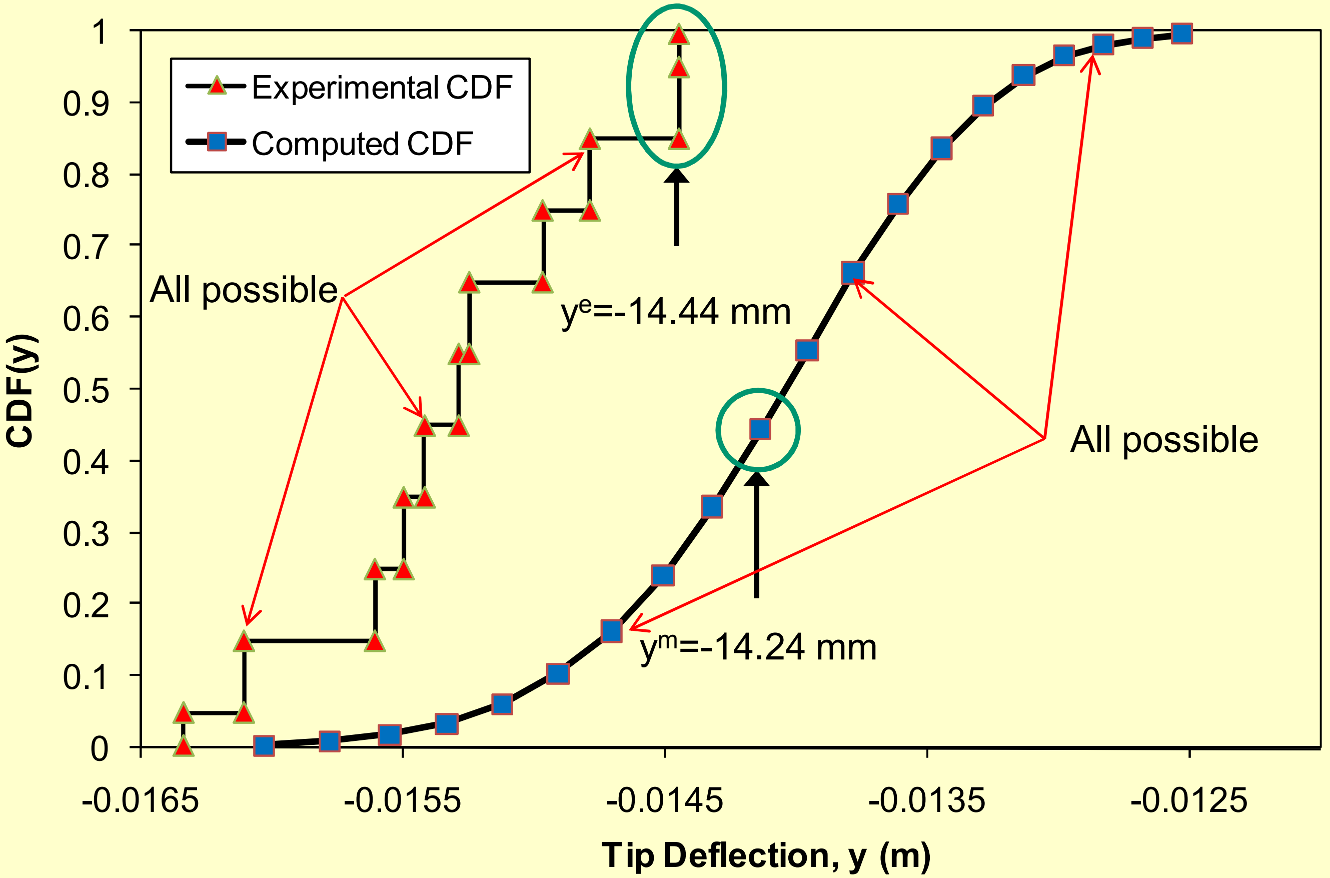
$$M_1^y = \left| \frac{y^{\text{mod}} - y^{\text{exp}}}{y^{\text{exp}}} \right| \le 10\% \quad \text{and} \quad M_1^{\varepsilon} = \left| \frac{\varepsilon^{\text{mod}} - \varepsilon^{\text{exp}}}{\varepsilon^{\text{exp}}} \right| \le 10\%$$

$$M_1^y = 1.39\% \quad \text{and} \quad M_1^{\varepsilon} = 6.98\%$$

Judged to be adequate

- **The Problem**
  - This represents a comparison of only one "sample" from both the experiment and the model

VALIDATION REQUIREMENT 1
DETERMINISTIC-DETERMINISTIC



Within requirements: Once Again Lucky! *(will be updated)*

SUMMARY

- A step-by-step illustration of the key concepts of *Verification and Validation:*
  - Beginning with the **Validation Plan**,
  - On to **Model Development**,
  - Then the two aspects of **Verification**, and
  - Finally model **Validation** illustrated using three alternative *Validation Requirements*.

- The document reader is also provided with a *framework* for approaching Verification & Validation efforts on a scale much larger than the simple cantilever beam example used in the illustration.

CONTACT INFORMATION

- Committee web site:

  www.ASME.org search “V&V 10”

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- Committee Chair:

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Questions

Website: www.nafems.org

NAFEMS

THE INTERNATIONAL ASSOCIATION
FOR THE ENGINEERING ANALYSIS COMMUNITY

Thank you!

EXTRA SLIDES

FUTURE EFFORTS

Verification – this ‘poor’ sister of validation needs more attention from the V&V research community. Reliance on regression testing for code verification provides minimal confidence when using today’s complex multi-physics and multi-scale software. Methods, and their implementation as tools, for verification of increasing software complexity are needed.

Quantification of the Value of V&V – if program managers are asked to spend resources on V&V, they needed some measure of the value they are receiving for the resources expended.

Incomplete V&V – if the V&V process is terminated before a successful conclusion, what is the best path forward for decision maker?

Validation Experimentation – most experiments consume large amounts of resources, the value of these experiments to the V&V process needs to be quantified to enable decision makers to appropriately allocate resources for this important activity.

Uncertainty Quantification – meaningful comparisons of simulations with experiments requires an estimate of the uncertainty in both sets of results, and a comparative assessment of these two uncertain outcomes.

Predictive Confidence – when validated models are applied beyond the limited range of validation experiments, how can the confidence in these results be quantified?

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INTERESTED IN V&V ?

National Laboratories – Sandia, Los Alamos, Livermore

Auto Manufactures – Ford Motors, General Motors, world wide

National Aeronautics & Space Administration – *M&S Standard (2008)*

NAFEMS – ISO9001 Quality System Supplement (QSS & Primer)
& proposed validation documents (AMWG)

Food and Drug Administration (FDA) – biomedical devices

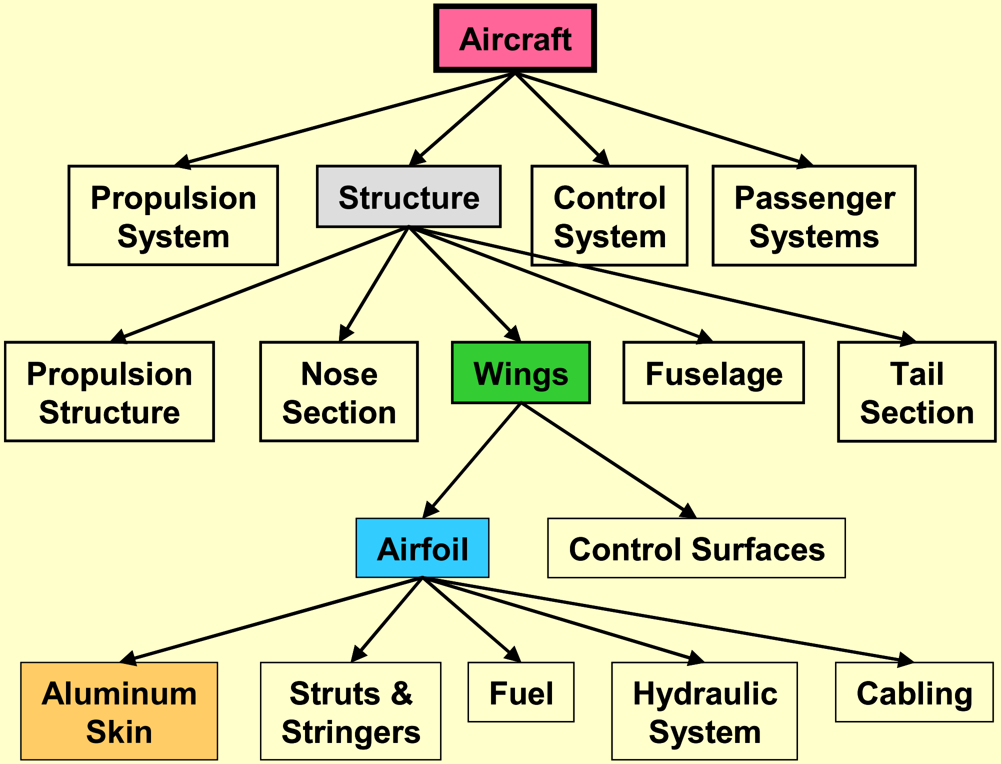
Federal Highway Authority – roadside structures

Federal Aviation Authority – passenger seat safety
Dynamic Seat Certification by Analysis

Predictive Science Academic Alliance –
5 universities to develop graduate level V&V programs

ASME
SETTING THE STANDARD

VALIDATION HIERARCHY & PROBLEM STATEMENT



The objective is to develop and validate a model suitable for the prediction of deflection of an aircraft wing subjected to static loads.

Validation Metrics

- Metric - a function which defines a distance between elements of a set[1]
  - Non-negative: $d(x,y) \geq 0$
  - Indiscernible: $d(x,y) = 0 \text{ if and only if } x = y$
  - Symmetric: $d(x,y) \geq d(y,x)$
  - Subadditive: $d(x,z) \leq d(x,y) + d(y,z)$
- In V&V, a metric is the yardsticks for comparing model responses with experimental data
  - Not the goal (or requirement), but rather the measurement system
  - Difference in response, statistics, probability distributions, etc.
  - Over all time or at each time step

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[1] http://en.wikipedia.org/wiki/Metric_(mathematics)

Validation Metrics

- Recommendations[1]
  1. Fully reflect modeling assumptions, approximations, estimates, etc.
  2. Include numerical error (or prove small and exclude)
  3. Include error in post-processing experimental results
  4. Include measurement error in experimental data
  5. Depend on the number of experimental measurement
  6. Reflect only the comparison (the measure) and not the adequacy (the requirement)
- Additional Recommendations
  - Include uncertainties in both the model and the experiment

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[1] Oberkampf and Barone, Measures of agreement between computation and experiment: Validation metrics, J. Comp Physics, 217, 2006

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