"The Building Block Approach in the 21st Century - the role of ICME & UQ"

5 January 2015

Manufacturing & Industrial Technologies Division
AFRL/RXM

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PA clearance #88ABW-2014-6017
Topics

• Context
• The Building Block Method
• The Philosophy of Design
• Materials & Processes to the Rescue
  – Integrated Computational Materials Engineering
  – “Defect Species:” An example from Additive Manufacturing
• Steps towards a New Design Paradigm
• Takeaways
Norfolk Dam, Arkansas
It’s the decision, not the model

Materials & Processes = Performance

GE’s Passport engine - the commercial debut of ceramic-matrix composites

HondaJet – unitized composite fuselage

CFM LEAP engine – Resin transfer molded fan blade

Increased use of Composites
"Advanced manufacturing technologies are out-pacing structural analysis capabilities"
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• Takeaways
Building Block Method

Confidence in system capability is developed through extensive fabrication and testing ...

COURTESY OF DAVE BOWDEN
Building Block Method

Engineering, Operations & Technology | BR&T

Structures Technology

<table>
<thead>
<tr>
<th></th>
<th>1980s</th>
<th>2000s</th>
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<tbody>
<tr>
<td>size of structural test programs</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Allowable development</td>
<td>25</td>
<td>2,500</td>
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<tr>
<td>Material specification development</td>
<td>500</td>
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</tr>
<tr>
<td>Material screening and selection</td>
<td>5,000</td>
<td>100,000</td>
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Major growth in cost & time
Component Life Data

Works fairly well for **evolutionary** design configurations, materials & manufacturing processes

Works less well when aircraft mission profiles & retirement dates **change**

Works poorly for **revolutionary** design configurations, materials & manufacturing processes

**Building Block Method**

- Allowable development
- Material specification development
- Material screening and selection

Analysis validation

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Major growth in cost & time

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Philosophy of Design
Common to All Structural Materials

Designs are Based on *Minima* - not *Averages*

Courtesy Michael Gorelick, FAA
We don’t know what we don’t know!

Minima are extrapolated - not measured

Deterministic design criteria

Uncertainty in Minima Often Lead to Expensive Re-designs, Especially:
- New Materials
- New Geometries
- New Processes
- New Application of Mature Processes

Courtesy Michael Gorelick, FAA
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ICME is becoming a critical enabler for reducing the design/make cycle time.
Powder Bed Fusion

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
Location-Specific Design: Building Block
Vision & Motivation

Defect Likelihood = \( f(\text{geometry, process}) \)

Optimized Design is Location-Specific and Assured through Digital Data & Informatics

Phased Approach:

1. Effect of **Process Parameters** on Defect Species: DOE of Simple Shapes

2. Effect of **Geometry** on Defect Species: “Canonical” Features connect process to feature

3. Effect of **Process & Geometry** on Defect Species

Develop Framework for Visualization & Analytics: integration of process data, in-situ data, inspection data with process models
Effect of Process Parameters on Defect Species

DOE Builds 1 through 4

10 mm

Laser Scan Path

hatch spacing
laser speed
stripe width

Global Energy Density (GED): energy input density (J/mm²) as laser beam is rastered across powder bed surface at constant speed

Global Energy Density (GED):

\[ G = \frac{P}{S \times H} \]

Where:
- G = Global Energy Density
- P = Laser Power
- S = Hatch Speed
- H = Hatch Spacing

**DOE # 3**

- Laser power (195 W)
- Laser diameter (70 μm)
- Laser speed (1,000 mm/s)
- Hatch spacing (0.1 mm)
- Stripe width (5 mm)

COURTESY OF MICK MAHER
Build Trials: As Built Defects

Low Energy - Lack Of Fusion

High Energy - Keyhole Porosity

~ 150 μm

Avg = 22 μm
Effect of Geometry on Defect Species

- Continuously-Changing Wall Thickness
- Continuously-Changing Wall Pitch

Process maps (beam current) for example geometries

Systematically vary geometrical features & local process parameters and catalog defect species
Defects in Full Scale Builds

Metallization: build-up and contamination

Raking: Powder distribution and swelling

Anomalous melting

Scale Matters!
Fully Integrate Process Data & Models with Lifing Models

- In situ data (Log-files, IR, Optical images)
- Characterization (Destructive & Non-destructive)
- Process Data
- Intended Geometry
- Process Models
- Property Models
- Probabilistic Design and Performance Lifing

Beam Power & other parameters

- Laser beam normal to image scanning from left to right

Yield Strength (ksi)
- 175
- 155

COURTESY OF MICK MAHER
Fully Integrate Process Data & Models with Lifing Models

- Beam Power & other parameters
- In situ data (Log-files, IR, Optical images)
- Intended Geometry
- μ-structural Models
- Property Models
- Over 60 Process Variables
- Characterization (Destructive & Non-destructive)

~1 Terabyte of data per Build!

COURTESY OF MICK MAHER
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Building Block Method

Confidence in system capability is developed through extensive fabrication and testing ...

Design Subcomponent Tests To Assess the Capability of The Process to Successfully Deliver the Full-Scale Article

Confidence in system capability is developed through extensive fabrication and testing ...

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Change the Testing Paradigm:
Use ICME to Design - 3 σ Validation Experiments that Delineate Process Capability

Combined Computational/Experimental Approach

- Vary material & process parameters
- Simulate fine-scale behavior, homogenize to higher level models
- Estimate impact of M&P variability on system performance
- Iterate

ASME V&V 10-2006
Change the Testing Paradigm:
Use ICME to Design - $3 \sigma$ Validation Experiments that Delineate Process Capability

Use ICME to understand processing effects & sensitivity due to scale up in size, manufacturing volume, and component complexity.
Change the Testing Paradigm: Use ICME to Design - 3σ Validation Experiments that Delineate Process Capability

Explore Digitally – Confirm Physically

Model Predictions - Experimentally
Of Defect Occurrences
Inspection

Use ICME to understand processing effects & sensitivity due to scale up in size, manufacturing volume, and component complexity
TODAY: Fully Integrate Manufacturing with Design & Risk Analyses

- **Data Informatics/Analytics**
  - Empirical/data-driven modeling
  - e.g. ICME, statistical process modeling, etc.

- **Material/Process Modeling and Simulation**
  - Advanced physics-driven modeling
  - e.g. ICME, FEA, CFD, etc.

- **Intelligent Process Monitoring/Control**
  - Linking math/physics models to process control
  - e.g. process monitoring parameters as model input

- **Integrated Quality Testing**
  - Inform modeling & simulation with quality test results
  - e.g. calibrating process models & process control
TOMORROW: Link Materials & Manufacturing to Fleet Management

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- **Quantifying & Understanding Manufacturing Variability**
- **Performance-based Decision Making in Manufacturing**
- **State Awareness & Prediction for Each Tail Number in the Fleet**

**ICME** = Integrated Computational Materials & Manufacturing Engineering

**FEA** = Finite Element Analysis; **CFD** = Computational Fluid Dynamics

**TOMORROW: Link Materials & Manufacturing to Fleet Management**

**State Awareness & Prediction for Each Tail Number in the Fleet**
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Takeaways

• The Building Block Approach doesn’t work well for new M&P
  – Surprises happen too frequently
  – We’re leaving too much information on the table

• Link Mfg to Design - it’s much more than Design for Mfg!
  – Fully exploit the emerging capabilities of ICME models

• Change the testing paradigm to better elucidate minima
  – *Design validation tests that accurately estimate the relevant physics of the full-size article*

• Change the value proposition for manufacturing!
  – Quantify the impact of manufacturing variability on system capability
  – Reduced Design Iterations = $$$$$$$ in cost savings

• It’s not the model, it’s the decision you make using the model results!