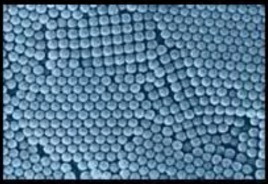
Advanced Composite* Material Modeling and Multi-Scale Progressive Failure Analysis

"Calibrate, Validate, Predict"




* Polymer/Ceramics/Metal Matrix and
Macro/Hybrid (Glare) Matrix Composites

AlphaSTAR
5150 East Pacific Coast Highway, #650, Long Beach, CA 90804 USA
Telephone: (562) 961-7827
www.alphastarcorp.com

Founded & Located

- *1989*
- *Long Beach, Headquarters*
- *Rome, Italy, European Union*

Mission

- **Provide** physics based material modeling simulation solutions
- **Service** industry for advanced composite parts/systems

Focus

- **Structural design using advanced simulation for Composites, Metals, Ceramics, Polymers, and Hybrid**

Industry Validated Software

Aerospace

- **Commercial Aircraft, Certification by Analysis with Reduced Tests, Durability and Damage Tolerance, Active/Passive Structural Health Monitoring**

Automotive

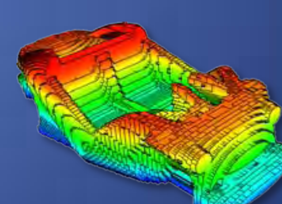
- **Racing Industry, Crush/Crash Analysis, Light-weighting, COPV, Fatigue/Residual Life**

Infrastructure

- **Bridge, Tunnel, Wind , Oil & Gas, Nuclear Power Plants, Power Engineering, Turbines**

Manufacturing

- **Additive/3D-Printing (thermoplastic, thermoset, powder metal), Injection Molding, Compression Molding, RTM/VRTM, Filament Winding, Automated Tape Layup, Sheet Molding Compound, Autoclave, Out-of-Autoclave**



Awards & Publications

- **2015 R&D 100, 2004 NASA CAIB; 2001 US Senate (SBA); 2000 R&D 100; 2000 NASA Turning Goals Into Reality; 1999 NASA Software of the Year; NASA Best of the 1990's;**
- **230+ published papers and 5 Books**

R&D 100
54 Years of Invention

What Sets Us Apart

Material Modeling

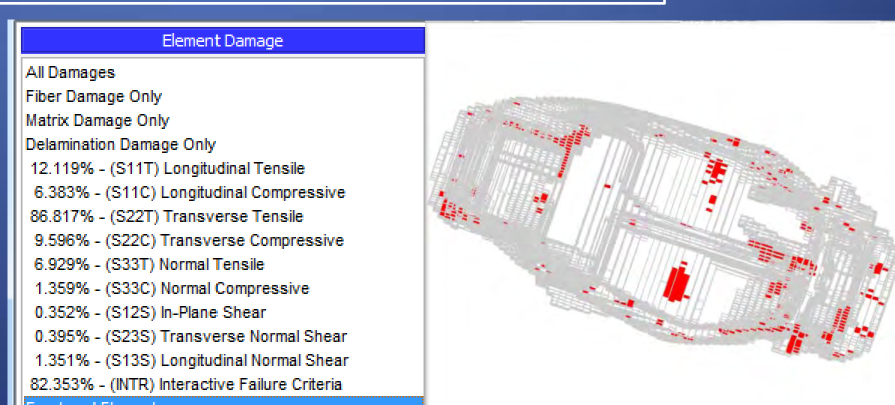
- Considers the Effect of Defects
- Accounts for Architecture, Manufacturing Anomalies
- Reverse Engineers in-situ fiber and matrix properties
- Simulates coupon tests to calibrate and validate laminate behavior
- Generates A- and B- Basis Allowables
- Identifies Non-Linearity and Failure Mechanisms
- Applicable to Continuous Fiber, Chopped Fiber, SMC
- Supports Polymer Matrix, Ceramic Matrix, Metal Matrix, Hybrid (Glare) Composites
- Validated Material Database

Multi-Scale Progressive Failure Analysis:

- Augments Existing FE Solver
- Closed Form Analytical Solutions with Low Computational Overhead
- Identifies Damage/Fracture Evolution
- Tells When, Where, Why & How composites fail, including percentage contribution
- Supports Injection & Compression Molding, Filament Winding, Autoclave, RTM, VARTM
- Supports Static, Impact (Crush/Crash) and Fatigue Load Cases

Experience:

- 25 Years in Business
- Subject Matter Experts
  - Material Science/De-Homogenized Material Modeling,
  - De-homogenized Multi-Scale Progressive Failure Analysis
  - High Performance Computing
  - Durability and Damage Tolerance
- Hundreds of Unique Peer Reviewed Journal Articles & Research Pubs



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Products and Product Brochures

Material Modeling

- MCQ Composites
- MCQ Chopped
- MCQ Ceramics
- MCQ Metals

Structural Analysis

- GENOA
- GENOA3D – Thermoplastics
- GENOA3D – Thermoset
- GENOA3D – Metal Powder

MCQ Composites Tested and Verified.™

3D PRINTING

GENOA Tested and Verified.™

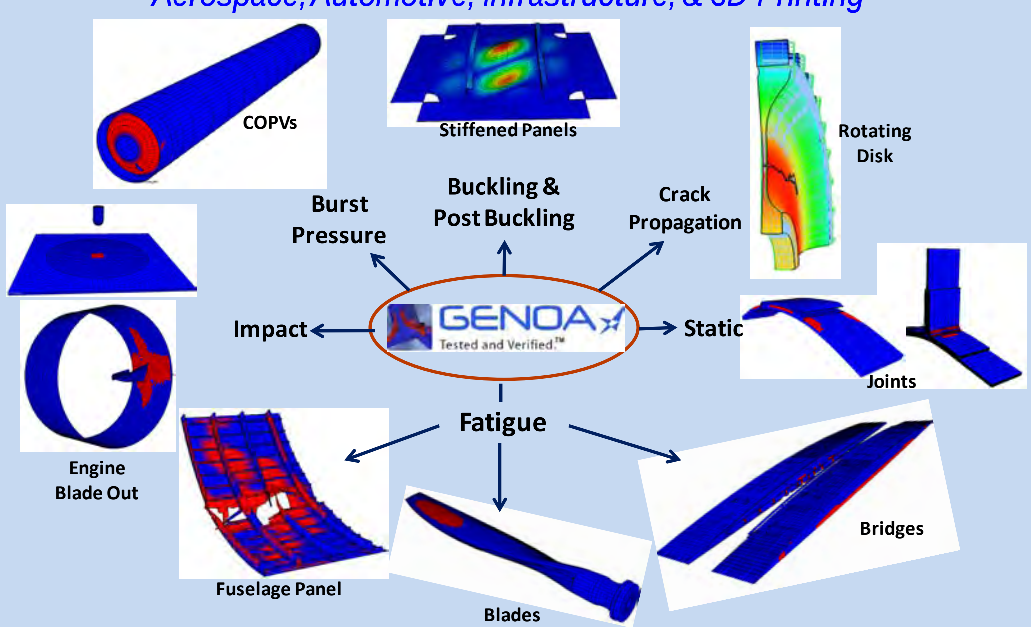
MCQ Ceramics

MCQ Chopped Tested and Verified.™

MCQ Nano

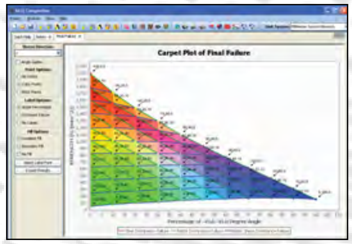
MCQ Metals Tested and Verified.™

Aerospace, Automotive, Infrastructure, & 3D-Printing

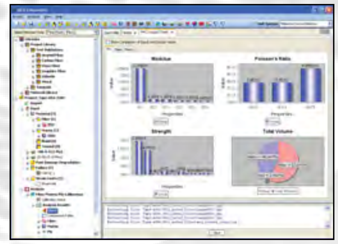


MCQ Composites

Tested and Verified.™



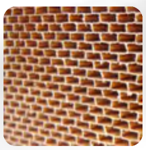
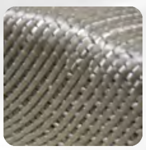
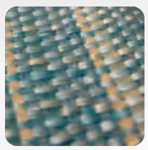
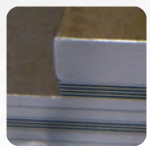
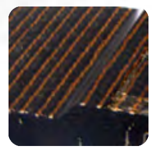
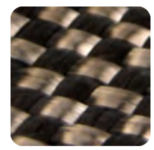
Parametric Carpet Plots



Fiber/Matrix/Ply Properties

Material Characterization & Qualification

MCQ-Composites enables engineers, designers and material specialists to quickly and accurately predict material properties of advanced composite laminates as well as calibrate them against the available ASTM standard coupon test data. It is independent of finite element modeling as it utilizes unit cell approach. It helps estimate material properties of a uniformly stressed un-notched laminate specimen based on available minimum in-plane ply level ASTM standard test data. It generates the ABD and engineering constants that are used as material property input file with NASTRAN, ABAQUS, ANSYS and GENOA for comprehensive structural finite element analysis.


MCQ-Composites Highlights

✓ **Supports full breadth of 2D/3D composite architectures**
- Textile Composites (Woven, Braided, and Stitched)
- Honeycomb
- Laminated Tape Lay-Up
- Polymer Matrix Composites

✓ **Determines laminate properties such as**
- Young's Modulus
- Poisson's Ratio
- Strength
- Coefficient of Thermal Expansion
- Electrical & Thermal Conductivity
- Moisture Diffusivity
- Residual Stresses

✓ **Determines at the laminate level**
- Lamina and laminate limit loads, stresses, and strain
- Damage initiation and propagation to final failure
- Alternate ply layups to meet design requirements
- Strength allowable for specific reliability
- Design failure envelope, fatigue analysis
- Effects of manufacturing defects

✓ **Supports Failure Criteria (In-built)**
- Tsai-Wu, Tsai-Hill
- Puck
- Strain Invariant Failure Theory (SIFT)
- Hoffman, Hashin
- Modified Distortion Energy (MDE)
- Maximum Stress, Maximum Strain, User Defined

✓ **Includes Test Validations for classes of Composite Materials**
- CFRP: IM7/MT45, AS4/3501, T700/2510, T800S, T300/913
- GFR: EGKG/DION, E-glass/LY556, S-Glass, Armid

"We have used MCQ for rapid and accurate prediction of A- and B-basis strength allowables for un-notched uniformly stresses coupons. The dedicated sensitivity analysis option in MCQ allowed us to explore the influence of manufacturing and material parameters on laminate properties, and identify potential avenues for improving the performance of the material."

- **Suresh Keshavanarayana (Raju), Wichita State University**

"We began using MCQ-Composites for modeling unit cell representative volume elements with ellipsoidal shape particles that need to be sub-structured into constituent parts. The versatility of the MCQ software seems to be only limited by the users' imagination. MCQ is a truly outstanding modeling tool for both particulate and also continuous fiber composites that may include a particulate composite matrix."

- **Professor Levon Minnetyan, Clarkson University**

Key Benefits

- Rapid assessment and selection of composite material layup models to meet Design Requirements
- Reduce Physical Test by over 65-70% thus saving significant cost
- Ease of use, results verified with test data for class of materials
- Predicts strength allowable for specific reliability
- Assessment of lamina and laminate limit loads, stresses and strain
- Identification of damage initiation and propagation to final failure & modes of damage/failure

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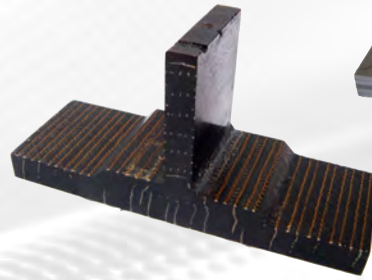
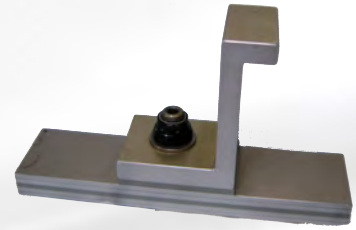
Key Modules

- **Fiber/Matrix/Ply Calibration**
  Reverse engineer the in-situ Young's modulus, Poisson's Ratio, Strength of transversely and isotropic fibers and isotropic matrix from tested in-plane ply properties. The analysis relies on optimizing the micromechanics process.
- **Ply Mechanics**
  Verify ply properties from fiber and matrix constituent properties and variation in fiber and void volume ratio. The analysis relies on micro-mechanics theory.
- **Ply Characterization**
  Predicts ply level thermal-electrical-hygral-mechanical level material properties (tape) from fiber/matrix level thermal-electrical-hygral-mechanical level material properties using micromechanics.
- **Laminate Mechanics**
  Predicts laminate level thermal-electrical-hygral-mechanical level material properties using fiber/matrix, ply, or matrix thermal-electrical-hygral-mechanical level material properties as input along with braid cards for fabric, woven or 3D architecture. The analysis relies on output from combined progressive failure analysis, micromechanics and classical laminate theory.
- **Material Non-linearity**
  Predicts effective matrix stress strain curve from in-plane shear ASTM standard test data. The analysis can be used to reverse engineer any fiber or ply nonlinearity as well. The analysis relies on progressive failure analysis, micromechanics and classical laminate theory. The reverse engineered effective matrix stress-strain curve lumps the effect of crack density, viscosity, and interphase.
- **Progressive Failure**
  Performs detailed analysis for input using material degradation models and iterative process based on user input to ultimately predict the strength, modulus, and laminate and layer-by-layer damage evolution process. It helps dissect the analysis and present great details; for example, information about stresses in the fiber and matrix and degradation in constituent modulus during the analysis because of progressive damage evolution.
- **Design Failure Envelope**
  Predicts first ply and final failure envelope for lamina or laminates based on the chosen failure criteria.
- **Parametric Carpet Plots**
  Provides graphical representation of strength and other material properties of laminates containing symmetric and balanced plies in three user defined different orientations. It helps during laminate layup selection process and ultimately test reduction.
- **A-& B- Basis Allowables**
  Predicts A- and B-basis strength allowables based on material and fabrication uncertainty in the composite laminate material based on user entered scatter from unidirectional ASTM standard tests as the variation in the constituents. It helps in test reduction, material selection process and improve reliability.
- **Manufacturing Defects Mechanics/Characterization**
  Predicts effect of manufacturing defects such as void shapes and size and fiber waviness on matrix or ply level material properties, respectively.
- **Constituent and Progressive Fatigue Life**
  Reverse engineer in-situ stress versus cycles to failure (S-N) curve for the matrix & fiber using in-plane shear, transverse tension, and longitudinal tension fatigue life curves obtained typically from ASTM standard tests or literature. Predicts fatigue life curve for laminates from ply or constituent level fatigue life input.

T-Joint Stitched Composite

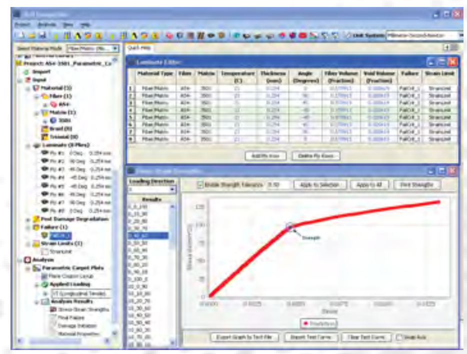




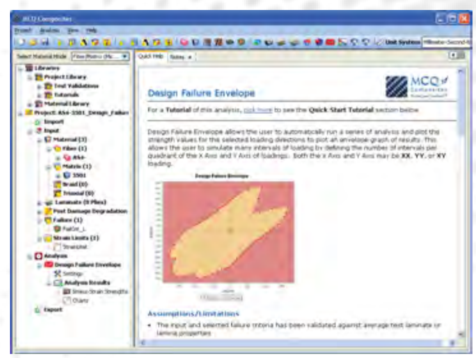
Glare/FML Joint

User Friendliness

- GUI provides an easy to learn and use navigation with all–in-one framework that organizes and manages multiple projects, input and output for material characterization
- Quick help and detailed step-by-step tutorials with technical support from experienced engineers and researcher when needed
- Easy creation, editing and quick import/export of material properties and laminate layups with commonly used third-party FE Solvers: Nastran (.bdf), ABAQUS (.inp), ANSYS (.cdb) and GENOA (.dat) formats



Laminate Stress-Strain



Design Failure Envelope

MCQ Composites
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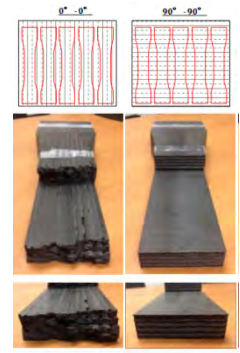
MCQ Chopped
Tested and Verified.™

Objective: Material Characterization & Qualification (MCQ) Chopped predicts chopped composite properties based on effective particles and matrix material properties including material non-linearity and several manufacturing, geometrical and material defects. The predicted material model is validated against test.



Key Benefits

- Effective and efficient calibration of Material Properties of Constituents using ASTM Tests
- Material database for several validated classes of Thermoplastic, Elastomer and Thermoset
- De-Homogenization Approach: models composite constituents and chopped fiber orientation
- Prediction of Chopped Fiber Composite Properties Considering Effect of Defects
- Time-saving Material Modeling for Progressive Failure Analysis of Crush Simulation, Bending, etc.

MCQ-Chopped Highlights

	MCQ	TEST	Ply-Layup
E (Msi)	1.09	1.19	0-0
E (Msi)	0.36	0.327	90-90
S (Ksi)	6.98	7.73	0-0
S (Ksi)	2.03	1.87	90-90

- ✓ Chopped Mechanics: (a) Predict aligned, in-plane random and 3D random material properties; (b) Reverse engineer effective constituent material properties
- ✓ Orientation Distribution Determination/Orientation Tensor Determination: Predict effective % orientation distribution of plies through-thickness
- ✓ Chopped Characterization: Graphically verify variation in aligned layer properties with variation in constituent material properties and manufacturing variables
- ✓ Material Nonlinearity: predict aligned layer, 2D random, 3D random and user defined layup stress-strain curve using matrix stress-strain curve
- ✓ Aligned Layer Nonlinearity: Reverse engineer aligned layer stress-strain curve from flow or cross-flow direction test stress strain curve
- ✓ Progressive Failure (PF): Predict damage evolution, damage growth and final failure for chosen orientation (e.g., user defined, flow or cross-flow direction un-notched coupons)
- ✓ Design Failure Envelope: Predict damage initiation and final failure of coupons subjected to biaxial loading
- ✓ Parametric Carpet Plot: Effective material property prediction for several different orientation % distribution of plies through-the-thickness
- ✓ Material Uncertainty: Predict average material properties (flow, cross-flow, user defined) directions considering material uncertainty, orientation, and thickness effect
- ✓ Fatigue: Predict effective S-N curve for the aligned layer, 2D random, 3D random and user defined orientation using matrix S-N curve as input

Industrial Application

Figure 1 shows simulation vs. test of crush analysis using de-homogenization approach.

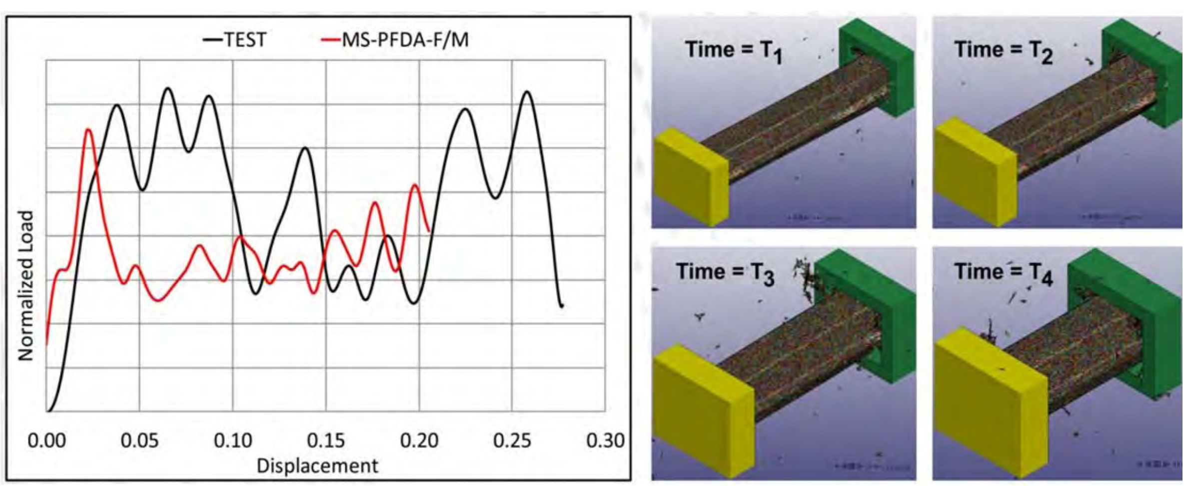


Figure 1: De-Homogenization Based Crush Analysis

MCQ-Chopped Capabilities: MCQ-Chopped typical inputs and capabilities (different modules) are shown in Figure 2

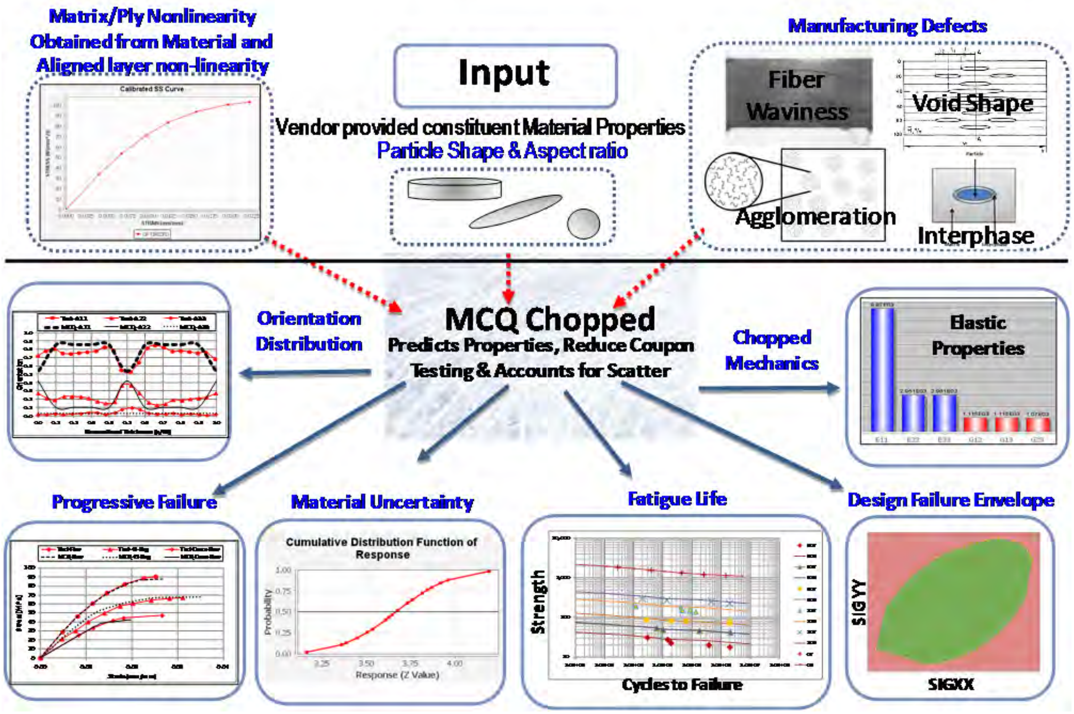


Figure 2: MCQ-Chopped Typical Input and Capabilities

Test Validation: Predicted progressive failure analysis based stress-strain curve vs. test and predicted orientation tensor vs. test for thermoplastic material are shown in Figure 3 and Figure 4. Three-point bending progressive failure analysis using MCQ-Chopped material model and Load-Displacement (L-D) curve from Test & Finite Element Simulation (GENOA/ABAQUS) are shown in Figure 5 and Figure 6.

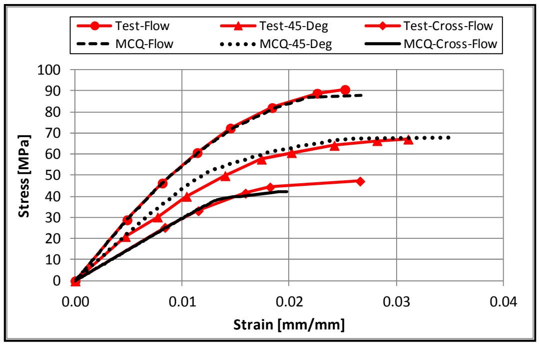


Figure 3: Simulated Stress-Strain Vs. Test (PBT-GF20) [1]

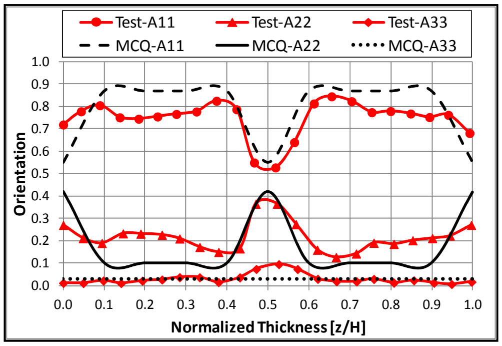


Figure 4: Orientation Distribution Vs. Test (PBT-GF20) [1]

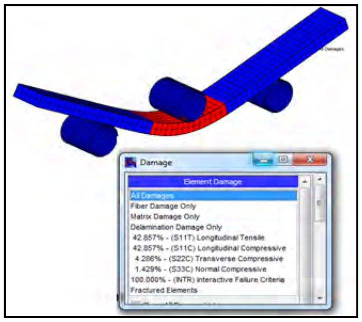


Figure 5: Three point Bending Coupon Analysis [2]

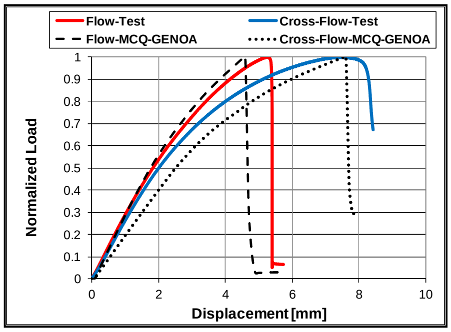


Figure 6: Simulated L-D curve vs. Test [2]

Reference:

1. Abumeri, G. H., Lee, M., (2006). A Computational Simulation System for Predicting Performance of Chopped Fibers Reinforced Polymer Composites. ERMR-2006-Elastomer-Reno.

2. H.K. Baid, F. Abdi, M. C. Lee, Uday Vaidya, Chopped Fiber Composite Progressive Failure Model under Service Loading. SAMPE 2015, Baltimore MD, May 18-21, 2015.

The Material Modeling Solution

www.materialmodeling.com

Material Characterization & Qualification – Ceramics

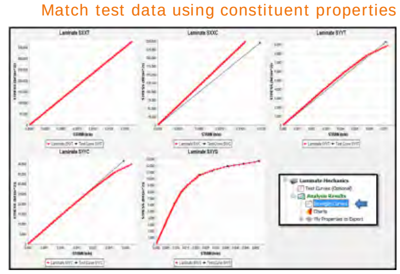
- ***MCQ-Ceramics is a Multi-Scale material modeling, characterization & qualification software that predicts ceramic material performance considering the effect of defects, material scatter and environmental degration under service load.***
- ***Validation cases available for several classes of Ceramic Matrix Composites:***
- ***Oxide/Oxide, 2) SiC/SiC-MI, 3) SiC/CAS, 4) SiC/SiC-CVI.***
- ***Easy to use interface and property generation for NASTRAN, ABAQUS, ANSYS***

MCQ-Ceramics enables engineers, designers and material specialists to quickly and accurately predict mechanical properties (stiffness, strength, conductivity) of advanced composite laminates (2-D/3-D) considering environmental degradation effects: (1) effect of defects, voids, fiber waviness (2) micro-crack density, (3) recession, (4) global and local oxidation, and (5) environmental/thermal barrier coating (EBC/TBC). In addition the non-visual measurement NDE technique such as electrical resistivity (ER), and acoustic emission (AE) is predicted. A building block reverse engineering approach is used to calibrate the "effective" constituent (fiber/matrix) properties. The effective properties are used to validate against the minimum available in-plane ply level ASTM standard test data. It is independent of finite element modeling as it utilizes a unit cell approach. It generates the ABD matrix and engineering constants that are used as material property input file with NASTRAN, ABAQUS, ANSYS and GENOA for comprehensive structural finite element analysis.

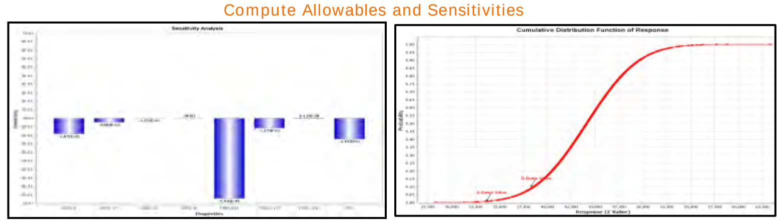
MCQ-Ceramics Highlights

- ✓ **Supports full breadth of 2D/3D composite architectures**
  - Laminated Tape Lay-Up, CVI, MI, EBC/TBC, SiC, Oxide
  - Fiber Architecture (Woven, Triaxial, Harness Satin Weave, Braided,and Stitched)
  - Fiber Coating (InterPhase)
- ✓ **Determines laminate properties such as**
  - Young's Modulus, Poisson's Ratio
  - Strength, Coefficient of Thermal Expansion
  - Electrical & Thermal Conductivity
  - Moisture Diffusivity, Residual Stresses
- ✓ **Determines at the laminate level**
  - Lamina and laminate limit loads, stresses, and strain
  - Damage initiation and propagation to final failure
  - Alternate ply layups to meet design requirements
  - Strength allowable for specific reliability
  - Design failure envelope, fatigue analysis
  - Effects of manufacturing defects
- ✓ **Supports Failure Criteria (In-built and User Defined)**
  - Translaminar (Matrix, Fiber, Ply)a
  - Interlaminar/Delamination (Tension, Shear, Relative Rotation)
  - Interactive Strength (Tsai-Wu, Tsai-Hill, Puck, MDE, Hoffman, Hashin)
  - Interactive Strain- Strain Invariant Failure Theory (SIFT)
  - Maximum Stress, Maximum Strain, User Defined
- ✓ **Supports Environmental Degradation**
  - **Micro Crack Density** – Formation of crack density in matrix loaded component reducing stiffness and strength
  - **Matrix Defects** – Void shape, size distribution reducing stiffness and strength, matrix creep, fatigue
  - **Fiber Strength Statistics** – Gradual failure "Rope effect" – Probabilistic Weibull distribution
  - **Interphase Mechanics** – Fiber bridging
  - **Recession** - Material vaporizes at high temperature and loss of mass with sufficient gas velocities

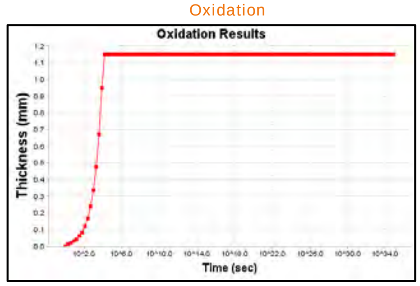
Match test data using constituent properties



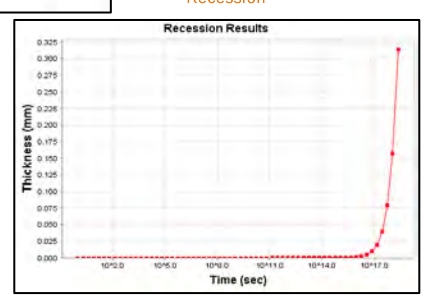
Compute Allowables and Sensitivities



Oxidation



Recession



- **Global Oxidation** – Composite infiltrated with oxygen diffusion, SiC reacts to form SiO2, which eats away fibers.
- **Discrete Oxidation** – Oxygen/moisture diffuses into surface cracks causing damage and accelerated oxidation

✓ **Supports Service Loading**

- Static (in-plane, out-of-plane, pressure), Fatigue,
- Creep rupture, thermo-mechanical, and strain rate effect

✓ **Includes Test Validations for classes of Ceramic Materials**

- **Oxide/Oxide**: Nextel 610 at 1050 °C, and 950 °C, and Nextel 720 at RT
- **SiC/SiC at RT:** Sylramic/IBN/MI, SiC/SiC CVI, and SiC/CAS
- **SiC/SiC :** SiC-iBN/SiC composite characterization at 1315° C
- **NDE tests***:* SIC/SiC ER, and AE
- **A/B-basis allowable:** Prediction for T300/SiC (0°/90°)

Key Benefits

- Rapid assessment/selection of ceramic composite material layup models to meet design requirements
- Reduce physical test by over 65-70% thus saving significant cost
- Ease of use, results verified with test data for class of materials
- Predicts strength allowable for specific reliability
- Assessment of lamina and laminate limit loads, stresses and strain
- Identification of damage initiation and propagation to final failure & modes of damage/failure

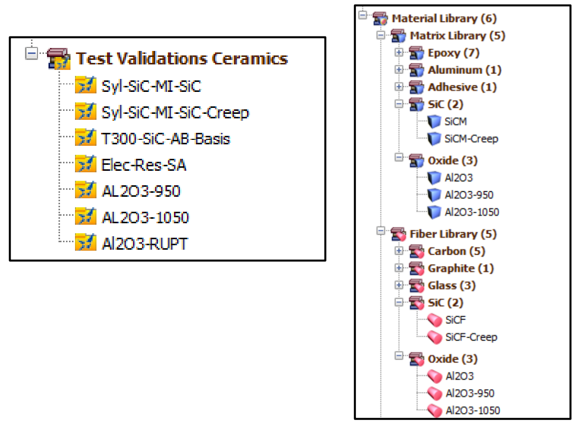
User Friendliness

- GUI is easy to learn with navigation tutorials and videos. Manages multiple projects, input and output for material characterization
- Easy creation, editing and quick import/export of material properties and laminate layups with commonly used third-party FE Solvers: NASTRAN (.bdf), ABAQUS (.inp), ANSYS (.cdb) and GENOA (.dat) formats

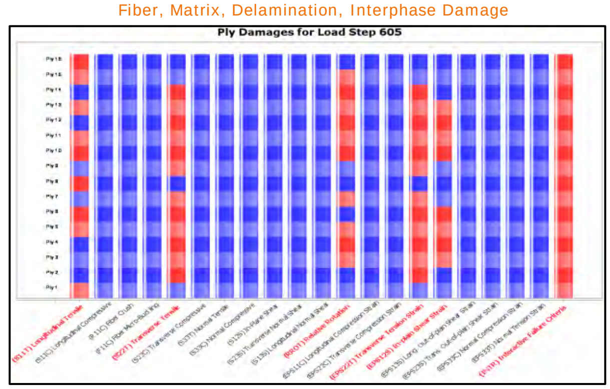
Key Modules

- **Fiber/Matrix/Ply Calibration** Reverse engineer fiber and matrix properties from tested in-plane ply properties. **Material Non-linearity** Predicts effective matrix stress strain curve from in-plane shear ASTM standard test data. The curve lumps the effect of crack density, viscosity, and interphase.
- **Ply Mechanics and Characterization** Compute thermal-electrical-hygral-mechanical ply properties from fiber and matrix properties, void, weave, and waviness information. Compute variation with respect to angle changes.
- **Laminate Mechanics** Predicts laminate level thermal-electrical-hygral-mechanical level material properties using fiber/matrix, ply, or matrix thermal-electrical-hygral-mechanical level material properties as input along with braid cards for fabric, woven or 3D architecture. The analysis relies on output from combined progressive failure analysis, micromechanics and classical laminate theory.
- **Progressive Failure** Performs detailed damage tolerance analysis to ultimately predict the strength, modulus, and laminate and layer-by-layer damage evolution process.
- **Design Failure Envelope** Predicts first ply and final failure envelope for lamina or laminates based on the chosen failure criteria.
- **Parametric Carpet Plots** Provides graphical representation of strength and material properties of laminates containing symmetric and balanced plies varying percentage of three user defined orientations. It helps during laminate layup selection process and ultimately test reduction.
- **A-& B- Basis Allowables**
  Predicts A- and B-basis strength allowables based on material and fabrication uncertainty and scatter from unidirectional ASTM standard tests. Helps in test reduction, material selection process and improve reliability.
- **Manufacturing Defects Mechanics/Characterization**
  Predicts effect of manufacturing defects such as void shapes and size and fiber waviness on matrix or ply level material properties, respectively.
- **Constituent and Progressive Fatigue Life**
  Reverse engineer in-situ stress versus cycles to failure (S-N) curve for the matrix & fiber using in-plane shear, transverse tension, and longitudinal tension fatigue life curves obtained typically from ASTM standard tests or literature. Predicts fatigue life curve for laminates from ply or constituent level fatigue life input.

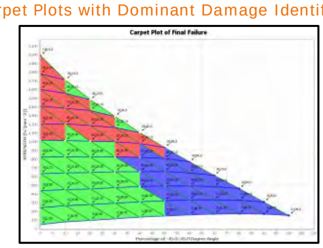
Includes Test Validation Cases and Material Libraries



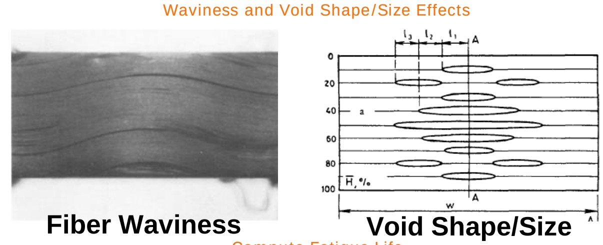
Progressive Failure Tracks All Damage Mechanisms: Identify Fiber, Matrix, Delamination, Interphase Damage



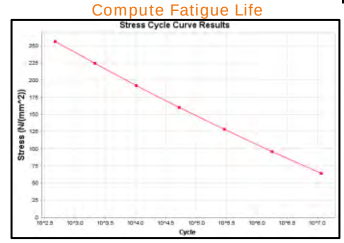
Carpet Plots with Dominant Damage Identified



Waviness and Void Shape/Size Effects



Compute Fatigue Life



The Material Modeling Solution

www.materialmodeling.com

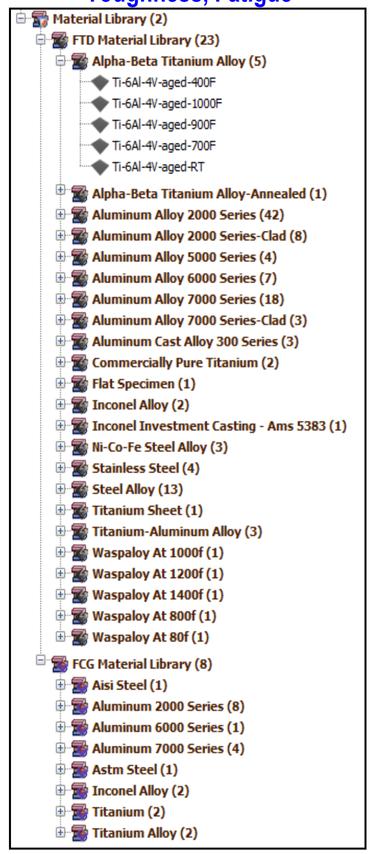
Material Characterization & Qualification – Metals

Analytical and numerical approach estimates the S-N data for the Kt.>1 through combined Progressive Damage, Fracture and Finite element modeling. The method is based on calculating the number of cycles to crack initiation and crack propagation which both when added will provide the total life.

- ***MCQ-Metals*** *is a Multi-Scale material modeling, characterization & qualification software that analytically predicts metallic material properties and performance*
- ***MCQ-Metals: Fracture toughness determination (FTD), Fatigue crack growth properties analytical determination (FCG), Fatigue cycle data (S-N)***
- ***GENOA/Metal:*** *S-N Curve of notched part is numerical FE based life prediction*
- *Comes with extensive amount of material data and building block test validation*

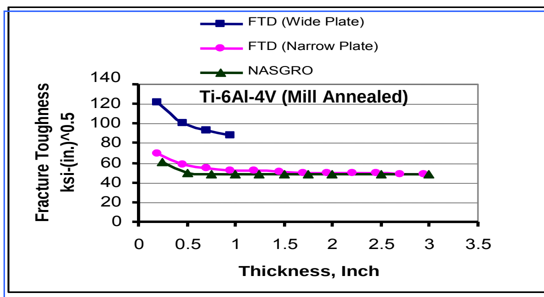
MCQ/GENOA-Metals is designed to characterize metal fracture and fatigue crack growth properties based on static tensile stress-strain behaviors, that includes: **1**) fracture toughness determination (**FTD**), **2**) fatigue crack growth properties determination (**FCG**), fatigue Strength-Cycle (**S-N**), **3**) for creep crack growth (**TRCrack**) rupture and creep fatigue interaction. MCQ-Metals allows characterizing metal properties as a function of several manufacturing, geometric, and material variables. The material properties at room and high temperature (RT/HT) can be used as input to MCQ-Metal. Metal fracture and fatigue data in literature show lots of scatter mainly due to scatter in the manufacturing, geometric and material property variables. The probabilistic analysis module in MCQ-Metals allows estimating the mean metal material properties as well as the statistical distribution of the properties [1-2].

Material Database, Toughness, Fatigue

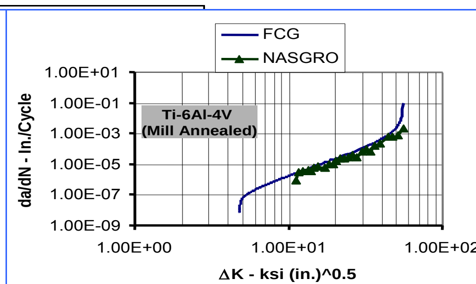


MCQ-Metals Highlights

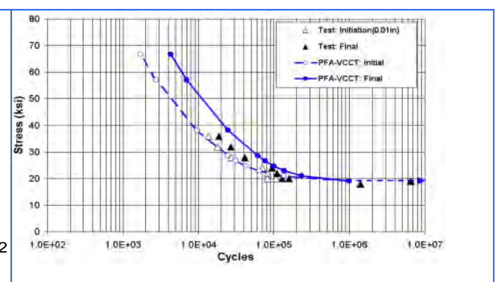
- ✓ **Characterize metal fracture and fatigue crack growth at RT/HT**
  - FTD Vs. thickness calculated from stress-strain curve
  - FCG regions (Threshold, Paris, Accelerated) curve (da/dn vs. dk) from fracture toughness
  - S-N Curve of notched part:
    - a-N curves from FCG curve
    - b) crack initiation: notched specimen using material (un-notched) S-N curve
  - Creep crack growth vs. time from full stress-strain curve
  - Fatigue and creep interaction
- ✓ **Include effects of the following variables**
  - Geometric, manufacturing, material, account for scatter
- ✓ **Perform probabilistic analysis**
  - Estimate mean and statistical distribution of properties
  - Probabilistic fracture toughness, probabilistic fatigue crack growth
- ✓ **Includes vast library of material data (i.e., Titanium, Aluminum, Inconel, Steel)**



Fracture toughness, Vs. Test (NASGRO)



Fatigue Crack Growth Vs. Test (NASGRO)



Fatigue Life initiation, growth (S-N)Vs. test

References:

1. Bob Farahmand, Frank Abdi, "Probabilistic Fracture Toughness, Fatigue Crack Growth Estimation Resulting From Material Uncertainties" ASTM Conference Paper 11569 November 6-7, 2002.
2. Frank Abdi, Bill Troha, Dade Huang, Kamran Nikbin, Arun Bhattacharya "Virtual Characterization and Test Validation for fracture toughness, fatigue crack growth and creep fatigue interaction of Metallic components". MesoMech - Conference Paper 7/2011.
3. B. Farahmand, C. Saff, De Xie and F. Abdi, "Estimation of Fatigue and Fracture Allowables For Metallic Materials Under Cyclic Loading". AIAA-2007-2381, Honolulu, Hawaii, April, 2007.

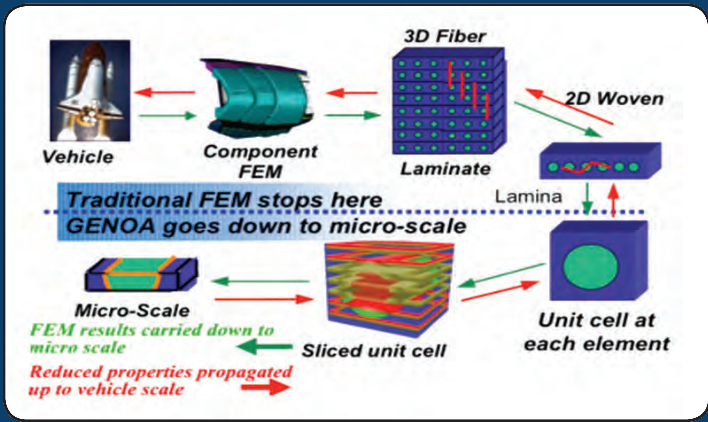
GENOA

Tested and Verified.™

Predict When, Where & Why Failure Occurs

AlphaSTAR's flagship product **GENOA** software provides engineers with the predictive computational technology to characterize and qualify advanced composites materials and structures considering manufacturing anomalies (i.e., matrix distortion, residual stress), effects of defects (void shapes sizes and fiber waviness), and scatter for "as-built/as-is" states of composite material and structures. **GENOA augments FEA analysis tools for Multi-Scale Progressive Failure Analysis** of structures made from advanced composite materials subject to static, fatigue, and impact loadings. GENOA has a full-hierarchical modeling that goes down to the micro-scale of sub-divided unit cells composed of fiber bundles and their surrounding matrix. GENOA's solution can be used for polymer composite structures, Hybrid Composites, (i.e. Fiber Metal Laminates) and Nano composites. In GENOA's progressive failure displacements, stress and strains derived from the structural FEA solution at every element and are decomposed to the laminate, lamina and micro-scale using laminate and micro-stress theory. This analysis is performed progressively all the way to failure, and asseses damage initiation and progression including fracture initiation on a micro level using failure criteria. GENOA integrates damage & fracture mechanics into one platform.

Multi-Scale Progressive Failure Analysis Flow Diagram



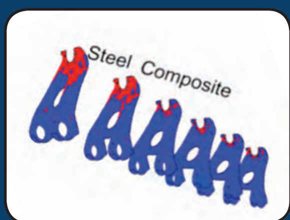
Verified & Validated for Numerous Materials

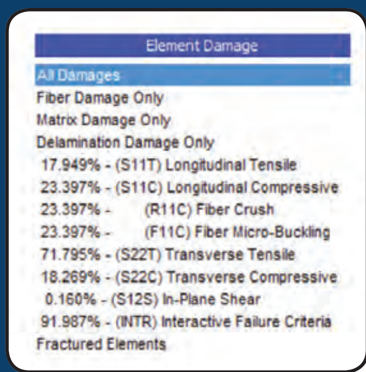
- Polymer (Chopped, Continuous), Thermoset, Thermo-Plastic, Elastomer
- Ceramic Matrix Composites (CMC)
- Hybrid (GLARE)
- Nano-Composites
- Metals

GENOA's Key Benefits

- Predict structural performance considering effects of defects (voids shapes, sizes, fiber waviness, curing residual stresses)
- Modeling & simulation of complex parts & materials
- Address design envelope parameters
- Accredited software can eliminate unnecessary tests
- HPC for parallel processing of large models
- Guides test by analysis to reduce testing up to 50%
- Optimize design of lightweight structures & vehicles

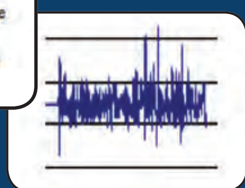
Static, Fatigue, Creep, Impact, Spectrum, Harmonic, PSD





Element Damage

All Damages
Fiber Damage Only
Matrix Damage Only
Delamination Damage Only
17.949% - (S11T) Longitudinal Tensile
23.397% - (S11C) Longitudinal Compressive
23.397% - (R11C) Fiber Crush
23.397% - (F11C) Fiber Micro-Buckling
71.795% - (S22T) Transverse Tensile
18.269% - (S22C) Transverse Compressive
0.160% - (S12S) In-Plane Shear
91.987% - (INTR) Interactive Failure Criteria
Fractured Elements

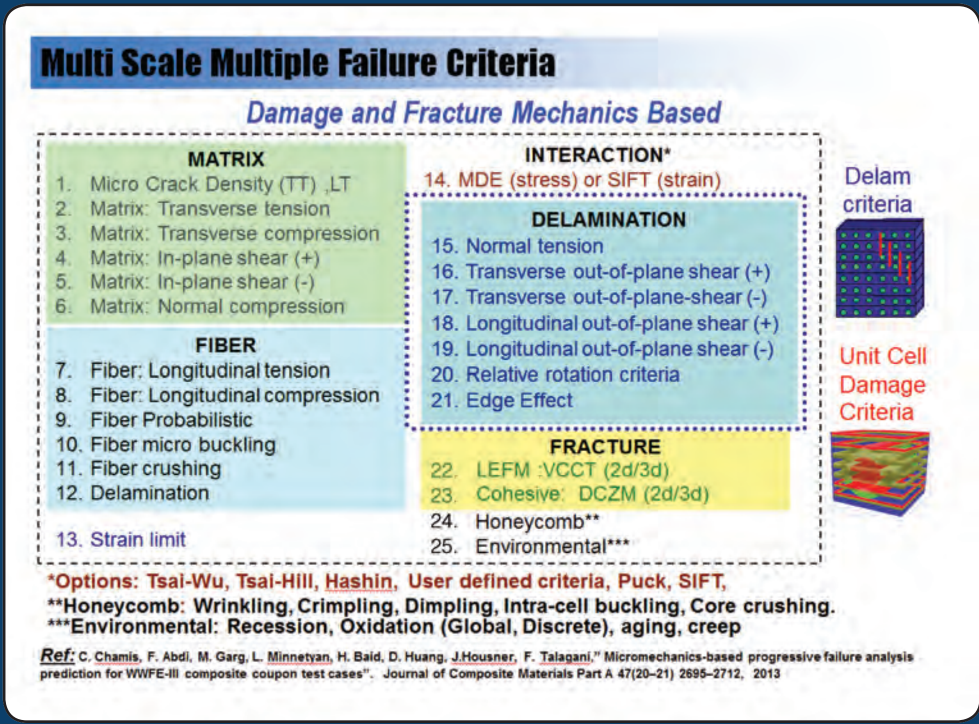


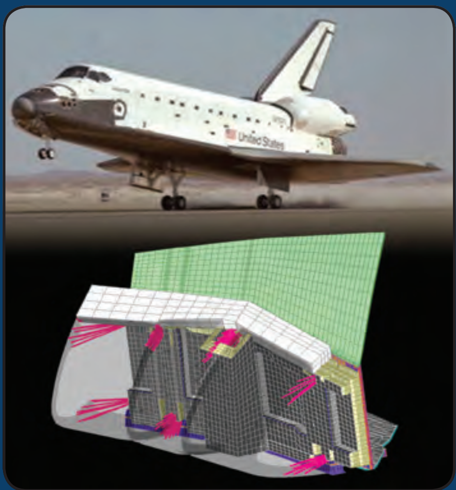
Fatigue & Life Reliability — *Build Trusted Products* — *Model & Track Damage*

Multi Scale Progressive Failure Methodology

We have utilized ASC's flagship product: GENOA, for the analysis of complex bonded structural components. Chief among the features that make GENOA an invaluable tool for the analysis of complex adhesively bonded structures is its step by step simulation of component response to loading up to and including failure; inclusive of first ply failure. This high fidelity simulation is made possible by a micromechanics based material representation and elaborate damage and fracture tracking capability. GENOA prediction has correlated well with test data for a variety of adhesively bonded joints and material systems."

– Nasir Munir Ph.D., Structural Engineer, Northrop Grumman, USA



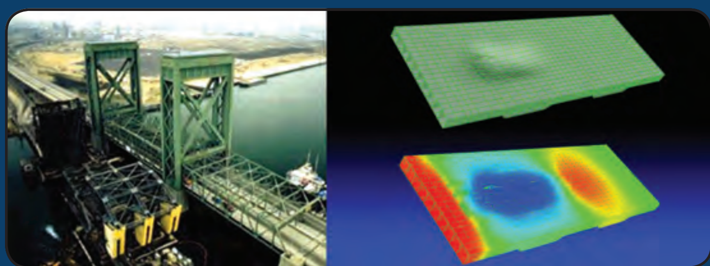


GENOA Chosen to Simulate Shuttle Columbia Accident

GENOA was selected to extensively investigate the shuttle Columbia accident after the vehicles disintegration upon re-entry into earths atmosphere. The study included analysis to show damage to the Orbiter's left wing leading edge and to simulate the aero-thermal structural response. GENOA successfully predicted results, which were provided to the Columbia Accident Investigation Board. GENOA's probabilistic and risk assessment capability calculated the probability of vehicle loss due to a foam impact.

Advanced Modeling & Simulation Augments Traditional FEM

GENOA investigated the structural response, strength and fatigue life of a composite replacement lift span. Results were generated independent of test. GENOA Failure modes of simulation matched test.



AlphaSTAR delivers tested and verified tools and methodologies for precise predictions by simulation reducing expensive physical tests, reducing your costs and time to market. www.alphastarcorp.com

GENOA

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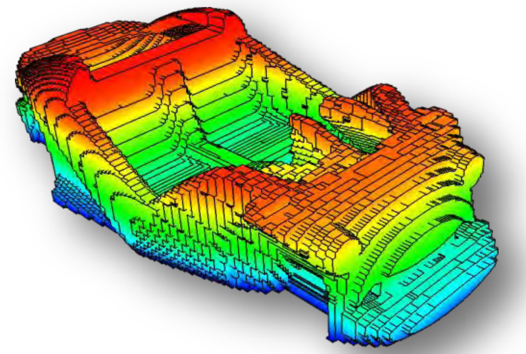
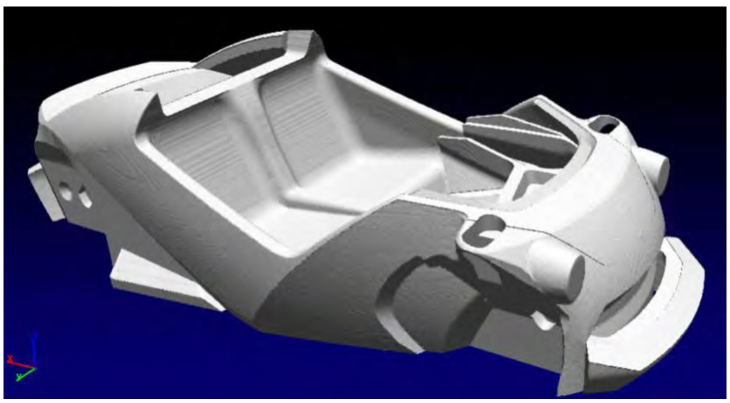
3-D Printing Simulation

AlphaSTAR Corporation (**ASC**) collaborated with Oak Ridge National Laboratory (**ORNL**) to offer 3-D printing simulation using GENOA suite of software to accurately predict the deflection, residual stress, damage initiation, and crack growth formation observed by 3-D printing machines. Advanced Multi-Scale Progressive Failure Analysis (**MS-PFA**) methods are used to determine the entire 3-D printing process at two levels: **1) Material Characterization** using quick and accurate analysis without the use of FEM and **2) Structural MS-PFA** that simulates the entire 3-D printing process using FEM. With the ability to import directly from the printer STL file and simulate the printing process, GENOA offers a micro view of the crack and damage formation that may occur.

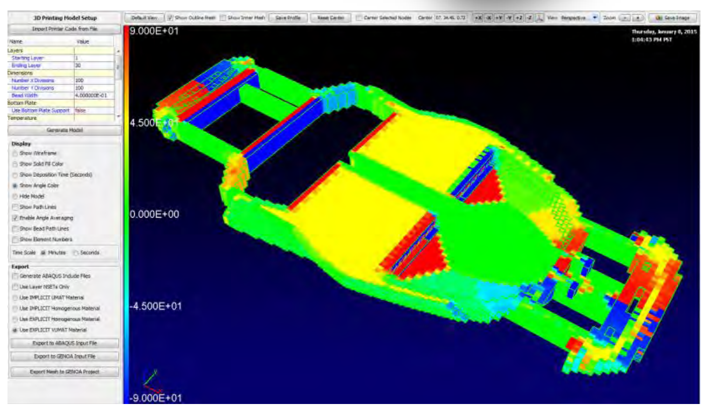
Automated FE Mesh Generator

- Import from G-Code Printer Code File (from STL source)
- Big Area Additive Manufacturing (**BAAM**) for fiber reinforced thermoplastics which can be extended to thermosets as well
- Re-simulate printing paths with bead width, angle and timing precision
- Define resolution of solid element model from low to high fidelity
- Preview or refine individual layers, with the option to mesh and include bottom plate for additional heat transfer variables
- Export either specific or all layers to ABAQUS input deck for analysis





Import from STL file to generate G-Code printer file that provides actual printer machine instructions

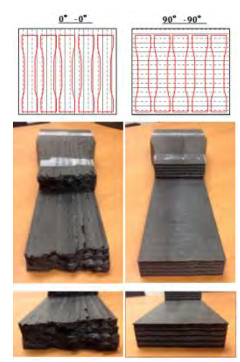


Visualize layer-by-layer the angle and time calculated in every element determined by paths printed

Material Characterization & Qualification - Chopped

MCQ Chopped Tested and Verified.™

- ✓ **Chopped Mechanics:**
  - Predict aligned, in-plane random and 3D random material properties
  - Reverse engineer effective constituent material properties
- ✓ **Orientation Distribution Determination/Orientation Tensor Determination:** Predict effective % orientation distribution of the fillers through-thickness
- ✓ **Chopped Characterization:** Graphically verify the variation in aligned layer properties with variation in constituent material properties and manufacturing variables
- ✓ **Material Nonlinearity:** Predict aligned layer, 2D random, 3D random and user defined layup stress-strain curve using matrix stress-strain curve as input.
- ✓ **Aligned Layer Nonlinearity:** Reverse engineer aligned layer stress-strain curve from flow or cross-flow direction test stress strain curve
- ✓ **Progressive Failure: Predict damage evolution, damage growth and final failure for chosen orientation (e.g., user defined, flow or cross-flow direction un-notched coupons)**
- ✓ **Design Failure Envelope:** Predict damage initiation and final failure of coupons subjected to biaxial loading
- ✓ **Parametric Carpet Plot:** Effective material property prediction for several different orientation % distribution of plies through-the-thickness
- ✓ **Material Uncertainty:** Predict average material properties (flow, cross-flow, user defined) directions considering material uncertainty, orientation, and thickness effect
- ✓ **Fatigue:** Predict effective S-N curve for the aligned layer, 2D random, 3D random and user defined orientation using matrix S-N curve as input



	MCQ	TEST	Ply-Layup
E (Msi)	1.09	1.19	0-0
E (Msi)	0.36	0.327	90-90
S (Ksi)	6.98	7.73	0-0
S (Ksi)	2.03	1.87	90-90

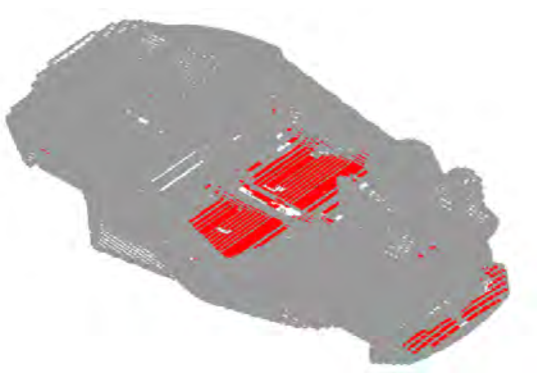
3-D Printing Simulation

In addition to the prediction of damage initiation and crack growth formation observed by 3-D printing machines, AlphaSTAR Corporation's GENOA software can visualize damages in the printed structure. Damage types (fiber, matrix, several delamination types – transverse shear, fiber crushing, fiber microbuckling, relative rotation, out of plane stresses) can be visualized and highlighted (identified) separetely in the GENOA GUI. Damage can be traced directly to 3D printing variables (deposition speed, bead width, overall path, bottom plate temperature, convection conditions, and, if necessary, radiation to enclosures and within itself) as well as material variables (fiber, matrix, chopped - agglomeration, long fiber waviness). This allows manufacturers to produce robust designs with predictable strength and fatigue life in a timely manner.

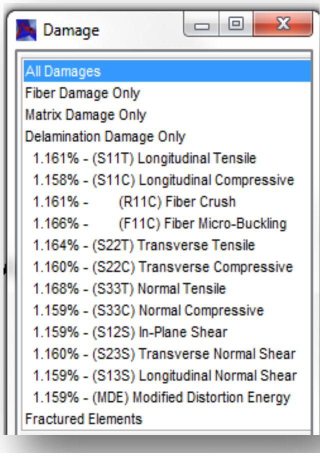
Temperature Changes, Damage Initiation, and Delamination Prediction

- Fully coupled structural and thermal/heat transfer model performed
- Damage types (fiber, matrix, several significant delamination types)
- Change printing and material variables to meet design requirements
- Post manufacturing strength/life predicted with any FE solver

Delamination Identified in Seat Region



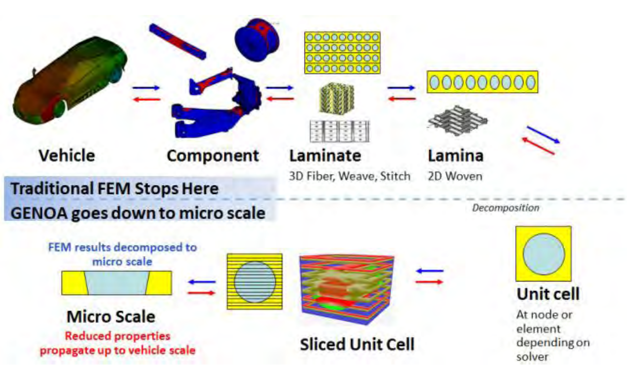
Full car model (420,000 elements, 4M dof), coupled structural/thermal/heat transfer simulated in 15 hours with 48 cpus on linux server (motherboard)



Delamination Reduced by Decreasing the Layer Deposition Time

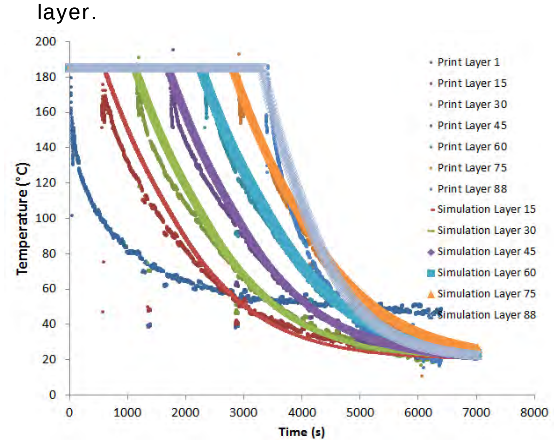
Identify root cause damage as either 3D printing variables (deposition speed, convection, bead width, etc...) or material (fiber, matrix cracking, or delamination)

Proven Multi Scale Technology

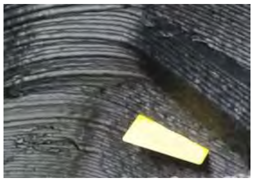


Test Verified Heat Transfer Simulation

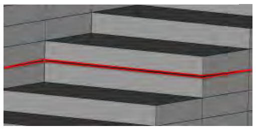
Convection, radiation, conductivity, with thermal gaps at every element and every layer.



Cracks From Printed Items Also Seen In Simulation



Cracks From Simulation Highlighted



References

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2. M. R. Talagani, S. DorMohammadi, R. Dutton, C. Godines, H. Baid, F. Abdi, V. Kunc , B. Compton, S. Simunovic, C. Duty, L. Love, B. Post, C, Blue, "Numerical Simulation of Big Area Additive Manufacturing (3D Printing) of a Full Size Car". SAMPE Journal, Volume 51, No. 4, July/August 2015.

3. Tekinalp, Halil L., Vlastimil Kunc, Gregorio M. Velez-Garcia, Chad E. Duty, Lonnie J. Love, Amit K. Naskar, Craig A. Blue, and Soydan Ozcan. "Highly oriented carbon fiber–polymer composites via additive manufacturing." Composites Science and Technology 105 (2014): 144-150.

Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC

Thermoset 3-D Printing Software

Reduces Wrinkle Rate and Residual Stress. Perform Virtual Thermoset (Graphene Platelet) Additive Manufacturing (AM) aimed at Part Qualification / Certification

AM Thermoset Graphene Inclusion (**Figure 1**): characterizes material performance using integrated multi-scale modeling considering : **a**) nano-mechanics, cure and distortion algorithms. Code examines effect of inclusion and voids resulting from graphene platelet to predict residual stress and wrinkles; **b**) micro-mechanics examines constituents (fiber/matrix/intephase/interface, residual stress); and **c**) macro mechanics addressing lamination theory. It provides detailed stiffness/strength/conductivity to FEM for full structural/thermal De-homogenized Multi-Scale Progressive Failure Analysis (MS-PFA) to address damage and fracture evolution

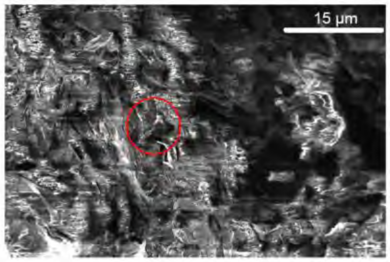
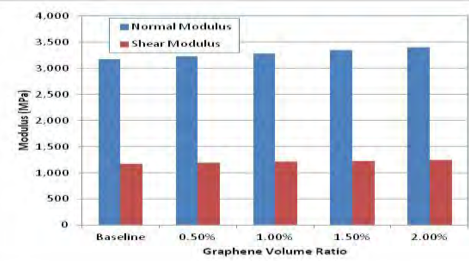


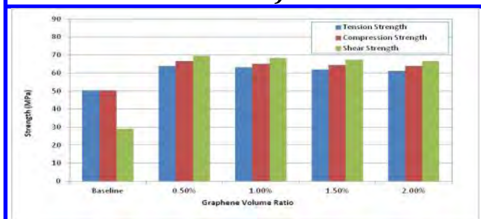
Figure 1. High-Resolution SEM images of Graphene Platelet [2]

Challenges and Limitations of Thermoset AM Technologies

3D-printed parts using **FFF** (Fused Film Fabrication) may introduce defects in the form of voids and crack, delamination between the beads, and residual stress and distortion. It is observed in the 3D printing of Graphene platelet inclusion in resin a wrinkling/distortion in final parts usually occurs due to thermal loading induced residual stresses. To overcome this typical issue of wrinkling/distortion a multi-scale modeling based analytical solution can be obtained to reduce the thermal residual stress at the interphase between inclusion and resin. As such, the end-user, empowered with GENOA 3D simulation technology, is able to 'design knowing post-manufacture part stresses during service and predicting process-inherent residual stresses, microstructure and defects. Consequently, the manufacturing lead time for highly-customized parts would be reduced, which would allow on-demand manufacture of components with tailored mechanical, thermal properties. **The end result is higher quality parts available at reduced costs.**



a) Modulus Vs. Volume fraction (Normal, Shear)



b) Strength Vs. Volume fraction (Tension, Compression, Shear)

Figure 2. Prediction of NGP Mechanical Properties [1]

Product Fact Sheet

- ✓ **Automated FE Mesh Generator from G Code**
- ✓ **Simulate printing paths** with bead width, angle and timing precision
- ✓ **Test Validated Database of Graphene based Thermoset Epoxy**
- ✓ **Strength, Stiffness, Conductivity prediction:** graphene inclusion Epoxy nanocomposite reinforced by two-dimensional graphene nanoplatelet (GNP), (**Figure 2**)
- ✓ **Temperature Dependent Properties Prediction** (**Figure 3**)
- ✓ **Fracture toughness prediction**
- ✓ **Fully Coupled Thermal-Structural Analysis**
  - Predict the Strength for Each Bead
  - Residual Stress and Strain and Delamination
  - Damage and Fracture Detection
  - Consider Effect of Defects Using the Measured/Predicted NDE defects (void/roughness)
- ✓ **Material Uncertainty:** Predict Scatter Effect on Material Properties

The Software Framework Incorporates the Thermoset AM Process: to assist the user in making choices with respect to material mechanical properties, failure criteria, and effects of defects such as inclusion

It provides a comprehensive guide on effectiveness of failure criteria, FE solver, and use of De-homogenized Multi-Scale Progressive Failure Analysis and probabilistic/statistical analysis to select the most important parameters and requirements to simulate 3D printing.

FE Mesh and Model Generation: customized local and global FE mesh generation for AM-fabricated part using digital information (G Code) printer pattern, printer head width, printer speed, and STL file used for mesh smoothing. The generated FE mesh includes:**a**) printing flaw recognition, **b**) material orientation for each element, according to printer path to accuratley model the reinforced thermoset

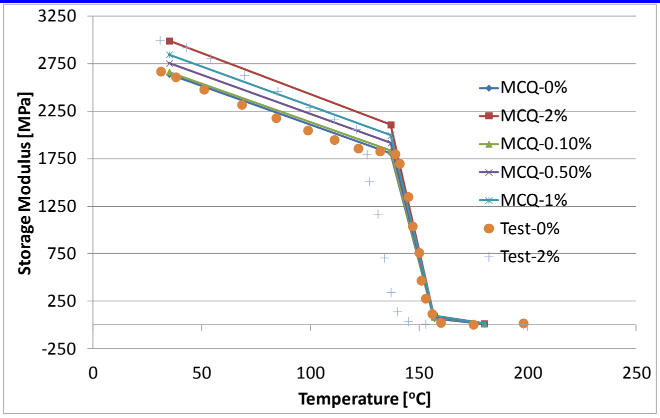


Figure 3 High-Resolution SEM images of Graphene Platelet [1]

Prediction of Alligned and Random Mechanical Properties: Multi-scale material modeling approach is used to estimate the performance of defect afflicted and as-built specimens **(Figure 4)**

Predict Material Fracture Toughness (Mode I): A simulation set was performed using Multi-Scale Modeling to detect damage and fracture eveloution using DCB (Double Cantiliver Beam) under static loading **(Figure 5)**. The simulation is capable of predicting crack initiation and growth as well as type and location of damages

Predict Wrinkle and Delmination: Delamination and wrinkling of a simple printed wall model **(Figure 6)** were predicted using GENOA 3D simulation software. The coupled thermal and structural FE, integrated with GENOA multi-scale damage mechanics, is used to compute induced thermal stresses. The real time residual stresses are calculated with the damage mode checked for each time step as the material properties and layer bonding are updated accordingly.

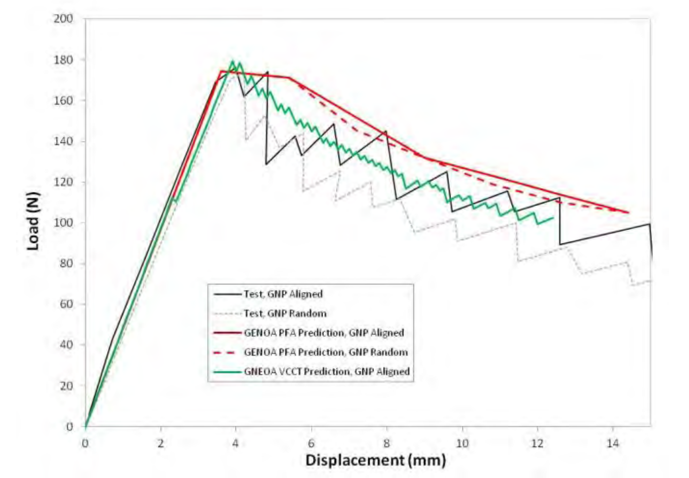


Figure 4 . DCB Specimen load-displacement curves [1]

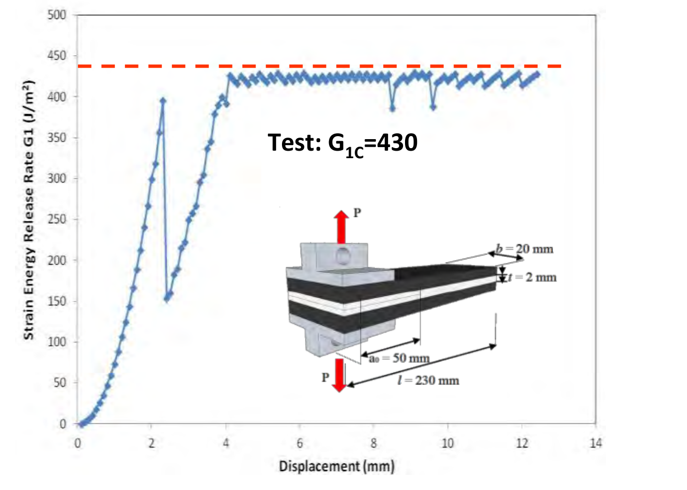


Figure 5. Fracture Toughness Calculation: Strain Energy Release Rate Vs. Mouth Open Displacement [1]

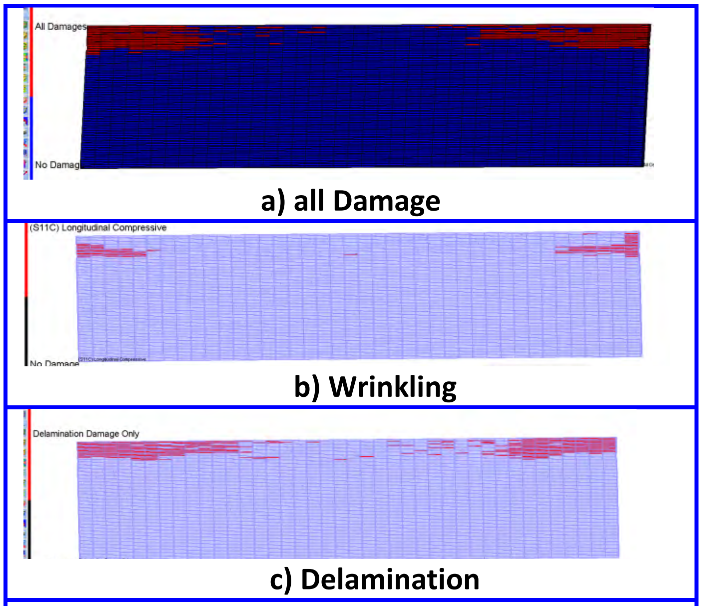


Figure 6. Damage Pattern of FE wall model for 3D printing[1]

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1. Frank Abdi, Jay Batten, Dade Huang, Harsh Baid, Saber DorMohammadi, Massimiliano Repupilli, Amos Nissim, "3d Printing Manufacturing Simulation Of Thermoset Nano Graphene Inclusion', SAMPE Conference 2016, Long Beach, CA, May 2016..

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GENOA Tested and Verified.™

Metal Powder 3-D Printing Software

Perform Virtual Additive Manufacturing for Metal Powder

Newly developed 2015 R&D 100 award winning 3D Printing computational tools predict powder metal mechanical properties, including: **a**) static, **b**) fatigue; and **c**) damages in the printed structure. A fully coupled thermo-mechanical solution of metal powder additive manufacturing may assist in qualification and certification of parts

Challenge and Limitations of AM Technologies

As noted in **Figure 1,** wrinkle and cracks are an unwanted by product of additive manufacturing. Common challenges include: (**i**) crack and void formation, (**ii**) material dependent system optimization, (**iii**) surface roughness (**iv**) thermal discontinuity, (**v**) residual stresses, (**vi**) inconsistent density (density can be influenced by un-melted entrapped powders), (**vii**) variations in desired strength, ductility, toughness, and modulus due to the rapid cooling rates that affect the microstructure. The SLM process can be tuned with the help of simulation, to additively manufacture components with more precision. As such, the end-user, empowered with GENOA 3D simulation technology is able to 'design for SLM' by knowing post-manufacture part stresses during service and predicting process-inherent residual stresses, initiation microstructure and defects. Consequently, the manufacturing lead time for highly-customized parts would be reduced, which would allow on-demand manufacture of components with tailored mechanical, thermal properties. **The end result is higher quality parts available at reduced costs.**

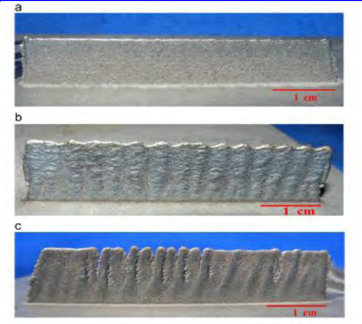


Figure 1. view of thin-walled parts with different defocusing distances

Product Fact Sheet

- ✓ **Validated Database of Titanium Alloy**
- ✓ **Automated FE Mesh Generator** (local, global)
- ✓ **Re-simulate printing paths** with bead width, angle and timing precision (**Figure 2**)
- ✓ **Export either specific or all layers to ABAQUS input deck for analysis**
- ✓ **Material defects and surface roughness (Local Model)**
- ✓ **Predict material stress -strain curve:**
- ✓ **Predict material fracture toughness and fatigue crack growth:** using extended Griffith theory
- ✓ **Predict thermal induced residual stress including void and defects**
- ✓ **Predict complex part performance:** using the measured/predicted NDE defects (void/roughness)
- ✓ **Predict: 1) thermal residual stress, and 2) fatigue S-N curve and crack growth vs. cycles using Stress-Intensity with defects (GENOA-ABAQUS).**
- ✓ **Material Uncertainty:** Predict scatter effect on material properties

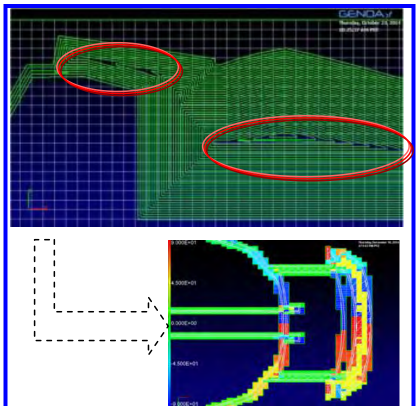


Figure 2. Zonings and Bald Spot Exhibited during AM

The Software Framework Incorporates the AM Process: to assist the user in making choices with respect to material mechanical properties, failure criteria, material trade studies, and effects of defects, in an effort to provide a comprehensive guide on effectiveness of failure criteria, FE solver, and use of De-homogenized Multi-Scale progressive failure analysis (**Figure 3**) and probabilistic/statistical analysis to select the most important parameters and requirements to simulate 3D printing.

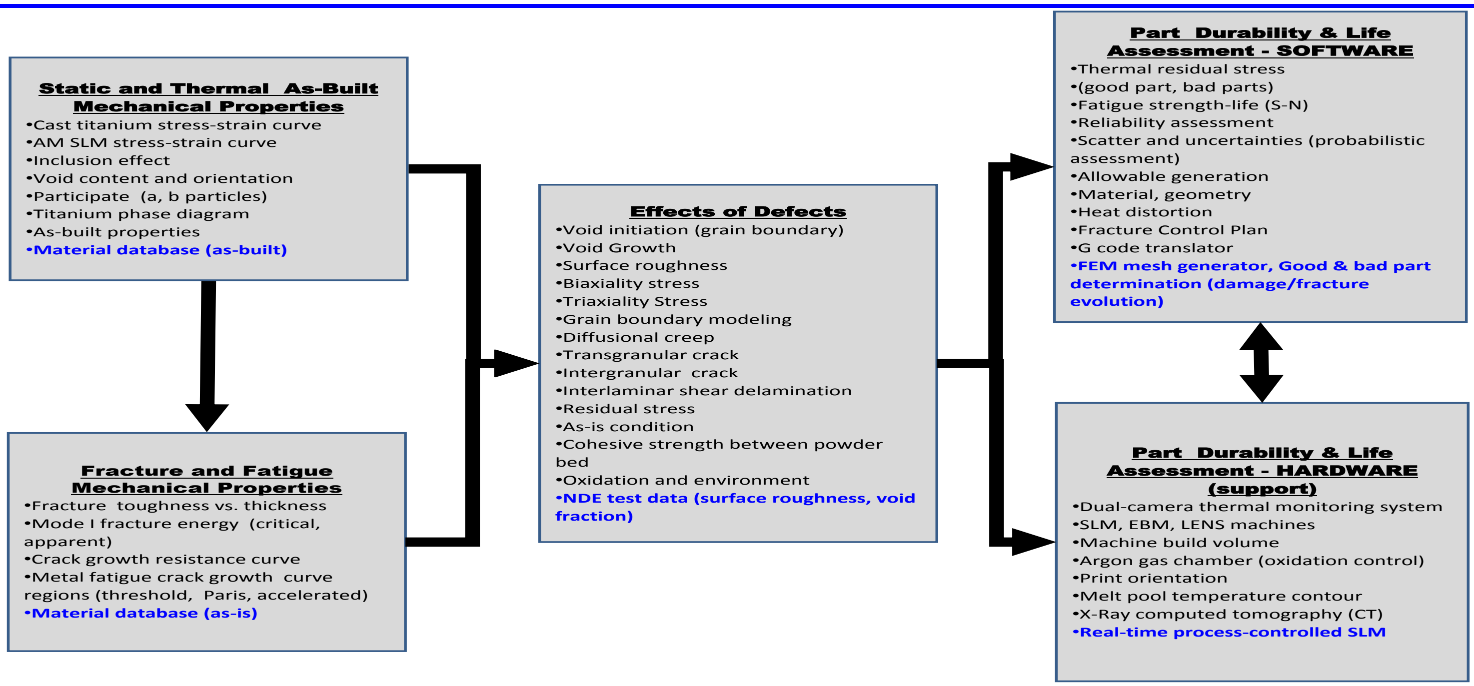
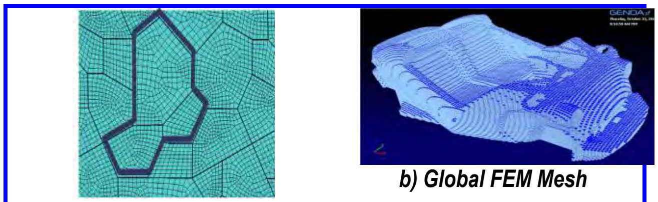


Figure 3. Flow process of powder material characterization and durability and damage tolerance (D&DT) predictive software

FE Mesh and Model Generation: Two types of mesh generation are available: a) metal powder novel sub-grain size finite element meshing technique can include precipitation formed (alpha-beta transformations)to allow for surface depletion and intergranular & transgranular cracking (**Figure 4a**); and **b**) customized FE mesh generation (**Figure 4b**) for AM-fabricated part; applying digital information used by machines for printing



b) Global FEM Mesh

a). Mesh of grain microstructure

Figure 4. Loacal global Mesh from digital (G Code)

Prediction of Void Nucleation/Growth, Surface Roughness, Residual Stress, and Oxidation: multi-scale approach is used to estimate the performance of defect afflicted as-built specimens, based on fracture mechanics diffusion creep crack nucleation and growth integrated to determine the intergranular crack and surface rouhness formation (**Figure 5**) under thermal-mechanical conditions during powder-based additive manufacturing process. Heat transfer analysis is used to model: **a**) temperature-dependent material properties and **b**) distortion due to thermally induced residual stresses and formed porosity resulting in vital manufacturing defects for subsequent service loading qualification of the manufactured parts (**Figure 6**).

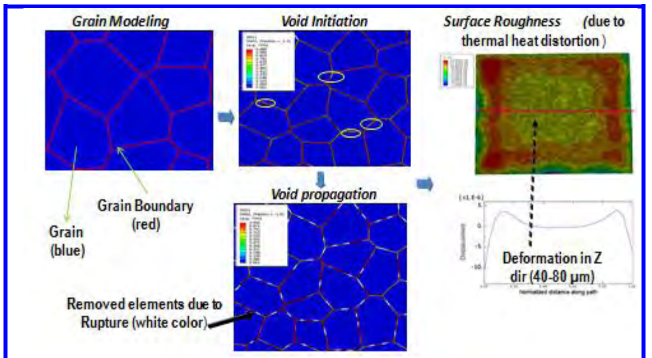
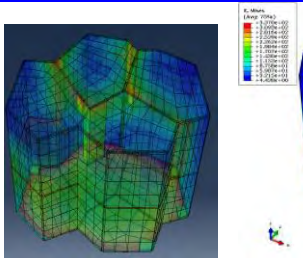


Figure 5. Intergranular/transgranular void nucleation/growth, surface roughness, and oxidation

Prediction of Material Stress-Strain Curve of 3D printed DMLS (Direct Metal Laser Sintered) material using nano-based inclusion/defects algorithm: A nano-mechanics based theory proposed by Mori-Tanaka and Eshelby was used to demonstrate the capability of GENOA 3D software to predict stress-strain curves with effect of inclusions. An example of such capability is shown for Ti-6Al-4V baseline selected material. A comparison of stress-strain curve is presented in **Figure 7**.

Predict Material Fracture Toughness and Fatigue Crack Growth using Extended Griffith Theory: A simulation set was performed using MCQ- Metals for Ti-6Al-4V (as-built) for fracture toughness determination (FTD) using stress strain curve for the material, fatigue crack growth (FCG) of CT specimens which computes ΔK vs. da/dN curves. The simulation was extended to GENOA Virtual Crack Closure Technique (VCCT) for fatigue life of a dog bone specimen which uses ΔG vs. da/dN (from ΔK vs. da/dN) curves to compute S-N curves for metallic components. All simulations compare with test data for titanium plate and DMLS titanium material with large defects representing the as-built condition. The MCQ-Metals process is the result of two theoretically-based breakthrough methodologies for metals that compute fracture/ crack growth properties from stress strain curves and specifics of CT specimen geometry and loading **Figure 8.**



(Left) surface/internal cracks, (Right) Residual stress

Figure 6. 3D printing process simulation; Local grain model analysis

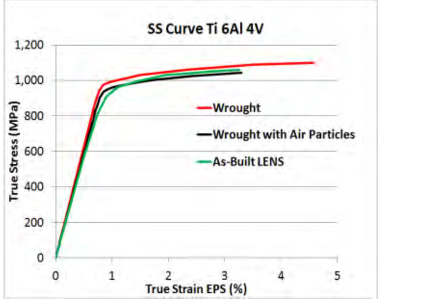


Figure 7. Predict material stress-strain curve of DMLS

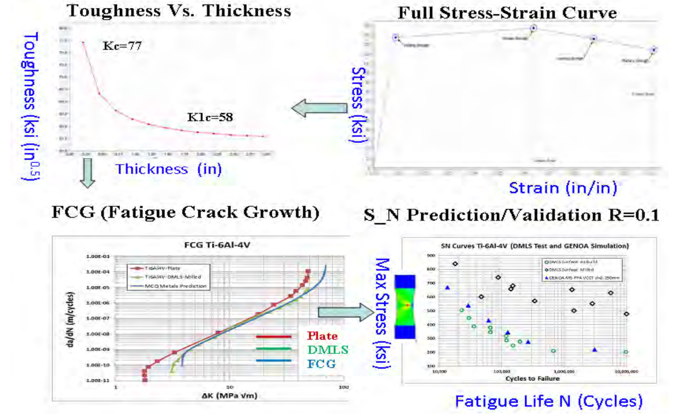


Figure 8. Global modeling of measured NDE defects and predict Fatigue S-N curve and crack growth vs. cycles

References

1. M. R. Talagani, S. DorMohammadi, R. Dutton, C. Godines, H. Baid, F. Abdi, V. Kunc , B. Compton, S. Simunovic, C. Duty, L. Love, B. Post, C, Blue, "Numerical Simulation of Big Area Additive Manufacturing (3D Printing) of a Full Size Car". SAMPE Journal, Volume 51, No. 4, July/August 2015.

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