Computational Modeling of Complex Systems using "Digital Twin" and "Digital Thread" Frameworks

October 29, 2015

Sanjeev Kulkarni, Animesh Dey, Robert Tryon

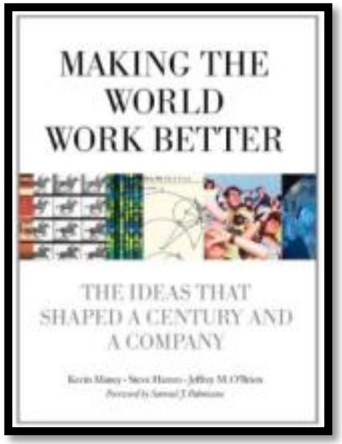
VEXTEC

Who is VEXTEC?

- **Founded in 2000**: Over $25 million from the United States Department of Defense Innovative Research programs for Technology Development
- **Proprietary Software and Seven Patents:** Virtual Life Management® (VLM®) generates VIRTUAL TWIN®
- **Customers**: Federal Government and Industries (Aerospace, Automotive, Electronics, Energy, Medical Devices)
- **Value Proposition**: Help companies improve products and reduce cost
  - New products to market quickly
  - Improve reliability of existing products
  - Reduce physical and prototype testing requirements
  - Forecast product durability and manage product life cycle risk
- **Business Model**: Hybrid – Consulting Services, Software Licensing and Training

United States Patent and Trademark Office · Department of Commerce

Official Selection · Forbes.com · America's Most Promising Companies 2009



WIRED

machine design

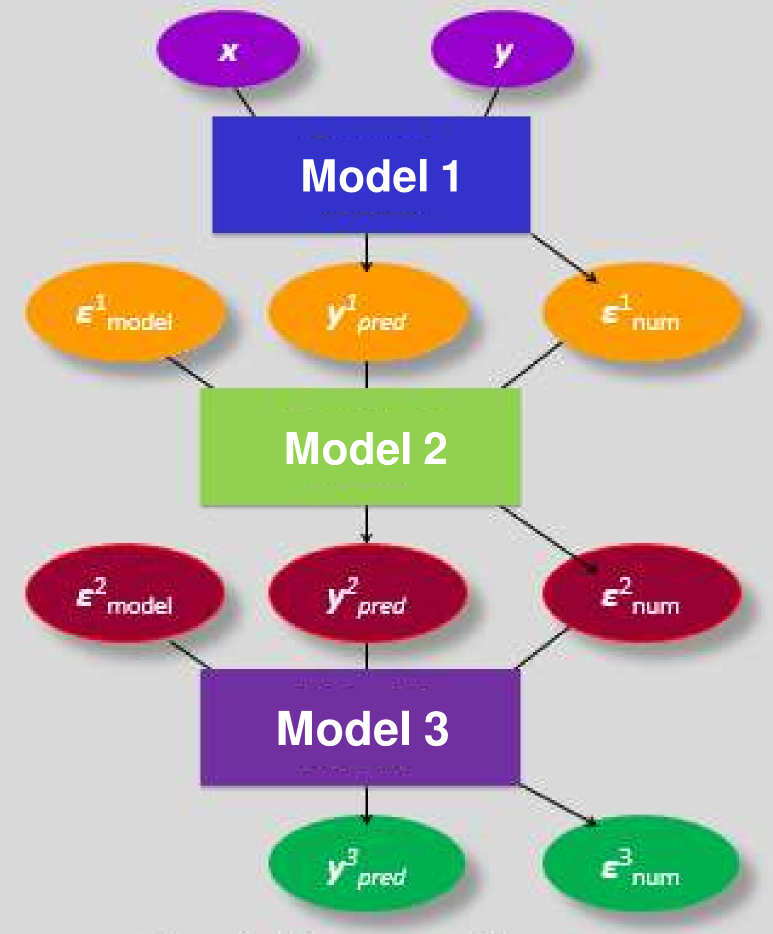
GEARSolutions

VEXTEC accepted into FDA's Medical Device Development Tool (MDDT) pilot Program

Uncertainty Management

Virtual Twin® representation of Uncertainty Propagation across multiple levels of a system

- A probabilistic multi-disciplinary uncertainty management analytical tool that links computational models
  - How will changing the input uncertainty of the analysis impact the uncertainty in the results?
  - Can the uncertainty be updated based on actual usage and observed damage state?
  - What is the sensitivity to uncertainty?

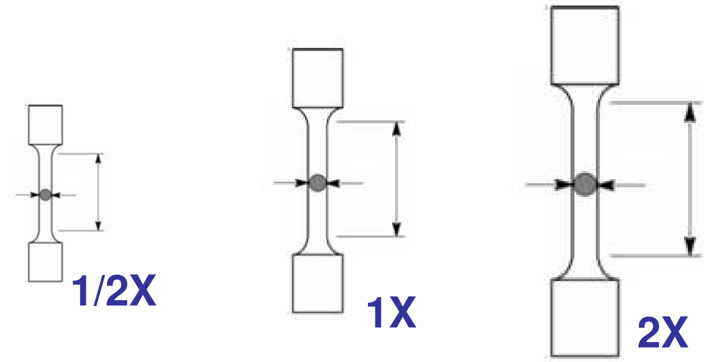


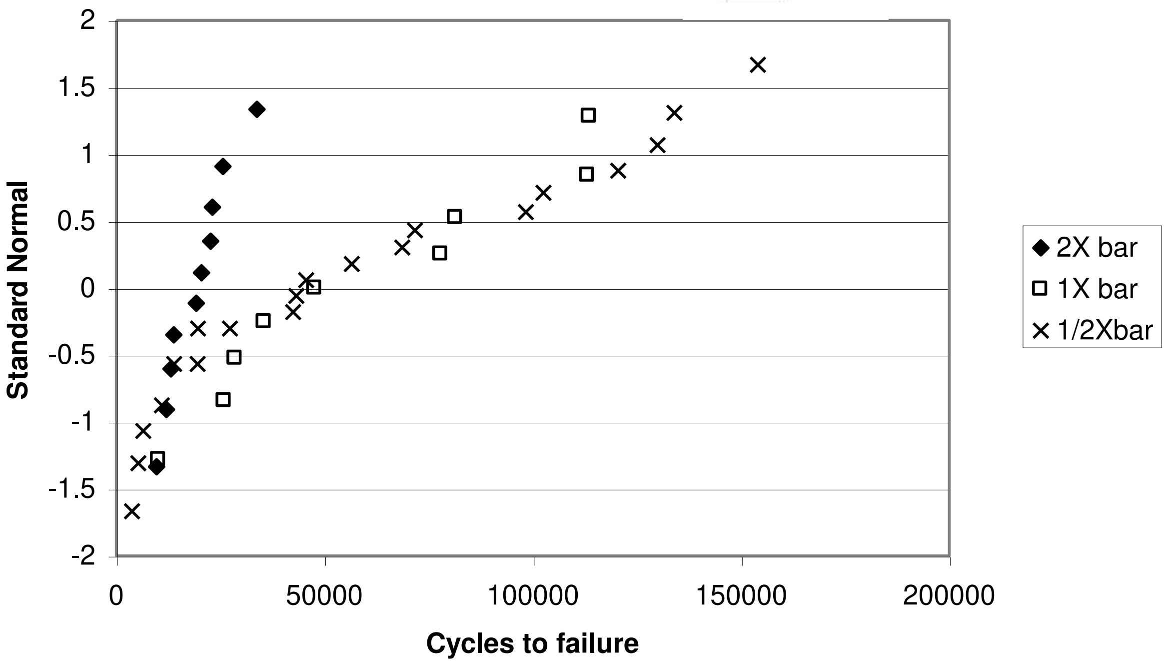
Uncertainty propagation across multiple levels in the Virtual Twin®

Fatigue Strength is not a Material Property

- **<u>Fatigue strength</u>** is governed by
  - Material
  - Processing
  - Surface Roughness
  - Temperature
  - Environment
  - Loading
  - **<u>AND Geometry</u>**

- Fatigue Strength of **<u>Simple Test Specimens</u>** has little correlation to the Fatigue Strength of **<u>Actual Hardware</u>**.

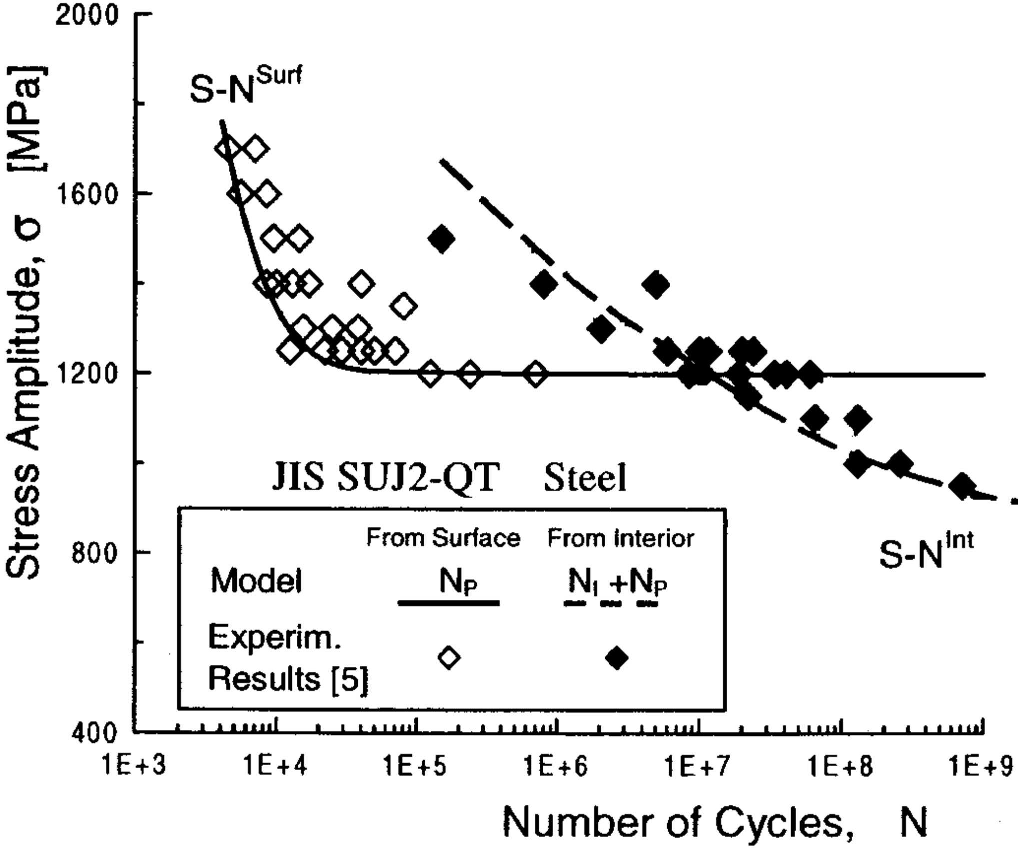




Laboratory fatigue test at the same stress for 3 different sizes of smooth round bar nickel specimens with ½, 1 and 2 times surface area.

Infinite Life? – Not Quite!

- Testing at 1E7 Cycles provides false assurance of a fatigue limit – Surface crack
- Testing beyond 1E7 Cycles shows no fatigue limit – Interior / Inclusion Initiated
- Testing to determine this behavior is prohibitively expensive
  - Testing to full life is very expensive
  - Testing production hardware is very expensive
  - Testing many samples is very expensive
- Computational models allow simulation of test protocols for risk assessment



Chapetta et al. (2003), "Ultra-long cycle fatigue of high-strength carbon steels," Mat Sci Engng, A356, 227-235

Dassault Systèmes and Digital Twin

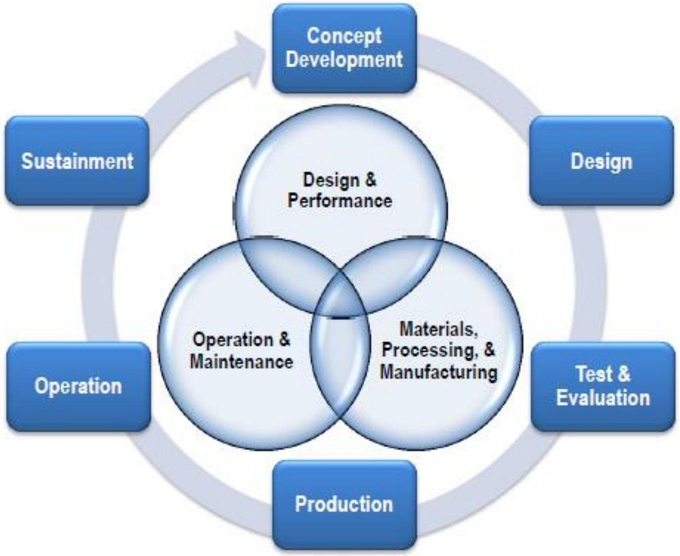
Desktop Engineering
http://www.deskeng.com/

Bernard Charlès at the SIMULIA Community Conference this year,

"Digital twins are not the visualization of the real thing, it means that you can innovate on things more than you could actually do on the physical products themselves. The digital twin is something that's going to revolutionize and transform the entire economy. It's much more than modeling, visualization and simulation."

Digital Thread and Digital Twin

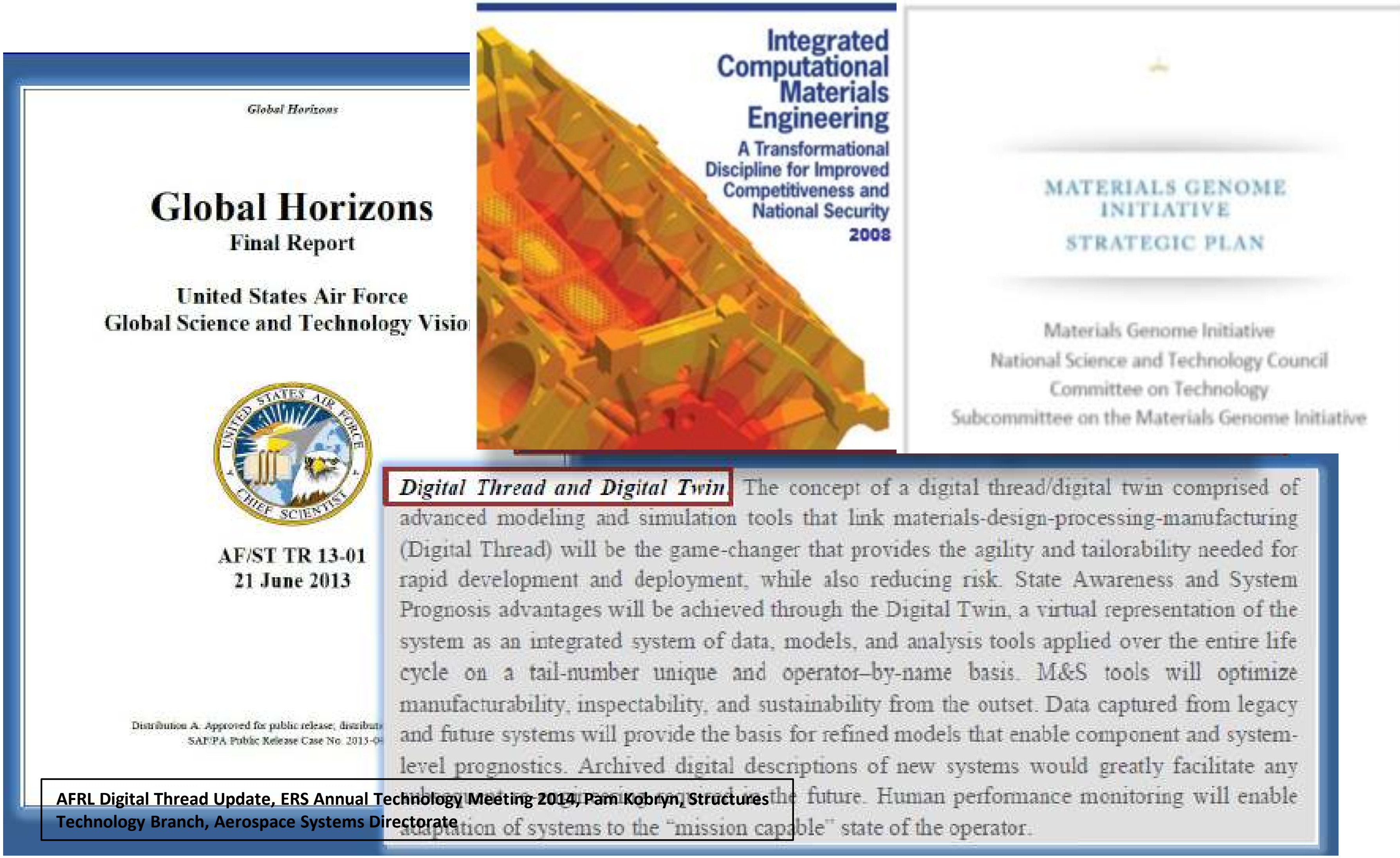
- ***Digital Thread*** –
  - Advanced modeling and simulation tools that link materials, design, processing, and manufacturing information
  - Provide the agility and tailorability needed for rapid development and deployment, while also reducing risk.
- ***Digital Twin*** -
  - Virtual representation of the System – integration of data, models, and analysis tools applied over the entire life cycle on an unique tail-number.
  - Modeling and simulation tools will optimize manufacturability, inspectability, and sustainability from the outset.
  - Data captured from legacy and future systems to refine and update models that enable component and system-level prognostics.



AFRL Digital Thread Update, ERS Annual Technology Meeting 2014, Pam Kobryn, Structures Technology Branch, Aerospace Systems Directorate

VEXTEC

Digital Thread and Digital Twin


Global Horizons

Global Horizons
Final Report

United States Air Force
Global Science and Technology Visio

AF/ST TR 13-01
21 June 2013

Distribution A. Approved for public release; distributi
SAF/PA Public Release Case No. 2013-0

Integrated Computational Materials Engineering
A Transformational Discipline for Improved Competitiveness and National Security
2008

MATERIALS GENOME INITIATIVE
STRATEGIC PLAN

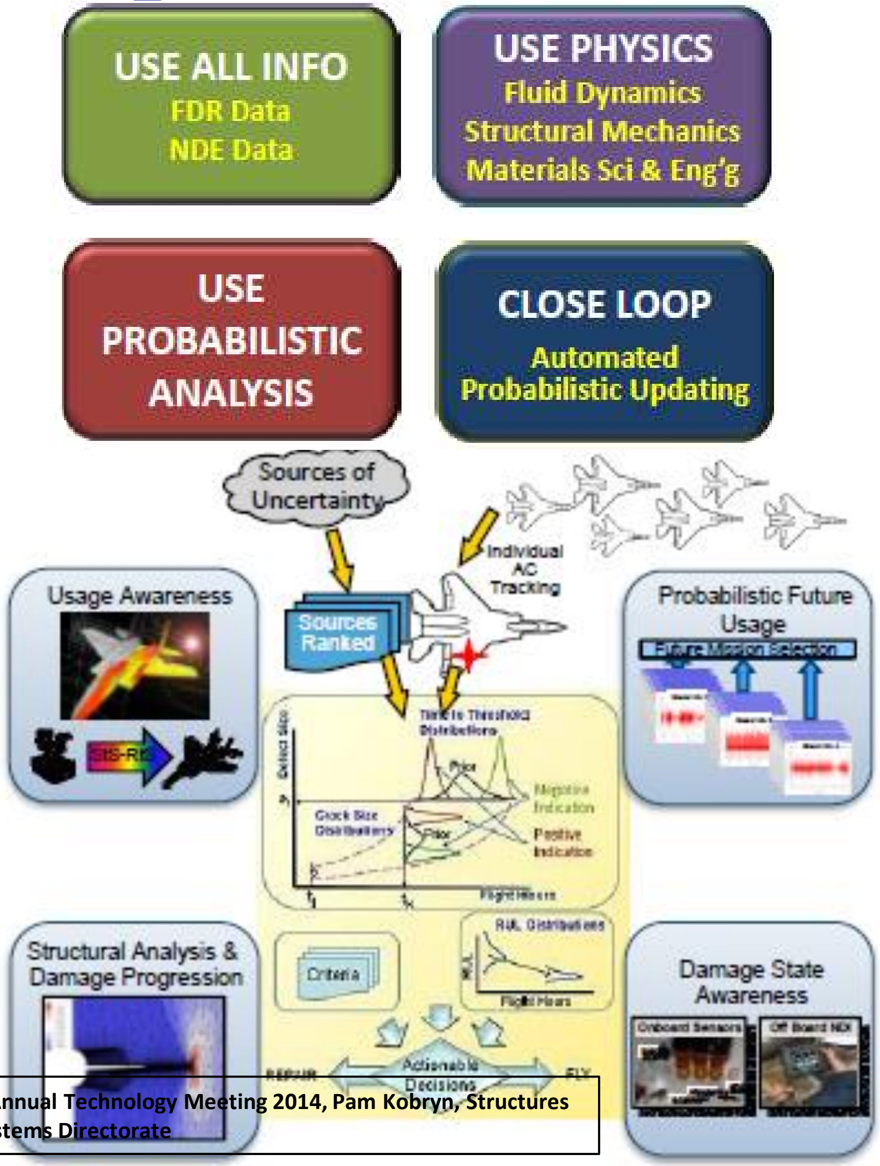
Materials Genome Initiative
National Science and Technology Council
Committee on Technology
Subcommittee on the Materials Genome Initiative

Digital Thread and Digital Twin. The concept of a digital thread/digital twin comprised of advanced modeling and simulation tools that link materials-design-processing-manufacturing (Digital Thread) will be the game-changer that provides the agility and tailorability needed for rapid development and deployment, while also reducing risk. State Awareness and System Prognosis advantages will be achieved through the Digital Twin, a virtual representation of the system as an integrated system of data, models, and analysis tools applied over the entire life cycle on a tail-number unique and operator–by-name basis. M&S tools will optimize manufacturability, inspectability, and sustainability from the outset. Data captured from legacy and future systems will provide the basis for refined models that enable component and system-level prognostics. Archived digital descriptions of new systems would greatly facilitate any subsequent re-engineering required in the future. Human performance monitoring will enable adaptation of systems to the "mission capable" state of the operator.

AFRL Digital Thread Update, ERS Annual Technology Meeting 2014, Pam Kobryn, Structures Technology Branch, Aerospace Systems Directorate

Digital Thread and Digital Twin

- Use <u>ALL AVAILABLE INFORMATION</u> in analyses
- Use <u>PHYSICS</u> to inform analyses
- Use <u>PROBABILISTIC METHODS</u> to quantify program risks
- <u>CLOSE THE LOOP</u> from the beginning to the end and back to the beginning of the lifecycle



AFRL Digital Thread Update, ERS Annual Technology Meeting 2014, Pam Kobryn, Structures Technology Branch, Aerospace Systems Directorate

Digital Thread and Digital Twin

Virtual Twin® of a Component/System/Assembly with Cyclic Loading – Estimate fatigue life subject to

- Sensitivity of uncertainty in input variables and
- Sensitivity of modeling approximations .

Flow of the design analysis:

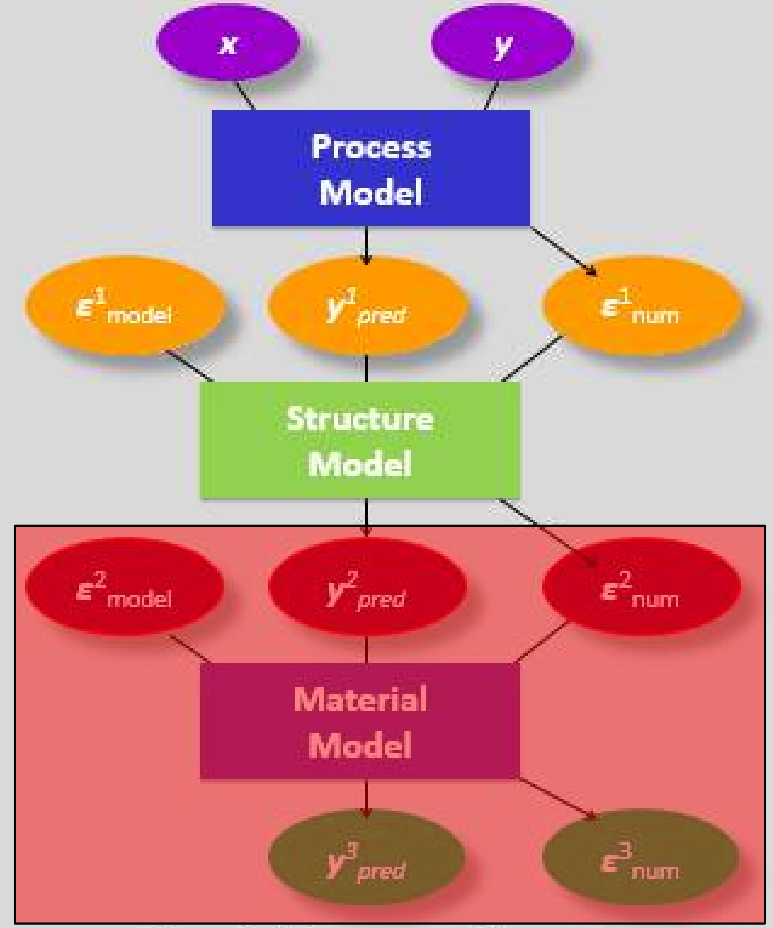
- Manufacturing process model provides residual stress
- Structural analysis provides stresses model
- Microstructural material model predicts fatigue

Sources of uncertainty:

- Manufacturing process uncertainty
- Predicted residual stress uncertainty
- Structural geometry uncertainty
- Loads and boundary conditions uncertainty
- FEA mesh size uncertainty
- Material microstructure uncertainty

Cumulative Probability Distribution Function (CDF):

- Cycles to failure considering all uncertainties vs. actual test results
- Fatigue durability results for a large population and at the fleet level.
- Simulations performed at and correlated and calibrated to values of manufacturing process output such as residual stress

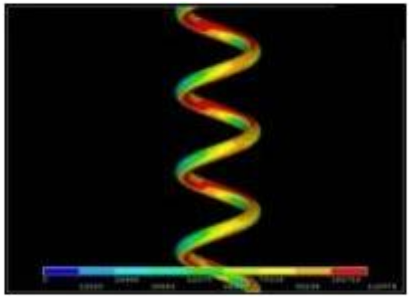


Uncertainty propagation across multiple levels in the Virtual Twin®

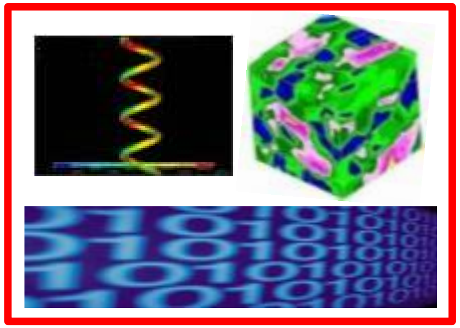
Digital Twin - VLM Integrates with FEA

Standard Industry Analysis

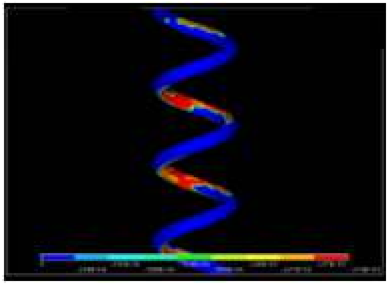
Design & Stress



VLM Analysis

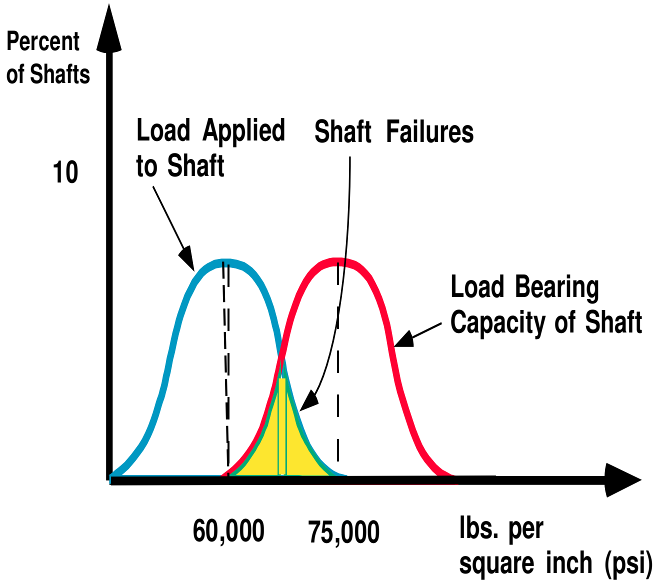


Life & Where & Why



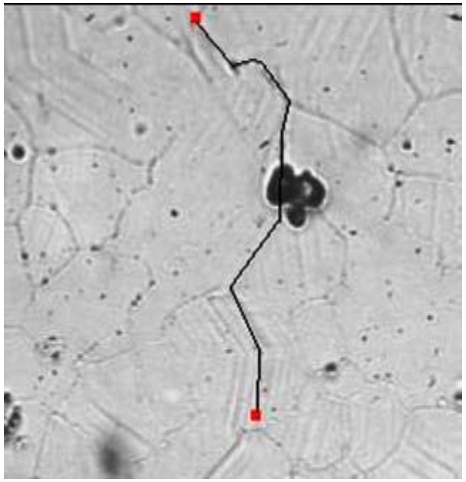
Digital Twin - How the VLM Process Compares with Conventional Methods?

VLM approach predicts failures



Fatigue strength is traditionally determined by testing

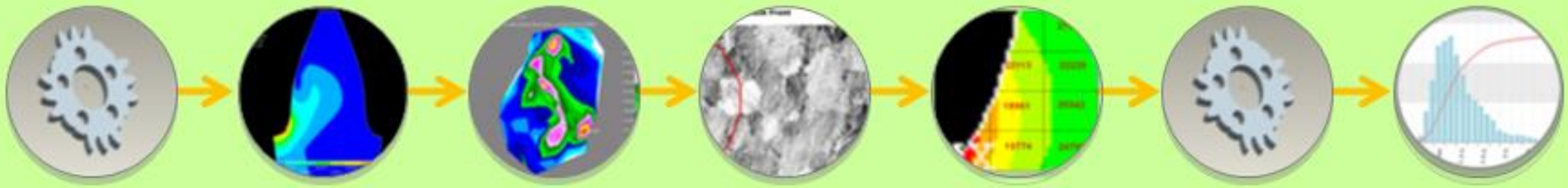
Conventional view of component



VEXTEC's view of component, grains & damage

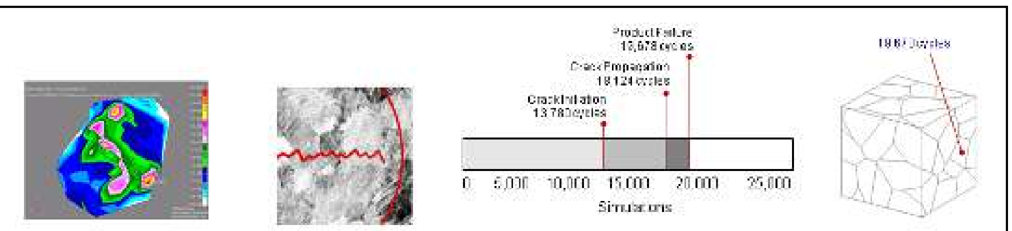
VEXTEC

Digital Twin Grain – FEA – Component – Fleet

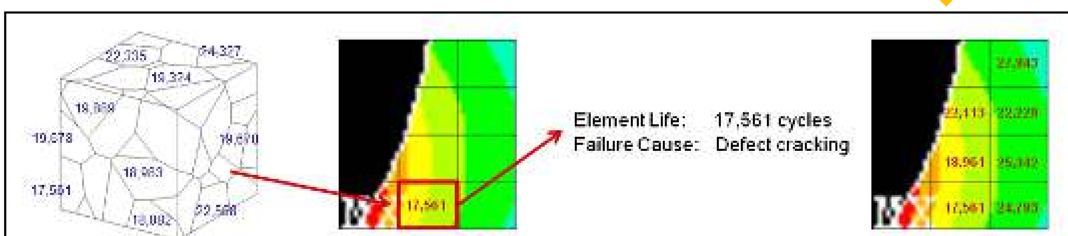


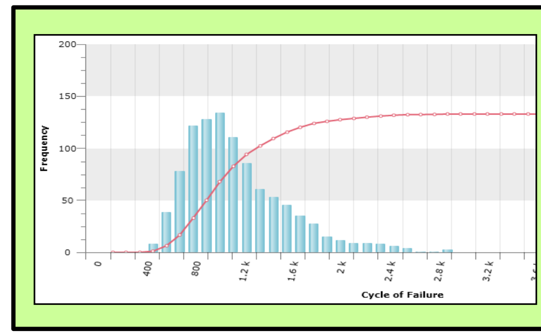
Component | Design Configuration | Material Configuration | VLM Computational Processing | Mapping the Elements | Component Simulation | Fleet Simulation

Sequential Multi-Physics Damage



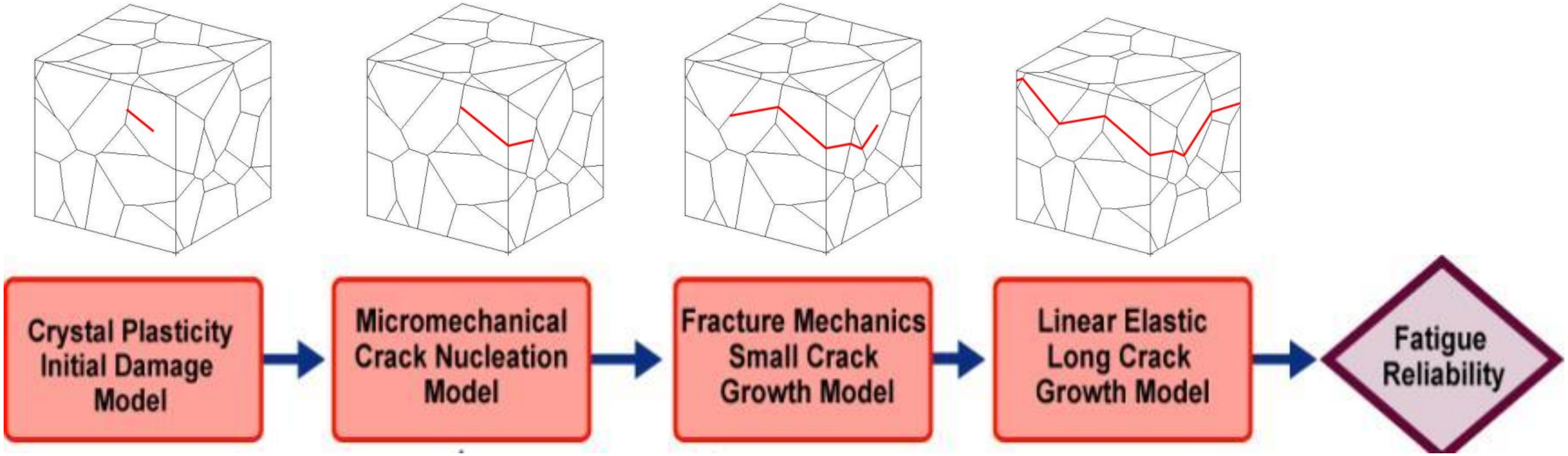
Life at Each Grain for All Elements





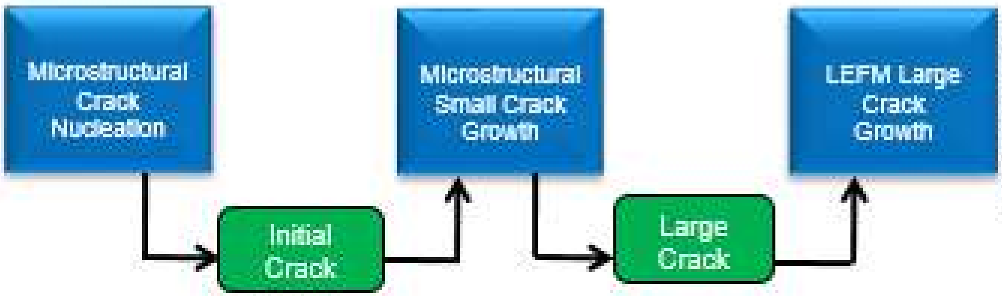
Life for All Devices in The Population

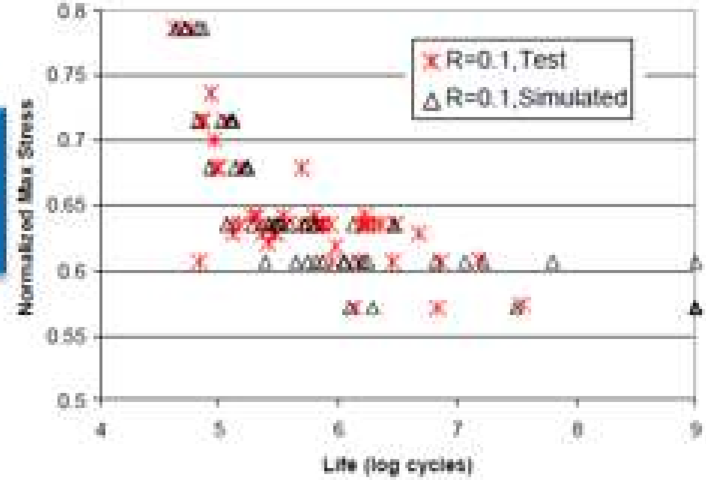
Digital Twin – Damage Initiation through Accumulation

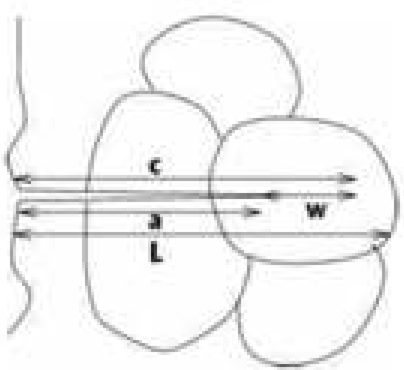


- The physics governing damage process changes as the damage accumulates
- Mathematical models (equations) exist to describe the physics at each stage
- VLM contains a library of damage models and stage transition rules that are applied as appropriate to the materials being simulated

Digital Twin – Damage Initiation through Accumulation to Failure



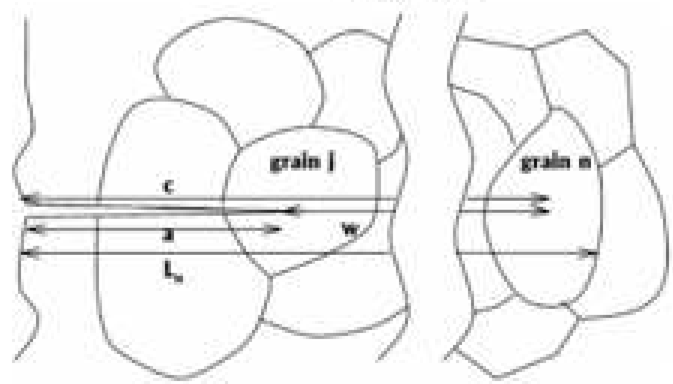




$$\phi_s = \frac{\beta\tau}{\pi A}\sqrt{c^2-a^2} + \frac{2k_s a}{\pi^2 A}\ln\frac{c}{a} + \sum_{m=j+1}^{n}\frac{(\tau_{m-1}-k_{m-1})-(\tau_m-k_m)}{\pi^2 A}g(a,c,L_{m-1})$$

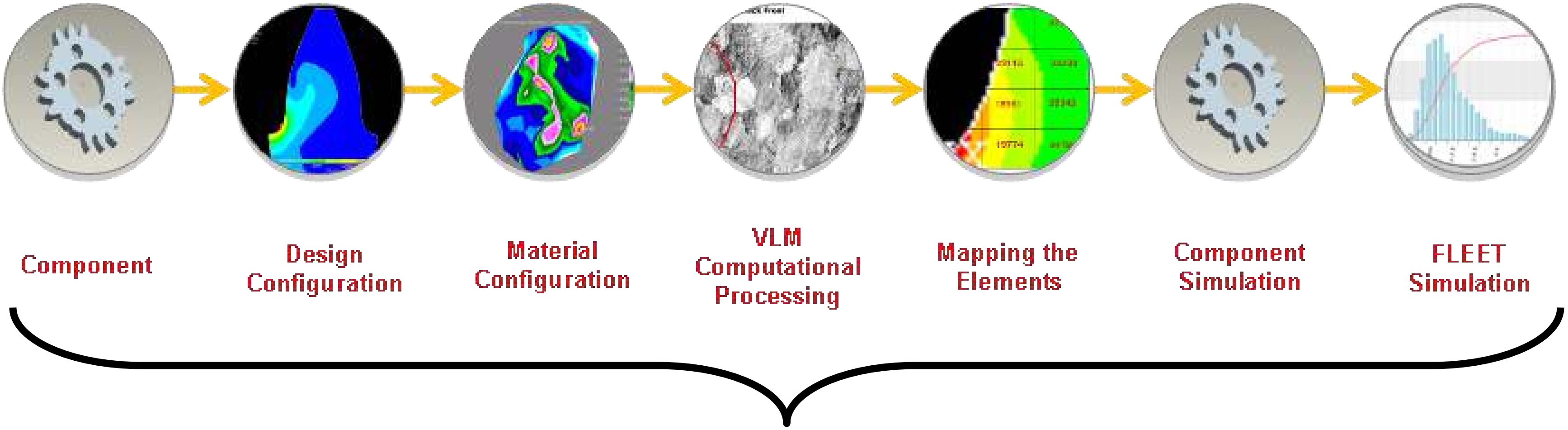
$$\beta = 1-\frac{2k_j}{\pi\tau_j}\arccos\frac{a}{c} - \sum_{m=j+1}^{n}\frac{2((\tau_{m-1}-k_{m-1})-(\tau_m-k_m))}{\pi\tau_j}\arccos\left(\frac{L_{m-1}}{c}\right)$$

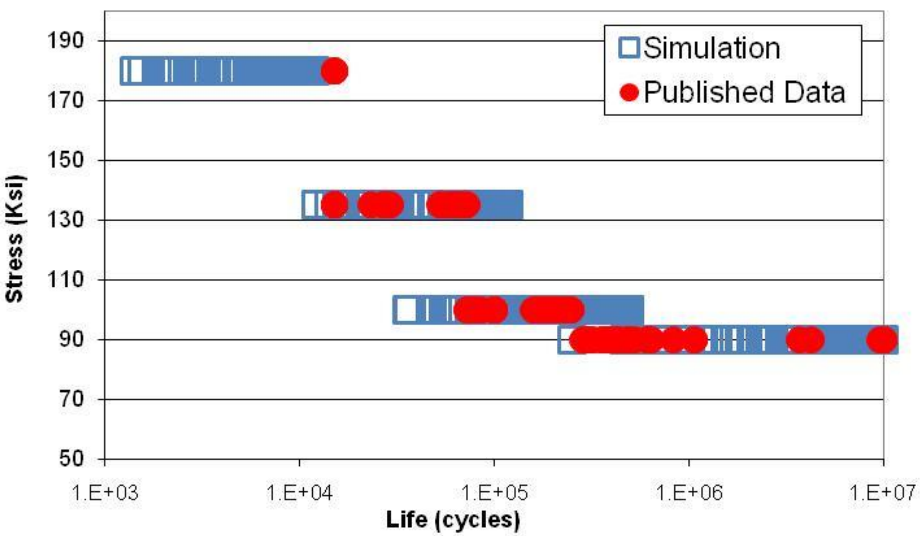
$$K_m = \beta\tau\sqrt{\pi c}$$

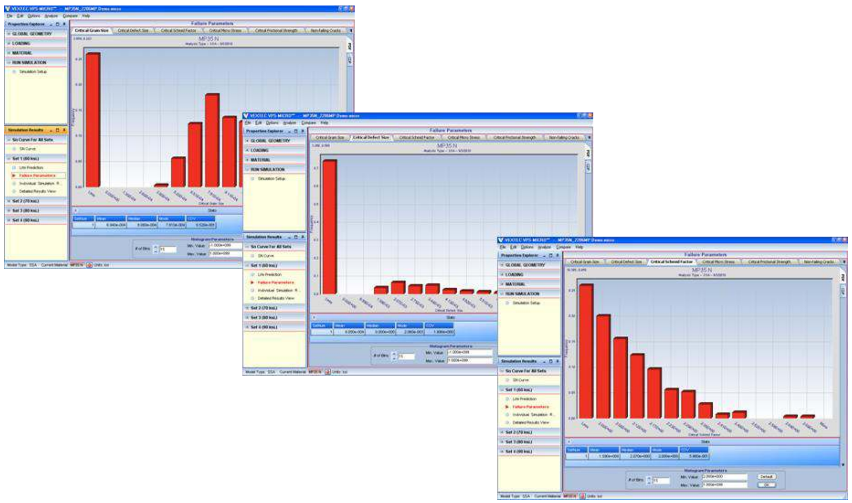


Tanaka, K., Mura, T., (1981) "A dislocation model for fatigue crack initiation." *ASME J. Appl. Mech.* Vol. 48, 97-103
Tryon, R. G., Cruse, T. A., (1997) "Probabilistic mesomechanical fatigue crack nucleation model," J. Engr. Mater. Tech., Vol. 119, pp. 65-70.
Tryon, R. G., Dey, A., (2001) "Reliability-Based Computational Model for Material Development and Structural Design," International Journal of Materials and Product Technology, Vol. 16, No. 4/5, pp. 333- 357

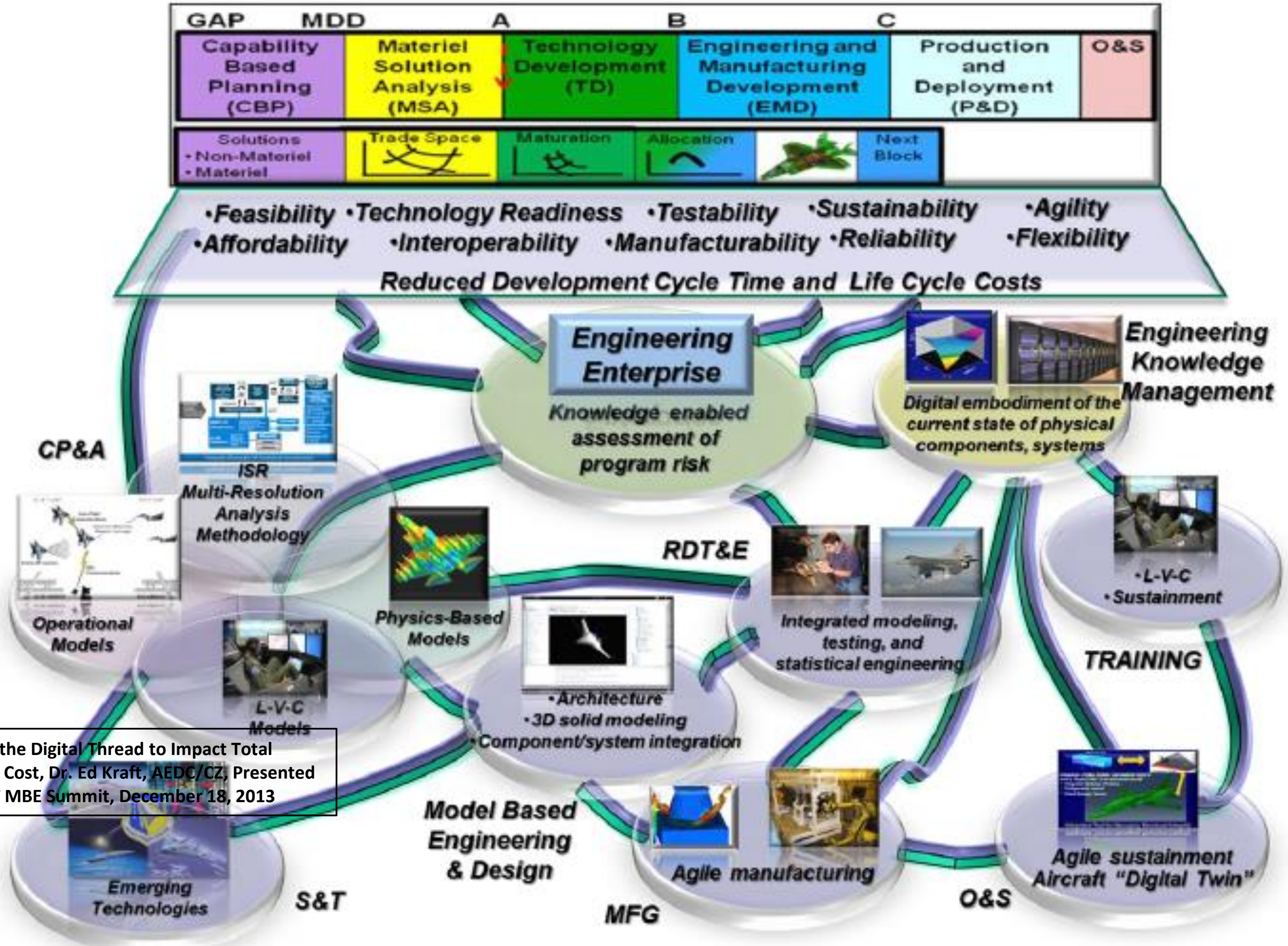
Digital Twin – Damage Initiation through Accumulation to Failure







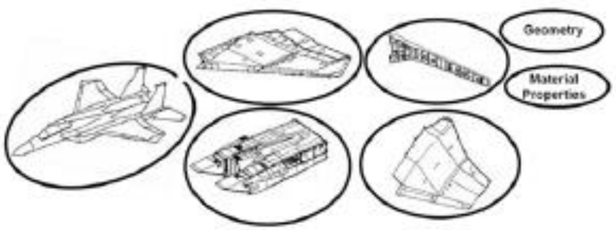
Example – Air Force – Digital Thread



Expanding the Digital Thread to Impact Total Ownership Cost, Dr. Ed Kraft, AEDC/CZ, Presented to the NIST MBE Summit, December 18, 2013

Example – Air Force – Digital Twin

Configuration Control

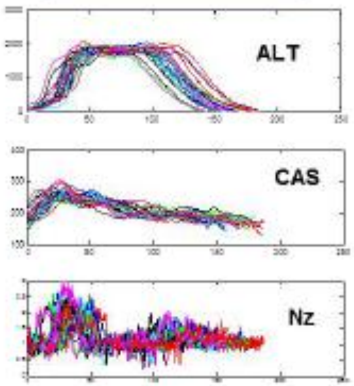


Inspections

Fleet & Tail # Lifecycle Management

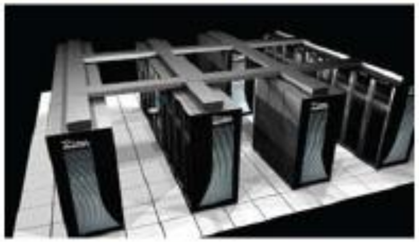
Expanding the Digital Thread to Impact Total Ownership Cost, Dr. Ed Kraft, AEDC/CZ, Presented to the NIST MBE Summit, December 18, 2013

Usage



Models

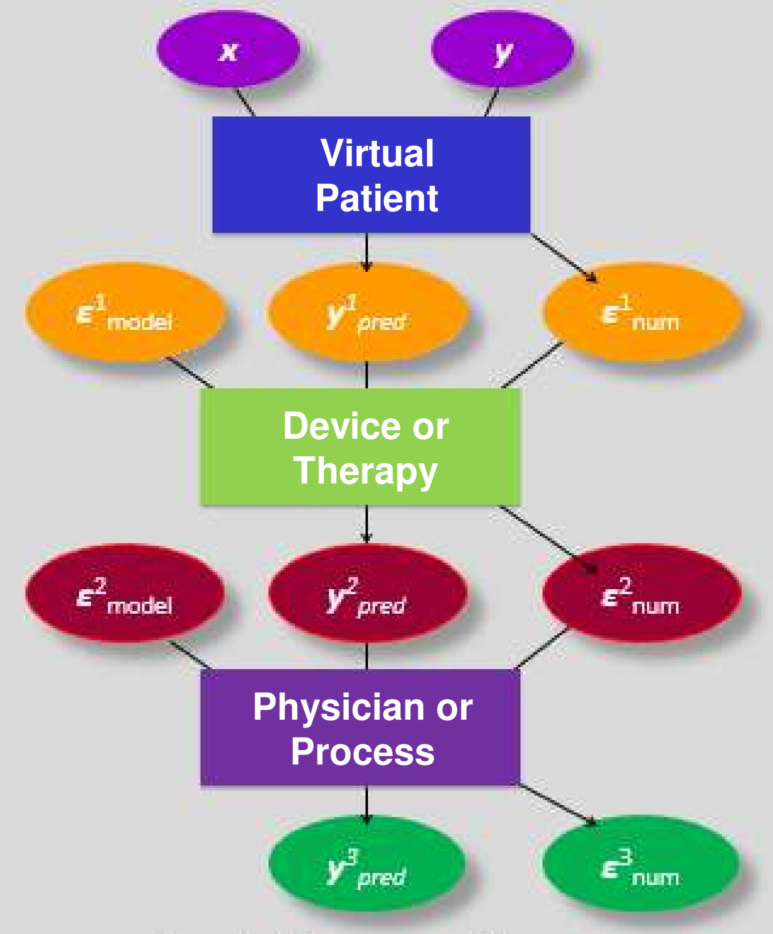
Computation / Data



Materials State Awareness

Example – Medical – Cardiac Leads

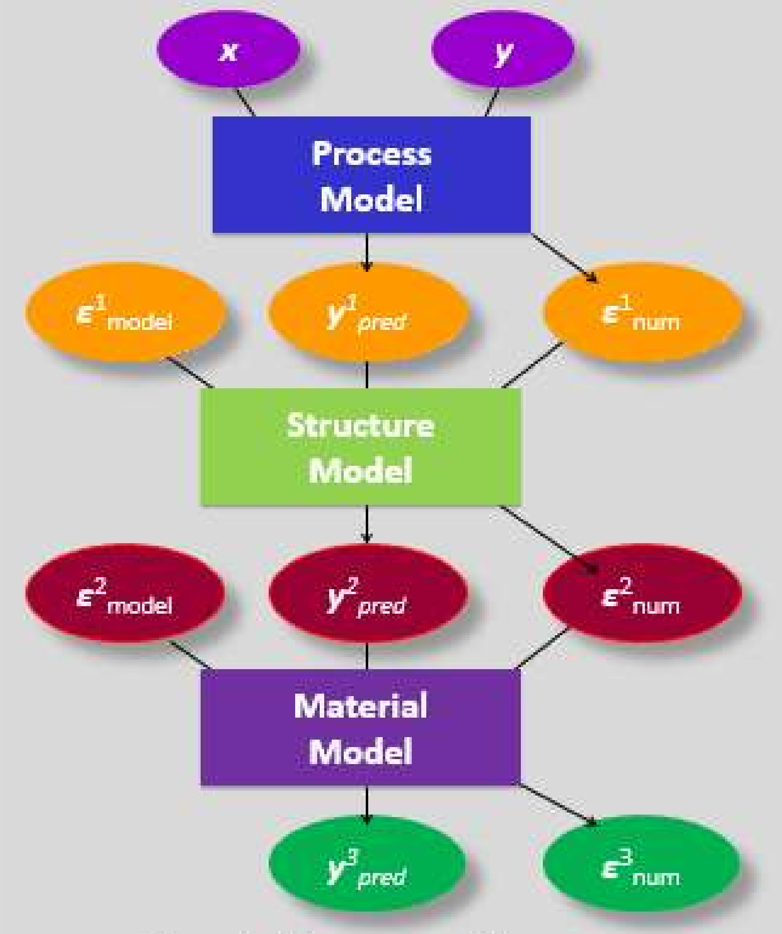
- Virtual Patient –
  - a narrowly defined parameter within an organ system (for Endoscopy – a detailed definition of Airways – sizes, shapes, textures)
  - an organ – such as the Heart (Living Heart Project)
  - or more (a system such as Cardio-vascular or Musculo-skeletal)
- Therapy/Device – thermal processing of the airway, a stent or hip joint
- Physician – ratings of physicians for a procedure
- Outcome – could be specifically defined in terms of efficacy and safety



Uncertainty propagation across multiple levels in the Virtual Twin®

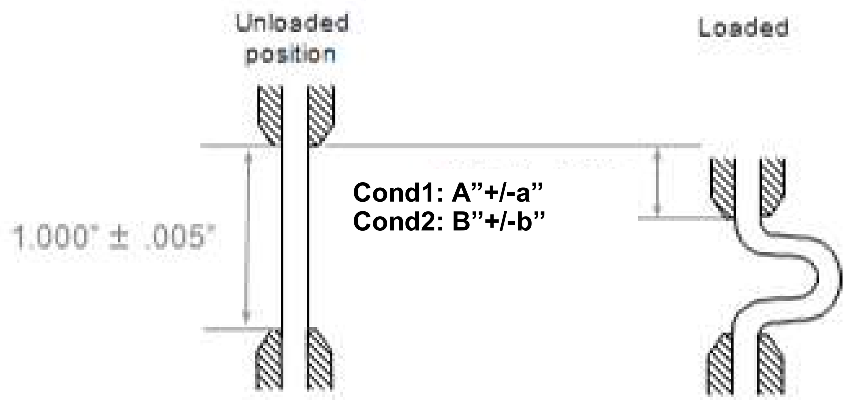
Example – Medical – Cardiac Leads

- Digital Thread – An Ecosystem that enables a Data Driven, Physics and Probabilistics Model possible that includes the above ingredients. With insights generated include Prediction of Performance for a broad population, Risk of Recall, ….and with the ability to update the model when more data is available
- Digital Twin – A Patient Specific model with a particular traceable device ID and procedure. That is tracked as a digital replicate including additional procedures, quality control and such.

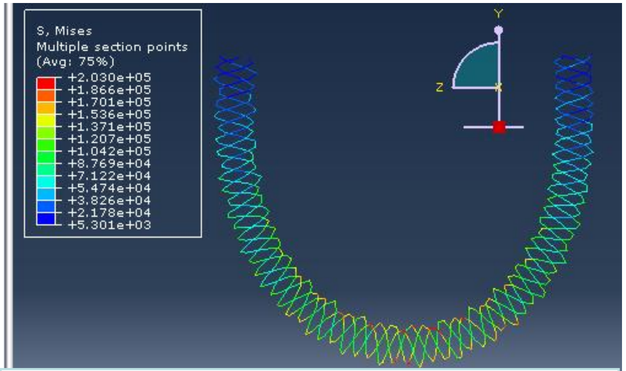


Uncertainty propagation across multiple levels in the Virtual Twin®

Example – Medical – Cardiac Leads

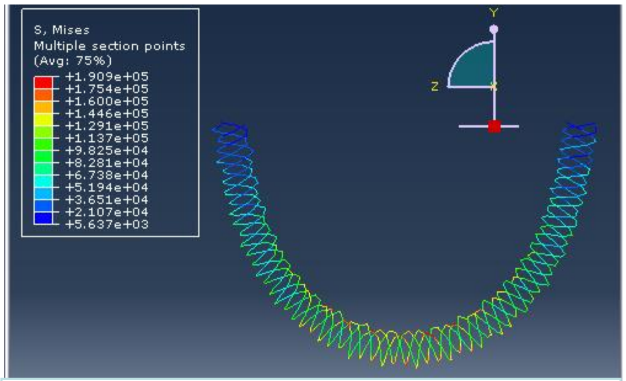


Schematic of the test condition. The gauge length of lead body between the grips is 1 in. ± .005 in.



Condition 1: A" Von Mises Stress; Max Stress=XX ksi

Deformed Var: U Deformation Scale Factor: +1.000e+00

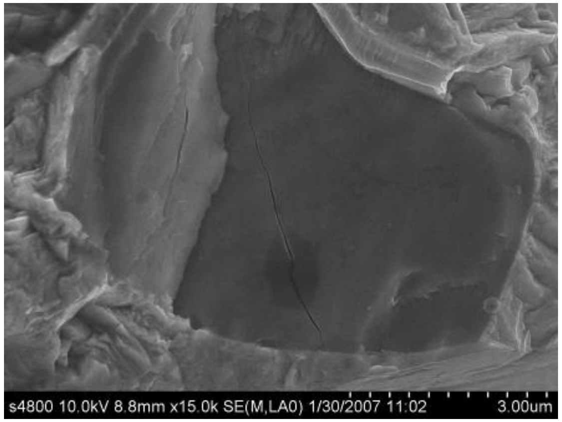


Condition 2: B" Von Mises Stress; Max Stress=YY ksi

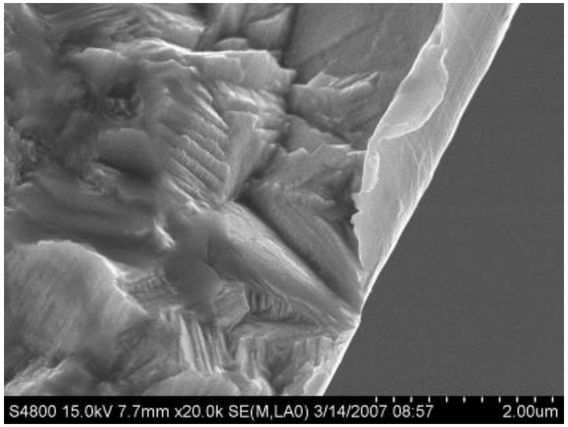
- **Simulation of two test conditions – Displacements A" and B"**
- **Cycling between maximum displacement and 0 displacement**
- **Cycling to 1E10 cycles and Runout (suspension) if no failure**
- **Measured difference in maximum Von-Mises stress between Conditions 1 and 2**

Example – Medical – Cardiac Leads

Nucleation

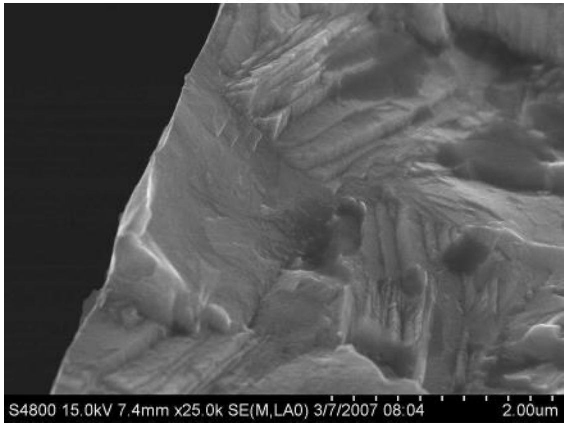


Near-initiation, cracked TiN particle

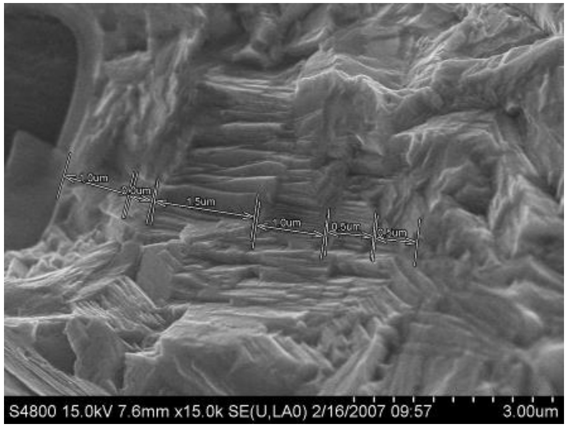


Chevron crack-initiating feature

Small Crack Growth



Crack front arrest at microstructural features.



Striation spacing at crack front

J. E. Schaffer: Masters Thesis, Purdue, 2007

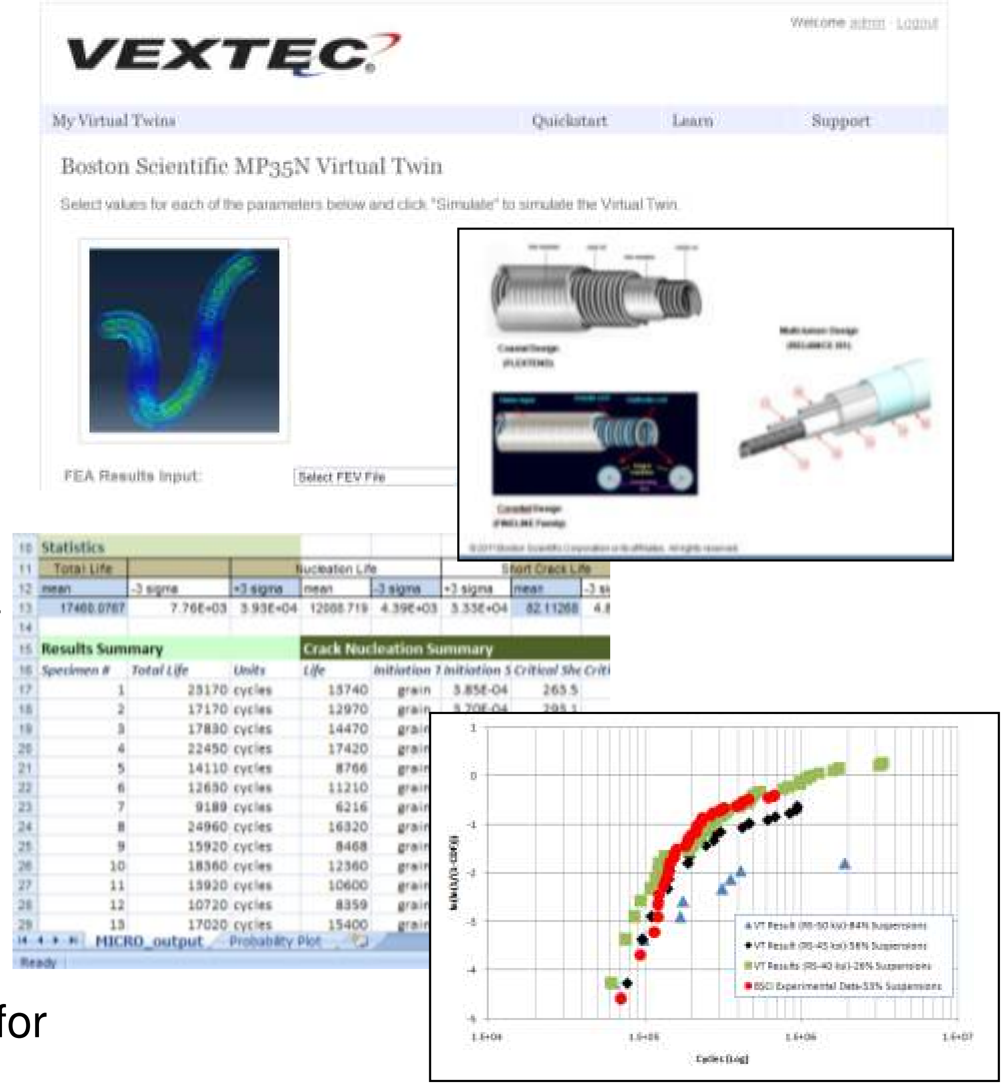
Cardiac Leads: Summary and Outcomes

Summary

- Simulated fatigue buckling test under 2 load conditions
- Virtual DOE consisted of 9600 individual coil simulations

Outcomes / Next Steps

- Sensitivity study around particle size, density and residual stress
- Determined residual stress to be a calibrated value - new knowledge
- Developed Insights - Design alternatives, Material substitution, Vendor management
- Potential - Sensitivity analysis, Design trade studies, Supplier controls, Design optimization
- Add Realism – Coiling Simulation for Residual Stresses

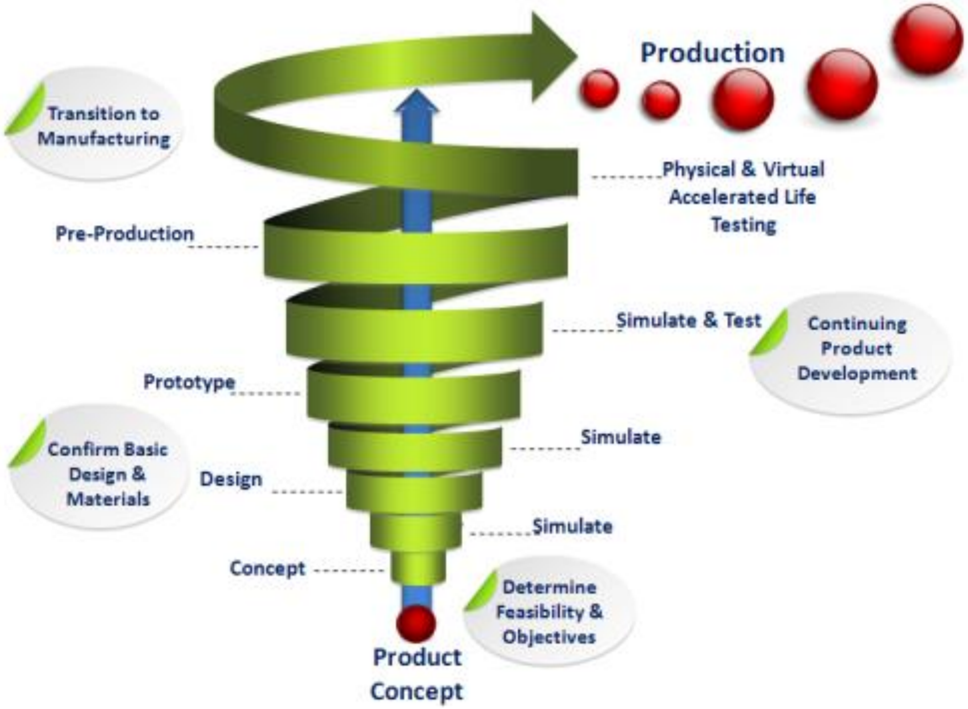


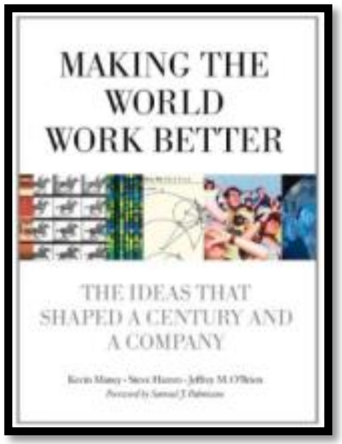
VDOE Results for Residual Stres

Summary

- <u>Digital Thread</u>: a digital surrogate of a system allowing dynamic, real-time assessment of the system's current and future capabilities to inform decisions
- This digital surrogate is a physics-based eco-system resulting from the generation, management, and application of pedigreed data, models, and information across the system's life cycle.
- <u>Digital Twin</u>: application of the Digital Thread to an unique tail number (aerospace / defense) or a specific patient (medical / health care)
- VEXTEC's VLM technology aligns based on the physics based microstructural material representation as well as the probabilistic modeling to capture uncertainties and evaluate risk.
- Examples in Aerospace/Defense and Medical/ Health Care presented.

Thank you





VLM software is applicable throughout a product's life cycle, constantly growing in capability and value