Why Wind Blades Brake)

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Agenda

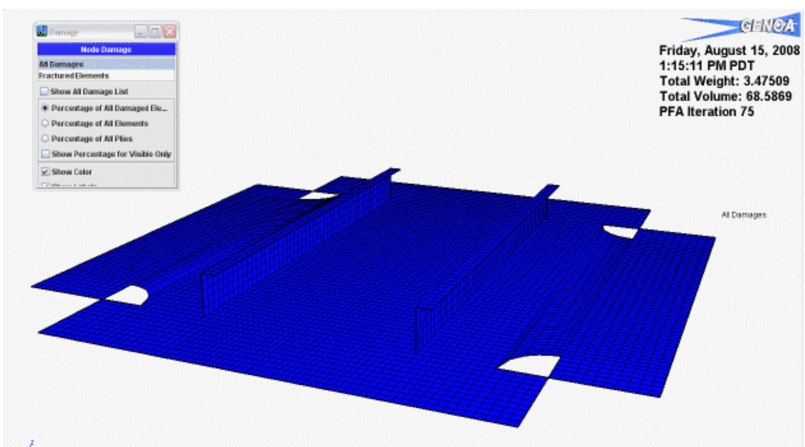
- **Issues in Composites**

- **Test Validations:**
  - Characterization and Effect of Manufacturing of Ply Drop-offs
  - 9-Meter Blade Validation – Static/Fatigue

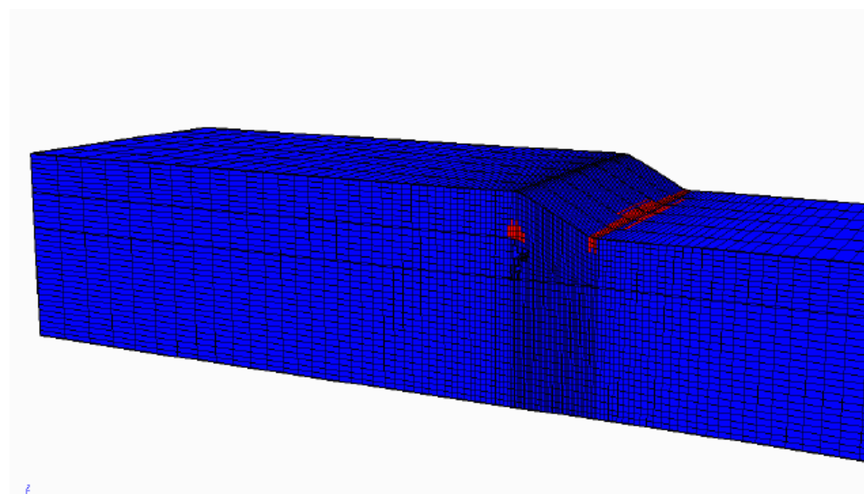
- **Methodology**
  - Material Characterization and Qualification MCQ
  - GENOA durability and damage tolerance (D&DT)

Issues of Interest

- **Premature Failure in Joints**
- **Optimize Layup of the composites (textile types/angles/layers)**
- **Manufacturing anomalies (waviness/porosity/fiber buckling/wrinkling)**
- **Critical modeling details (e.g., changes in thickness, ply drops, gaps, voids, overlaps, debonding)**
- **Failure near the root and 1/3rd section of the blade during static and service life (fatigue)**
- **Tape/fabric glass/carbon fiber composites**
- **Weight reduction issues**



Buckling –Stiffened panel

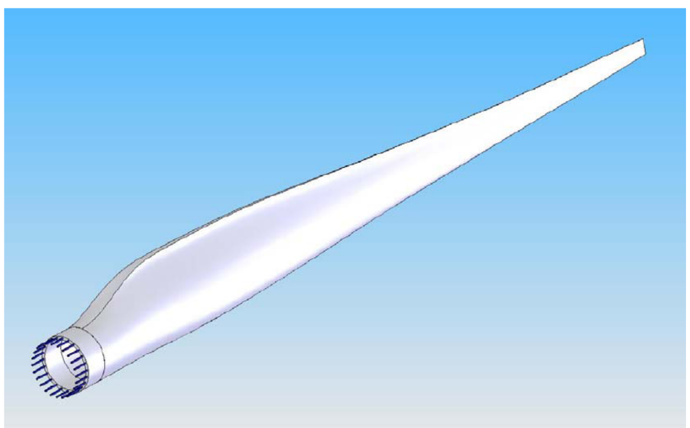


Ply drop off

Sandia Blade Details

Design Basis
9m Blade Length
Planform Fc Scaled to 9m

Structure
Gelcoat
¾ oz mat
DB1708 outer and inner skins
¼" forward and aft panel balsa
¼" carbon spar
DB1708/balsa/DB1708 shear web
DB1708/balsa/DB1708 flatback



Blade System Design Computer Model[1]

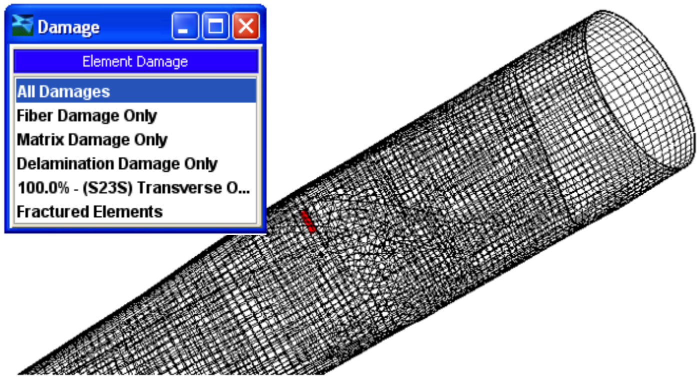
BSDS Blade Assembly

BSDS Blade Finishing

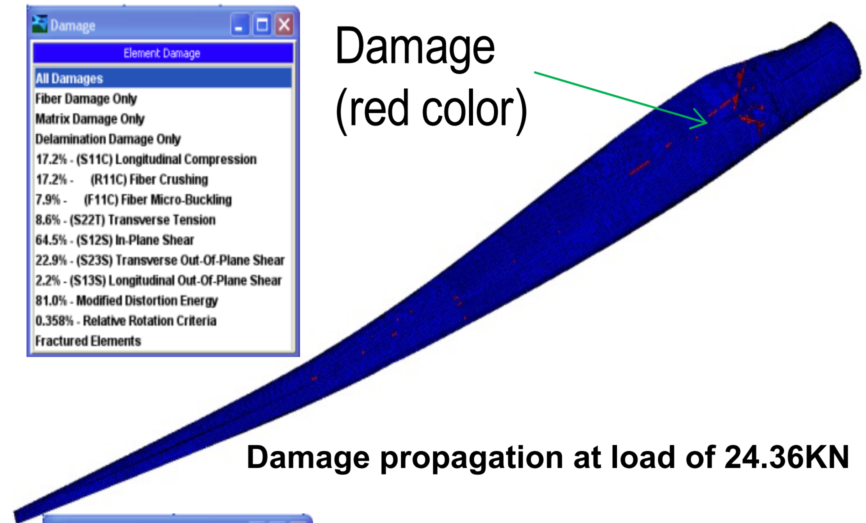
[1] ***Reference:*** D. Berry, **Blade System Design Studies Phase II: Final Project Report**. Sandia Report SAND2008-4648, July 2008.

Analytical Simulation of Sandia's Blade Static Test

Multi-Scale Progressive Failure Analysis (MS-PFA) Identifies all Damage Evolution Stages

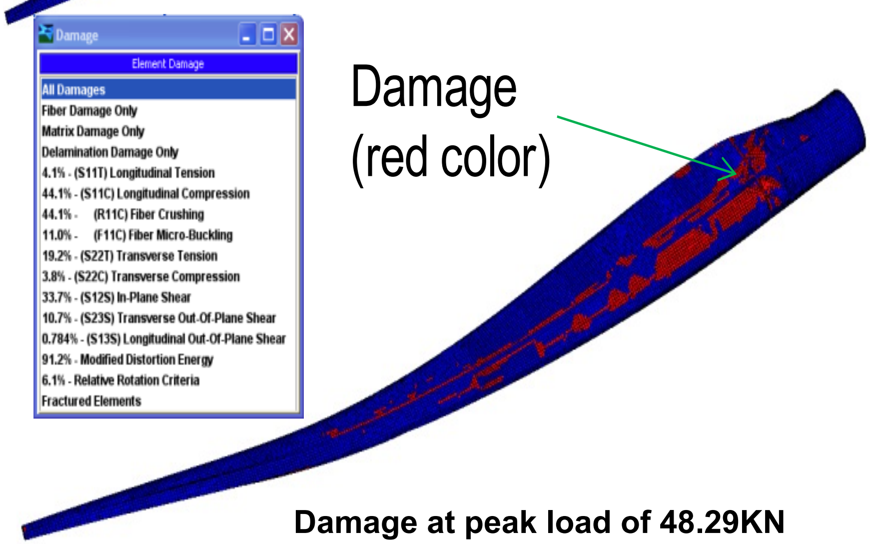


Damage initiation at load of 8.7KN (transverse out of plane stress)



Damage propagation at load of 24.36KN

Damage at test peak load of 48.612KN (2 m from root of the blade)

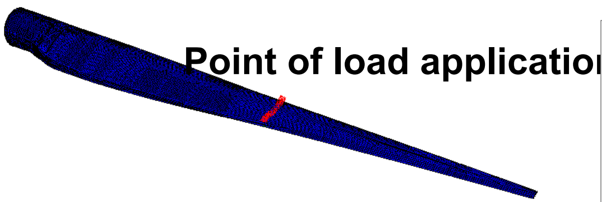


Damage at peak load of 48.29KN

Ref: Galib Abumeri, Joshua Paquette, Frank Abdi, "***Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach,*** ", AIAA-SDM 2011 conference, Denver Colorado, AIAA_SDM_945357

Blade Fatigue Analysis

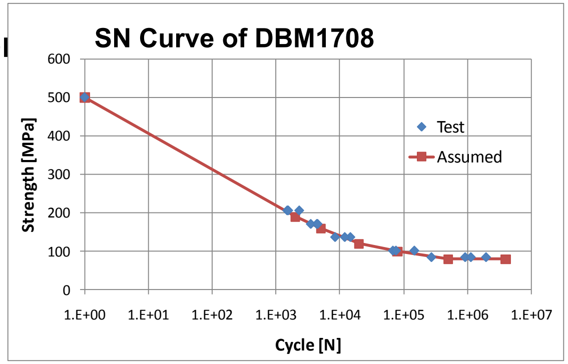
Blade failed in test after 17 blocks of loading

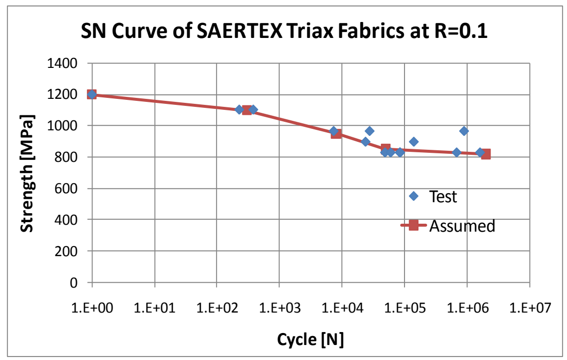


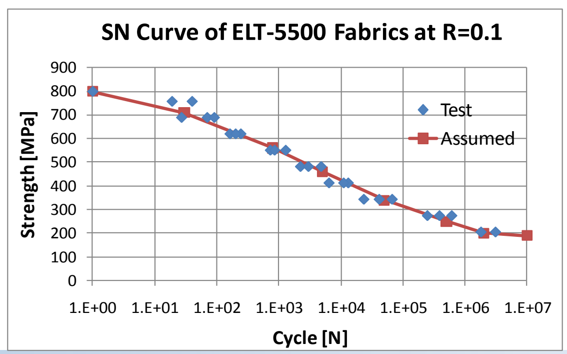
Fatigue load sequence

Load Block	Load Type	Start Cycle	End Cycle	Number of Cycles	Mean Load (N)
1	Flap	1	1045762	1045761	3797
2	Edge	1045762	2071869	1026107	797
3	Flap	2071869	2572033	500164	4271
4	Flap	2572033	3075051	503018	4659
5	Flap	3075051	3576257	501206	4929
6	Flap	3576257	4078930	502673	5489
7	Flap	4078930	4329294	250364	5962
8	Flap	4329294	4582725	253431	6388
9	Flap	4582725	4833015	250290	6989
10	Flap	4833015	5085684	252669	7783
11	Flap	5085684	5336174	250490	8166
12	Flap	5336174	5588916	252742	9094
13	Flap	5588916	5838815	249899	9941
14	Flap	5838815	6101283	262468	10748
15	Flap	6101283	6188069	86786	14252
16	Flap	6188069	6439067	250998	11873
17	Flap	6439067	6686541	247474	13026

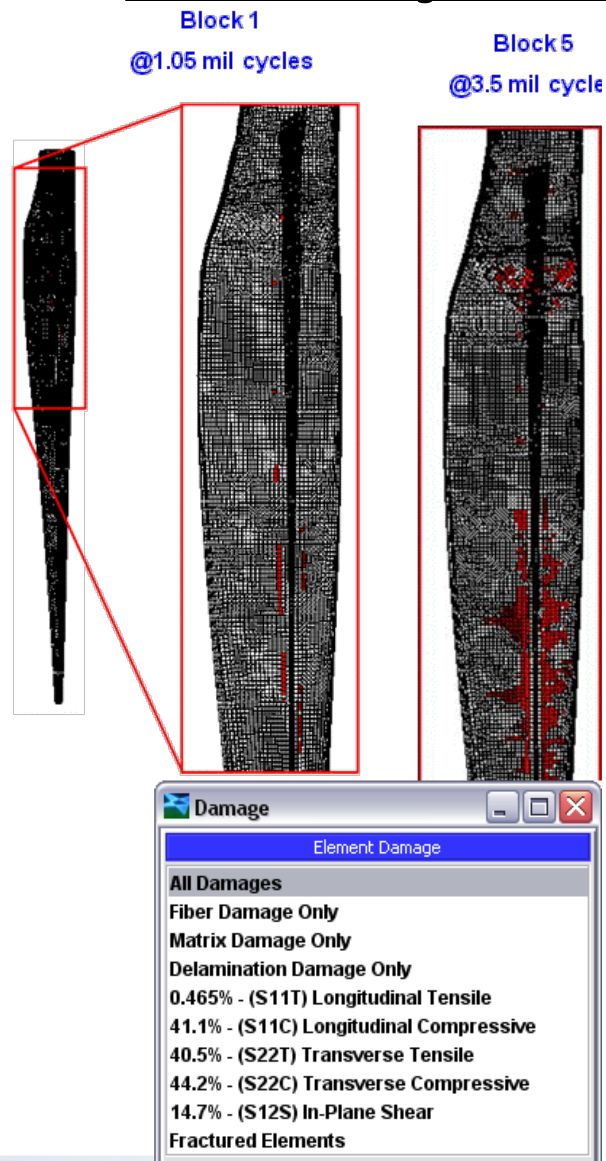
Typical SN Curves







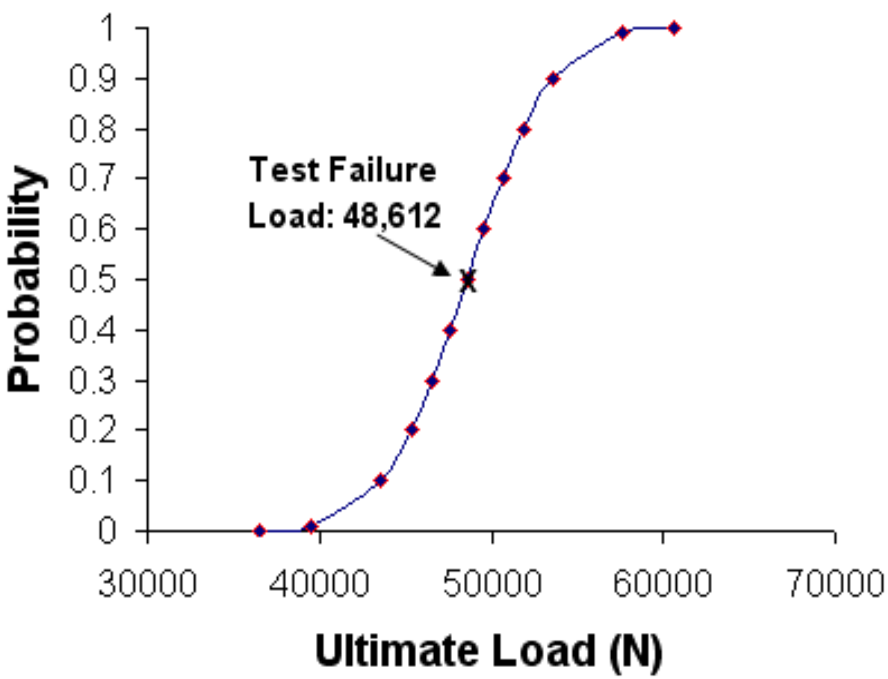
Structural Damage in Blade



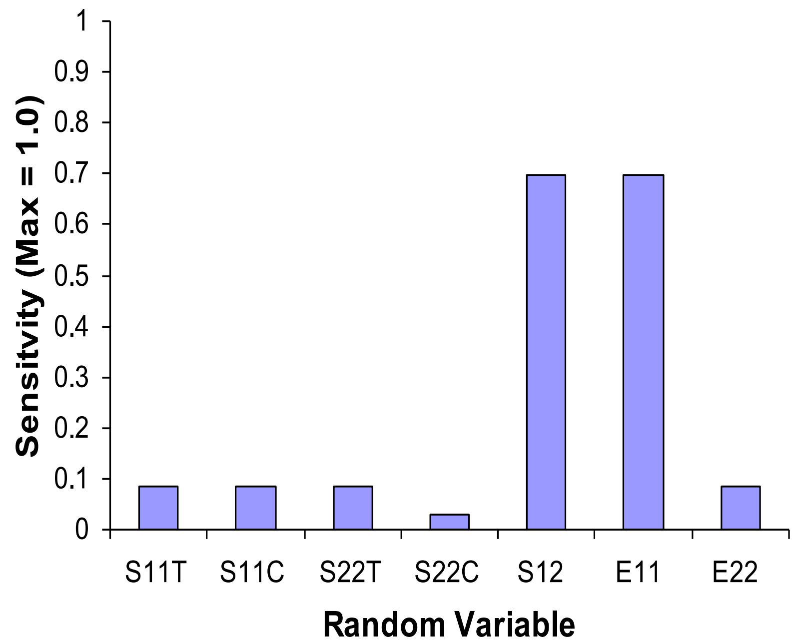
Blade Probabilistic Sensitivity Analysis

Probabilistic analysis provides measure of reliability for given loading
Sensitivity analysis ranks random variables influence on material or structural response

Probabilistic scatter in blade failure load subject to static loading due to uncertainties in properties of DBM1708 material



Probabilistic sensitivity of random variables due uncertainties in properties of DMB1708 material



S11t ply longitudinal tensile strength; S11c ply longitudinal compressive strength; S22t ply transverse tensile strength; S22c ply transverse compressive strength; S12 ply shear strength; E11: ply longitudinal modulus; and E22: ply transverse modulus.

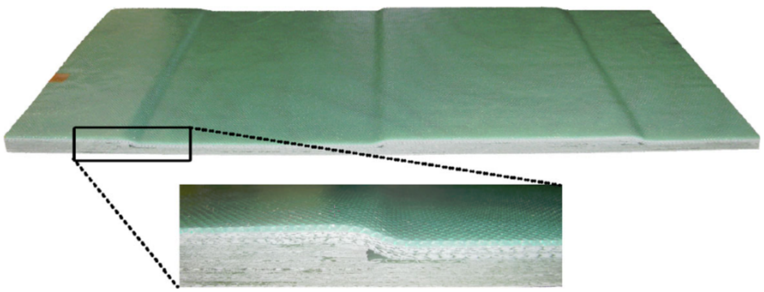
Reference: Galib Abumeri, Joshua Paquette, Frank Abdi, "***Durability and Reliability of Wind Turbine Composite Blades Using Robust Design Approach,*** ", AIAA-SDM 2011 conference, Denver Colorado, AIAA_SDM_945357

Progressive Failure Analysis of Thick Laminates for Wind Turbine Blades Application

Accuracy

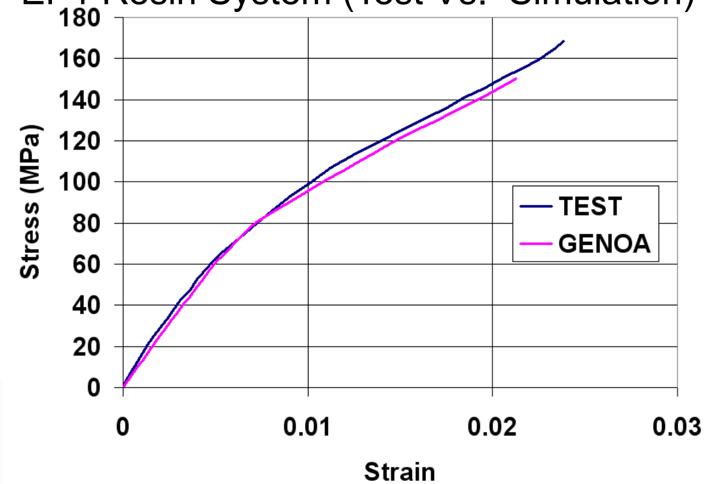
Simulate Complex Test Coupons with Ply Drops under Tension Loading

Infused Panel Containing Ply Drops

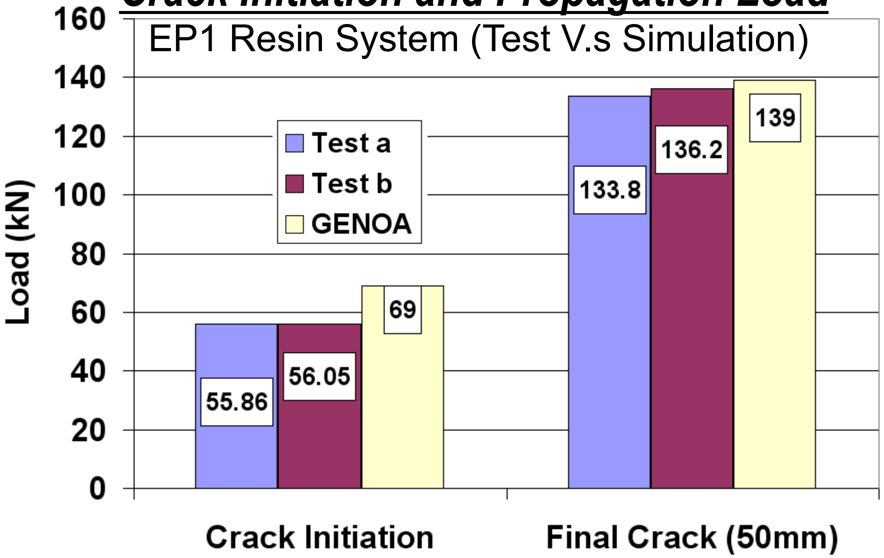


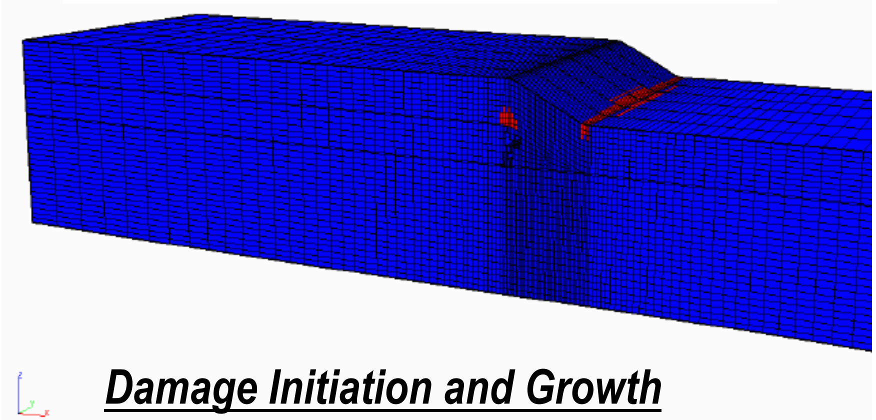
Coupon Tensile Test Shear Stress-Strain

EP1 Resin System (Test Vs. Simulation)



Crack Initiation and Propagation Load



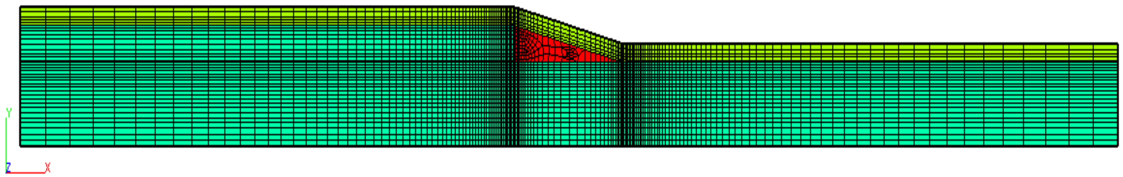


Damage Initiation and Growth

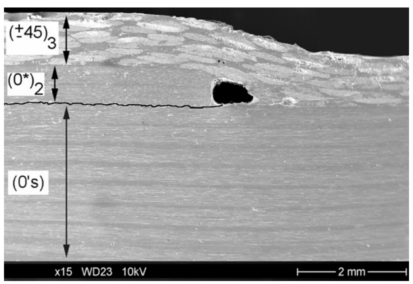
Ref: *P. Agastra, D. Samborsky, and J. Mandell, "Fatigue Resistance of Fiber Glass Laminates at Thick Material Transitions."* ***AIAA 50th SDM Conference,*** *Palm Spring, CA 2009.*

Simulation of Complex Ply Drop-off Laminates

Compressive Static Loading

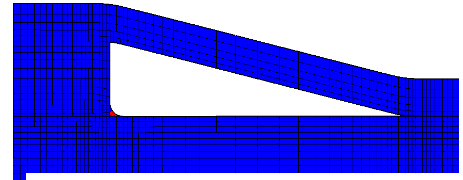


Shell finite element model for laminates with ply drops

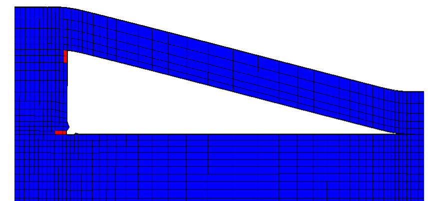


- Red color identifies damaged elements
- Damage and failure modes: longitudinal compression and in-plane shear

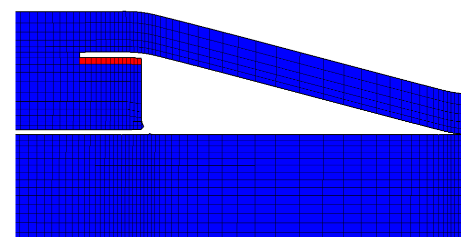
Damage Progression in Ply Drop Coupons Under Compression



Damage Initiation Stress: 138.75 MPa



Damage Propagation Stress: 294.34 MPa



Final Failure Stress: 588.46 MPa

Compression Static stiffness and strength with Test

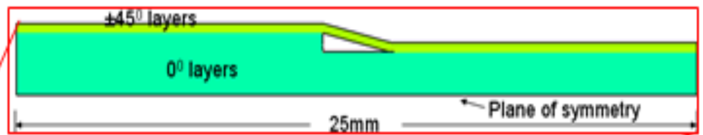
Laminate with ply drop	Compressive Strength MPa		error %	Compressive Strain %		error %
	Test	GENOA		Test	GENOA	
$[\pm45/0_2^*/0_9/0_2^*/\pm45]$	617	588.46	-4.63	0.64	0.57	-10.94

Ref: Daniel D.Samborsky, Timothy J. Wilson, Pancasatya Agastra, and John F. Mandell. "**Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading**," ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.

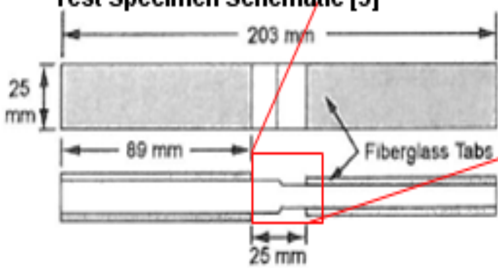
Simulation of More Complex Ply Drop-off Laminates

Tension Static Loading

FEA Model Generated for progressive failure analysis



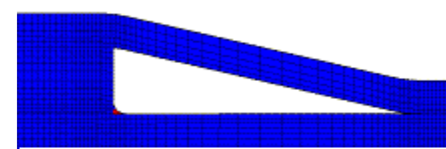
Test Specimen Schematic [3]



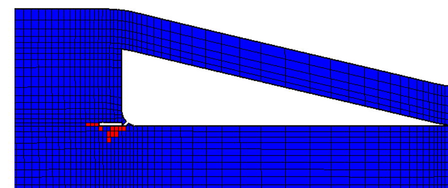
Layup Details: $[\pm45/0_2/09/0_2/\pm45]$
E-glass epoxy in ±45 plies (2 D weave)
Carbon epoxy in 0 deg plies

- **Red color identifies damaged elements**
- **Damage and failure modes: longitudinal compression and in-plane shear**

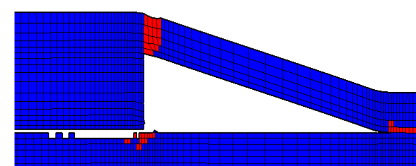
Damage Progression in Ply Drop Coupons Under Tension



Damage Initiation Stress: 161.52 MPa



Damage Propagation Stress: 161.52 MPa



Final Failure Stress:

852.77 MPa

Tension Static stiffness and strength with Test

Laminate with ply drop	Tensile Strength			Tensile Strain		
	MPa		error	%		error
	Test	GENOA	%	Test	GENOA	%
$[\pm45/0_2^*/0_9/0_2^*/\pm45]$	827	852.77	3.12	0.85	0.85	0
* Dropped Plies						

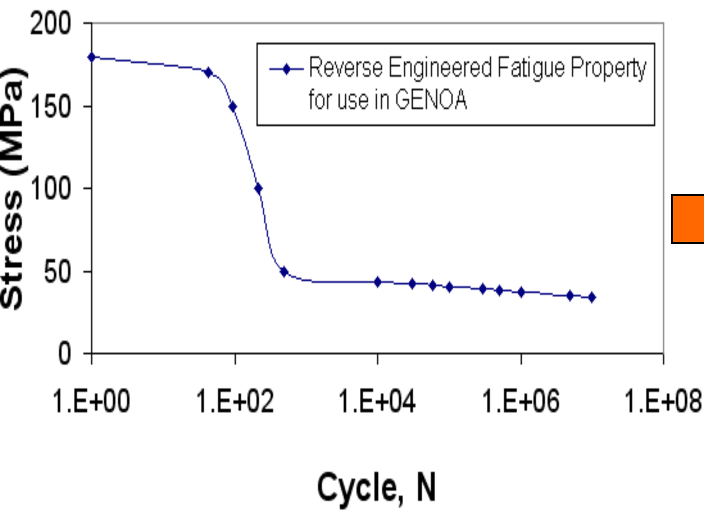
Ref: Daniel D.Samborsky, Timothy J. Wilson, Pancasatya Agastra, and John F. Mandell. "**Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading**," ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.

Fatigue Results Compared to Test (Coupon without Ply Drop)

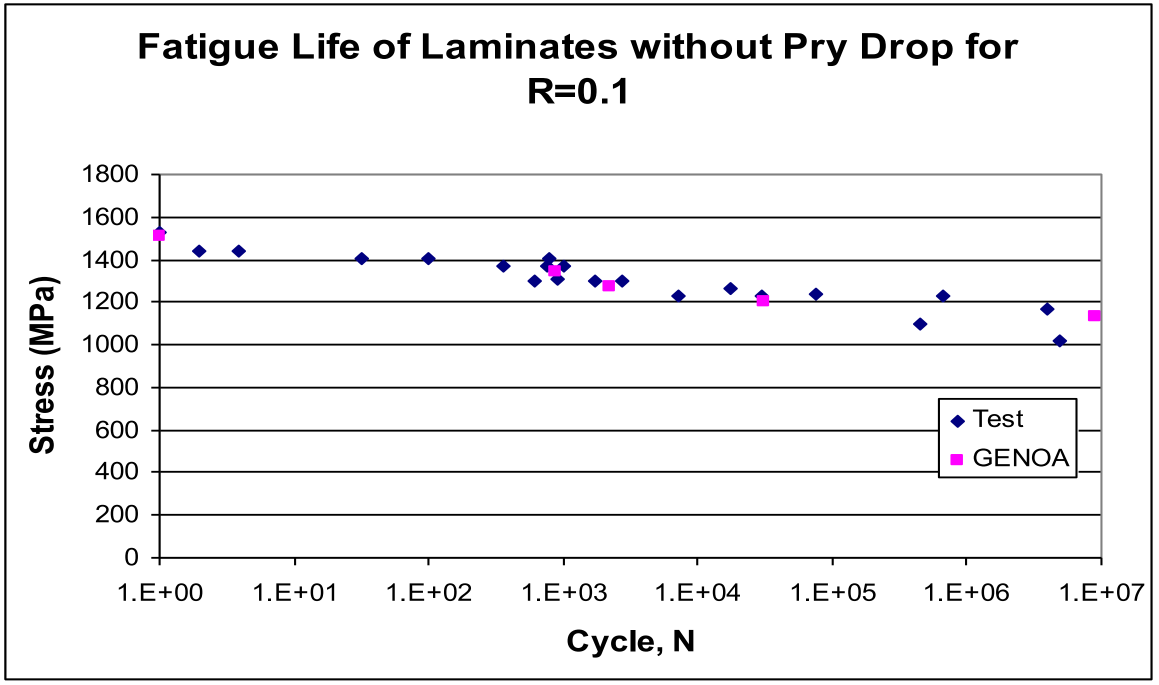
Subjected to a tensile loading under a stress ratio of 0.1

- Fatigue property of a $[\pm 45/0_4]_s$ coupon [Ref]
  - carbon/epoxy in 0^0 layers and E-glass/epoxy in $\pm 45^0$ layers
  - 0.3mm ply thickness

Input: Resin Fatigue Properties from MCQ Composites



Output: Fatigue life

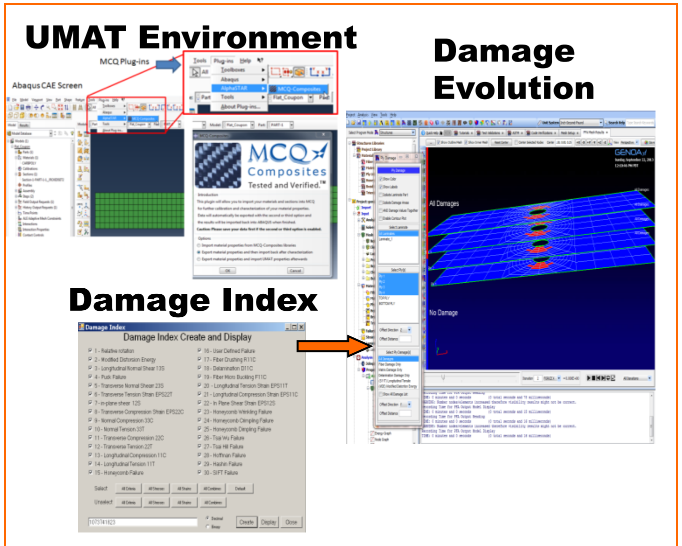


Ref: D.D. Samborsky, T.J. Wilson, P. Agastra, and J.F. Mandell. "**Delamination at Thick Ply Drops in Carbon and Glass Fiber Laminates under Fatigue Loading**," ASME Journal of Solar Energy Engineering, Vol.130, No.3, pp.1-22, 2008.

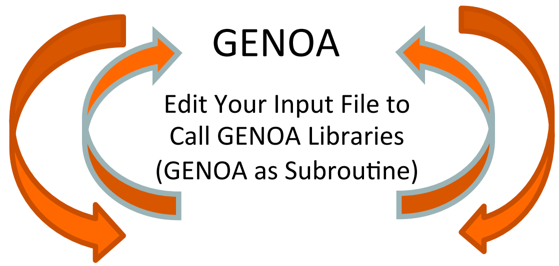
METHODOLOGY

GENOA Platform Augments Commercial FEA Software

GENOA augments FEA software in 2 ways + Web Based GUI:



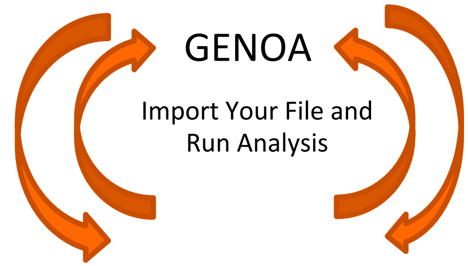
UMAT + GENOA



Radioss/Abaqus/
Ansys/LS Dyna

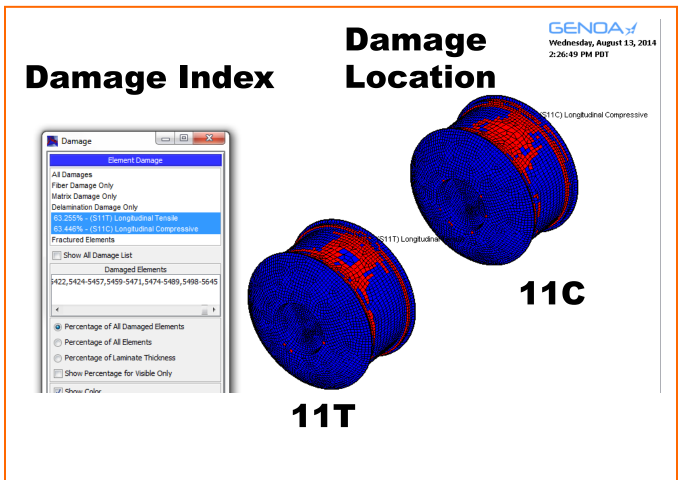
GENOA GUI tracks damage and fracture

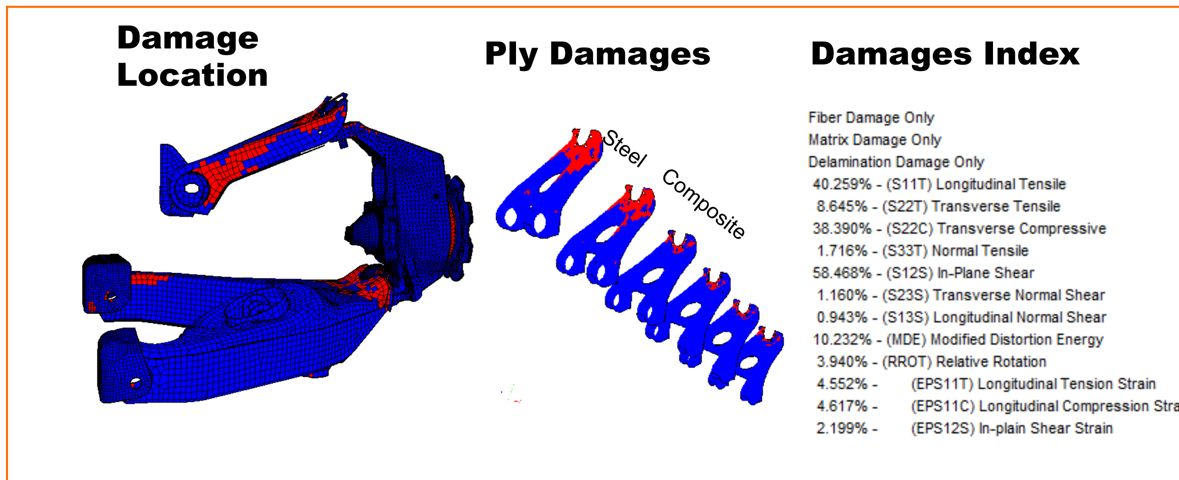
GENOA + ALL FEA



ALL FEA:

ABAQUS, Optistruct, Radioss, LSDYNA, ANSYS, NASTRAN and MHOST





1. GENOA with Graphical User Interface (implicit, explicit, static, and fatigue (low/high cycle, spectrum))
2. GENOA has a database of composite materials by class, test validations & simulations with I/O and tutorials.

Objective - Quick Accurate Decision Making

Modeling Complexity Approach Conforms to FAA Building-Block Validation Strategy

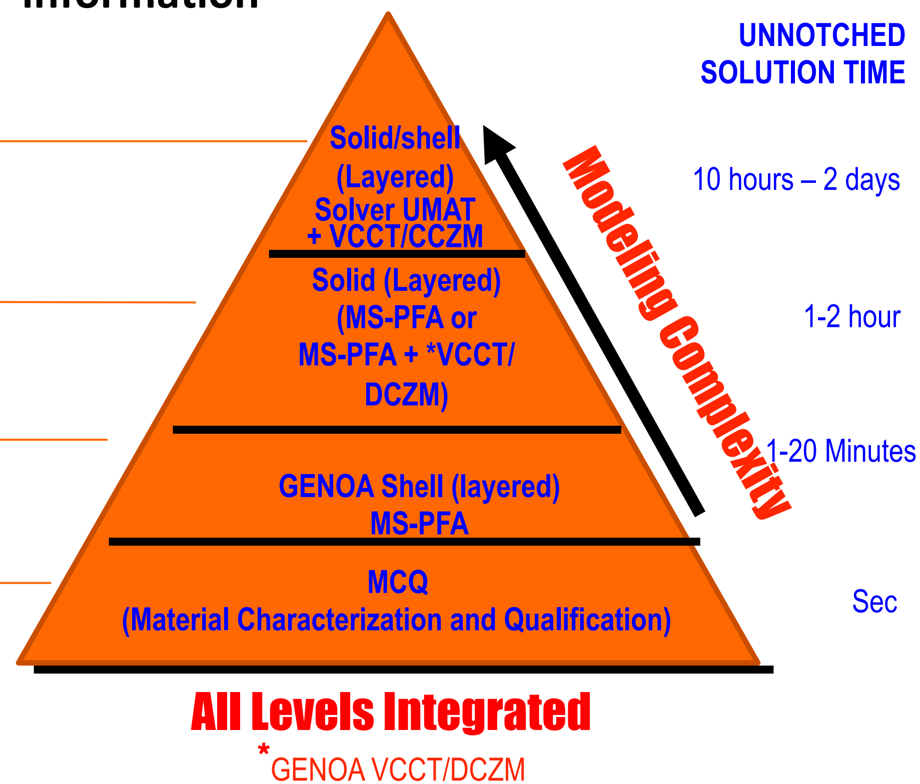
- **All methods give extensive damage Evolution information**

GENOA USERMAT: **Advantages:** Within solver environment all capabilities supported. **Disadvantages**: Post failure convergence. Must use Solver's VCCT or CCZM thus only linear cohesive strength supported. Fracture can go only straight.

GENOA Solid: **Advantages:** More accurate model. Integrated with MCQ modeling and all FE Solvers. Gives non linear cohesive failure. **Disadvantages**: Long run time and more complex modeling issues to deal with. Not practical for subsystems.

GENOA One Shell For Full Laminate: **Advantages:** Fast and accurate model. Integrated with MCQ modeling and all FE Solvers. **Disadvantages**: Does not give you cohesive failure.

MCQ: **Advantages** Unnotched, 2-D: Tape /Fabric; 3-D (Braid, Stitched) Laminate Strength/Strain, Properties, Effect of Defects Carpet plots/Failure envelope, Strength Allowable Generation (reduced test), Environmental Degradation, Micro-crack density (leakage, stiffness reduction). **Disadvantages:** Unnotched



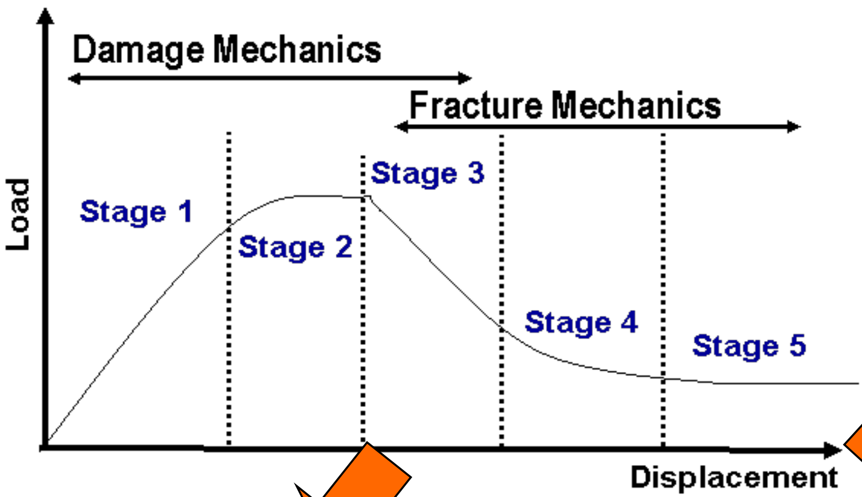
Quickly Predict Results, Consider Uncertainties/Defects, and Build Toward Complex and Advanced Solid Modeling

Hierarchy - Low Fidelity Model Feeds Into Higher Models

Technical Approach

Cont'd

GENOA PFA Combines Damage & Fracture Mechanics



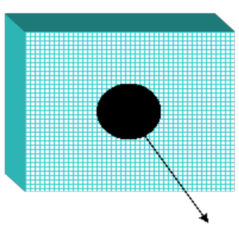
STEP 1: Simulate with PFA
- **Estimate damage accumulation in FE model**
- **Predict damage and failure initiation and damage propagation**
- **Predict crack path, g1c, g2c**

STEP 2: Use VCCT (2d/3d) or DCZM (2d/3d)
- **Prepare a coarser FE model again with pre-defined crack path (predicted via PFA simulation or test)**
- **Simulate and predict complete damage and failure process (damage initiation and propagation, crack initiation and propagation and final failure) of the component**
- **DCZM combined with PFA to account for damage accumulation for improved predictions**

STEP 3: Combined PFA + VCCT/DCZM

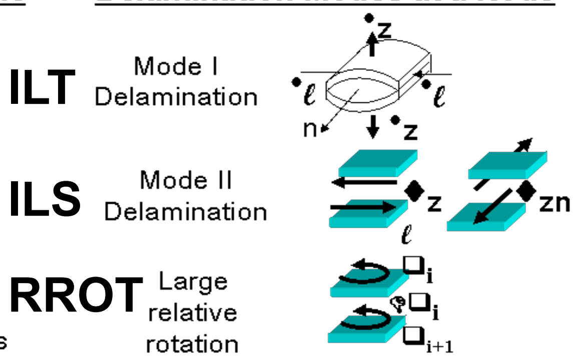
Damage Mechanics Delamination Type

Sub-Divided Unit Cell at a Node



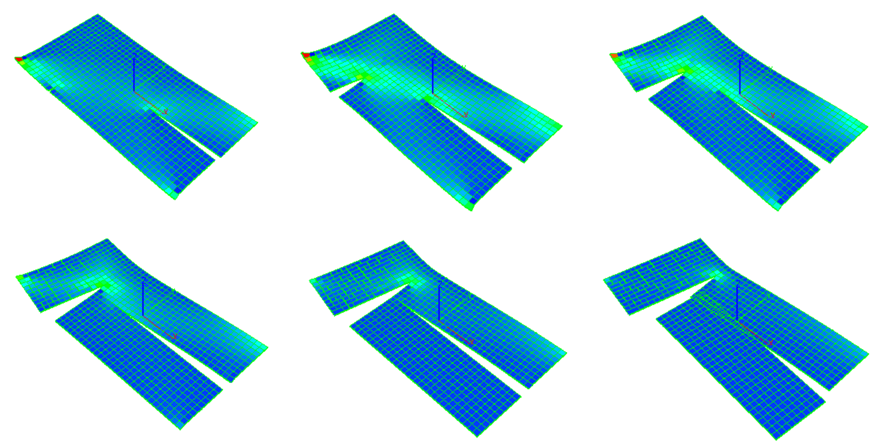
- Employ micro-stress theory
- Determine stresses in sub-divisions
- Interogate sub-divisions for violations of 16 failure criteria

Delamination Modes at a Node

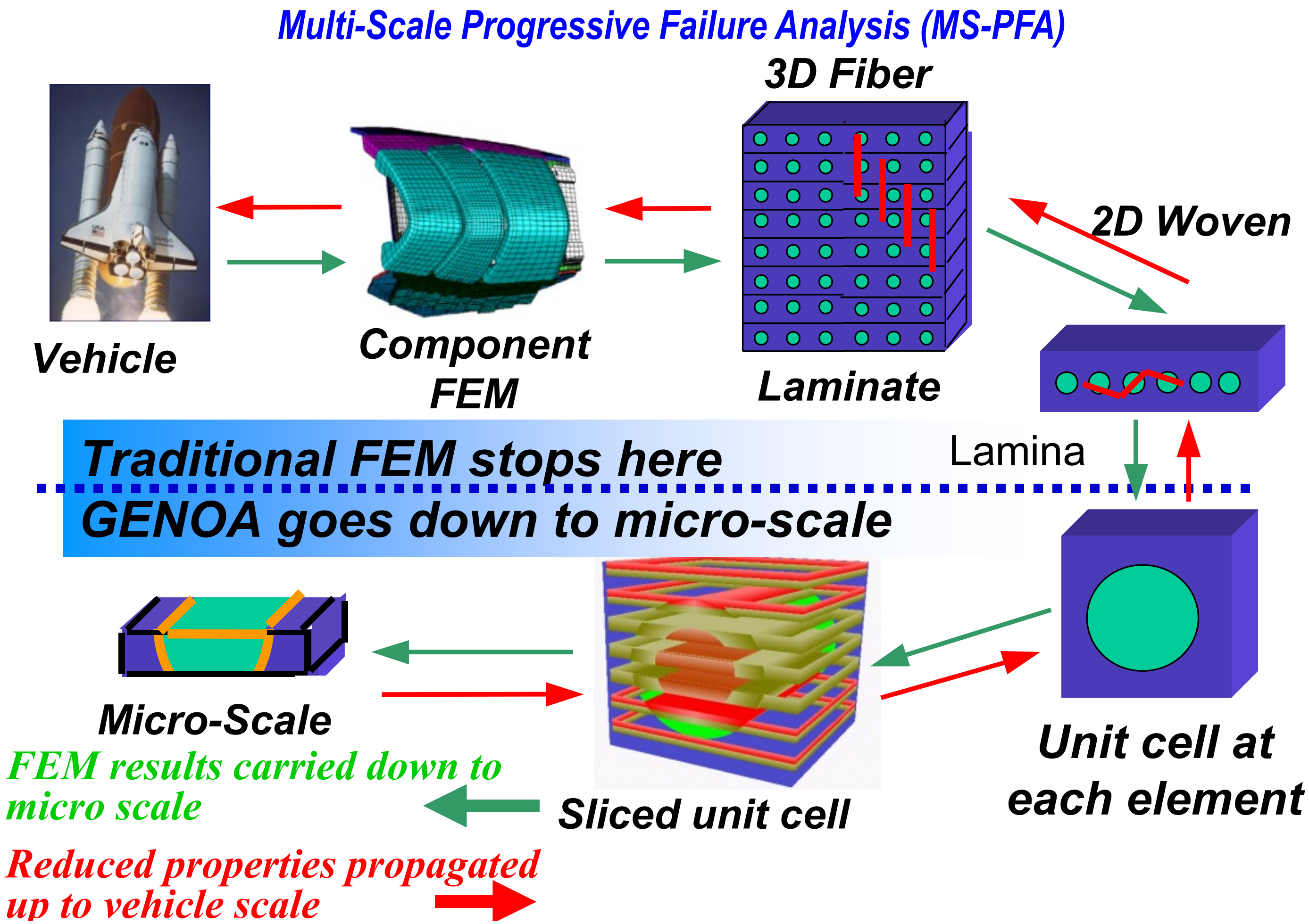


- Employ micro-stress theory
- Determine interlamina stresses
- Interogate lamina for violations of 6 failure criteria

Fracture Mechanics Delamination



In-Depth Evaluation of Multi-Scale Process



PFA takes full-scale FEM and breaks material properties down to microscopic level. Material properties are updated, reflecting any changes resulting from damage or crack

Multi-Scale Multiple Failure Criteria

Strength and Fracture Mechanics based

1. Matrix: Transverse tension
2. Matrix: Transverse compression
3. Matrix: In-plane shear (+)
4. Matrix: In-plane shear (-)
5. Matrix: Normal compression
6. Matrix: Micro crack Density

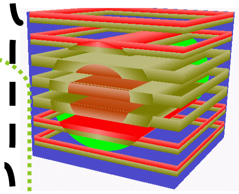
7. **Fiber: Longitudinal tension**
8. **Fiber: Longitudinal compression**
   - Fiber micro buckling
   - Fiber crushing
   - Delamination
9. **Strain limit**

10. **Interactive***
    - **MDE (stress)**
    - **SIFT (strain)**

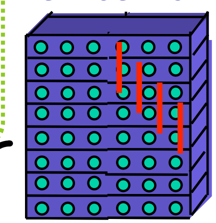
11. Normal tension
12. Transverse out-of-plane shear (+)
13. Transverse out-of-plane-shear (-)
14. Longitudinal out-of-plane shear (+)
15. Longitudinal out-of-plane shear (-)
16. Relative rotation criteria
17. Edge Effect

18. **VCCT, DCZM-2d-3d (LEFM)**
19. **Honeycomb****

Unit Cell damage criteria



Delam criteria



* **Options: Tsai-Wu, Tsai-Hill, Hashin, Puck, User Defined Criteria**

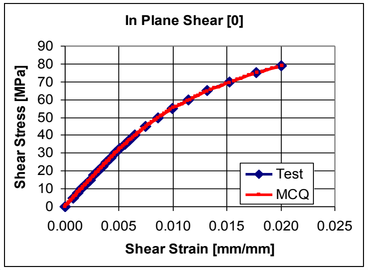
** **Wrinkling, Crimpling, Dimpling, Intra-cell buckling, Core crushing**

Ref: D. Huang, F. Abdi, A. Mossallam, "Comparison of Failure Mechanisms in Composite Structure." SAMPE 2003 Conference Paper.

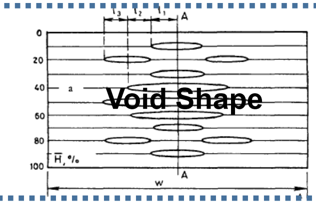
PMC Material Characterization and Qualification (MCQ)

Input

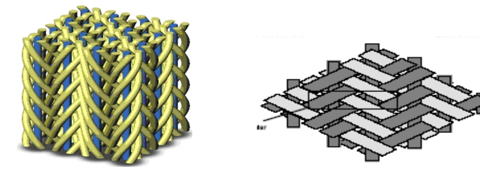
Material Non Linearity



Manufacturing Defects, As-Built

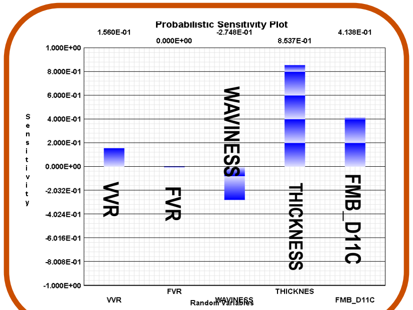


Fiber Architecture

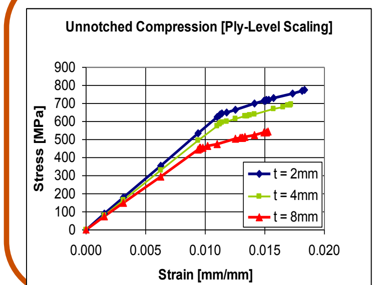


MCQ Composites

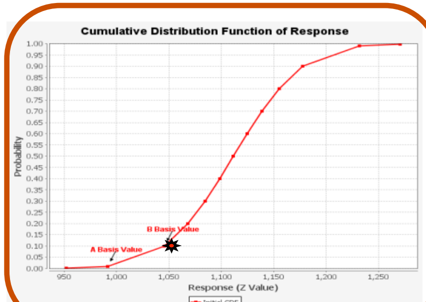
Probabilistic Sensitivity



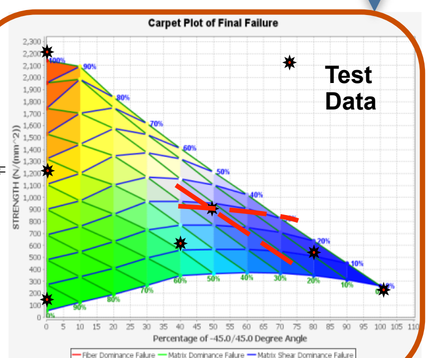
Thickness Effect



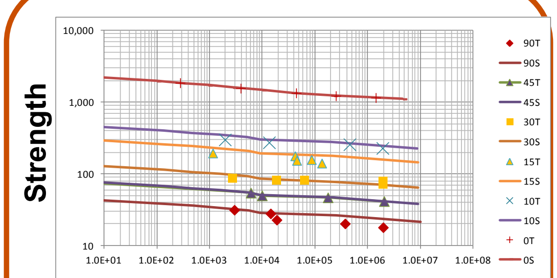
A- & B-Basis Allowables



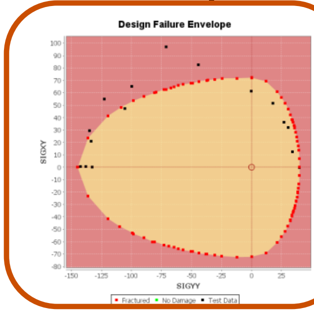
Parametric Carpet Plots



Fatigue Life



Design Failure Envelope



Characterization of T700GC/2510 (Tape)

T700GC/2510 (Tape): FVR=52.4536%; VVR=2.0443%

Material		T700GC/2510		
Property	Units	Test	MCQ	% Error
E11	[GPa]	125	125.1	0.08
E22	[GPa]	10	10	0.00
E33	[GPa]	-	10	-
G12	[GPa]	4	4	0.00
G13	[GPa]	-	4	-
G23	[GPa]	-	2.39	-
v12	[-]	0.309	0.309	0.00
v13	[-]	-	0.309	-
v23	[-]	-	0.5457	-
S11T	[MPa]	2167.623	2168	0.02
S11C	[MPa]	1447.895	1448	0.01
S22T	[MPa]	48.857	48.86	0.01
S22C	[MPa]	198.665	198.7	0.02
S33T	[MPa]	-	48.86	-
S33C	[MPa]	-	198.7	-
S12S	[MPa]	154.74	154.8	0.04
S13S	[MPa]	-	154.8	-
S23S	[MPa]	-	127.1	-

Note: Shear strain decreased to match 10/80/10 tension test
Note: Shear strength is ultimate strength and not 5% value

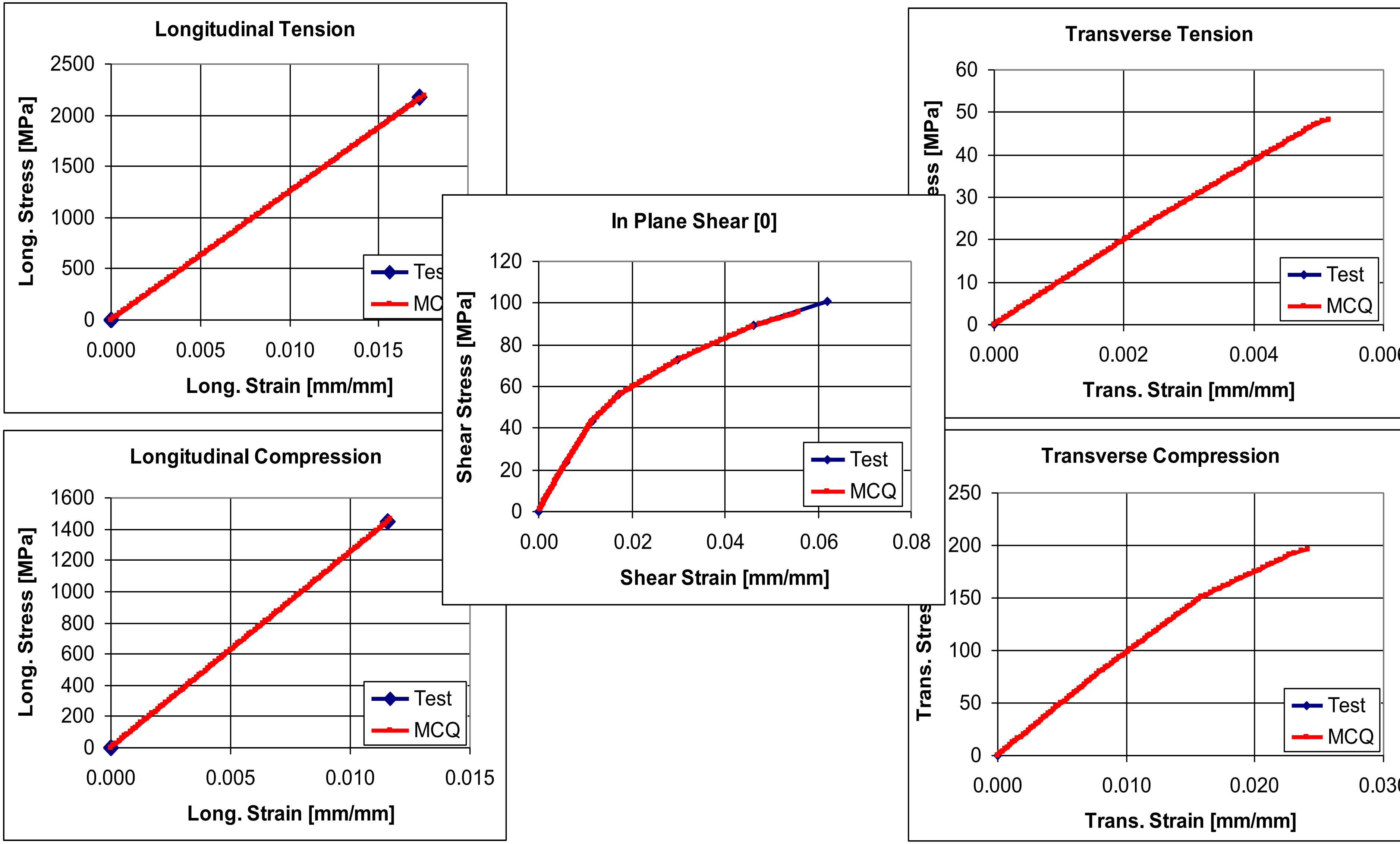
Fiber Volume Ratio FVR = 52.45%

Void VVR = 2.04%

Ply Strain Limit	Value
Eps11T	1.756E-02
Eps11C	1.158E-02
Eps22T	5.150E-03
Eps22C	2.500E-02
Eps12S	5.000E-02

Ref: NIAR Report http://www.niar.wichita.edu/agate/Documents/Materials/WP3.3-033051-132.pdf

Simulate Lamina Tests of T700GC/2510 (Tape)



Ref: NIAR Report http://www.niar.wichita.edu/agate/Documents/Materials/WP3.3-033051-132.pdf

Virtual Test Benefits

- **Reduced testing**
  - Generates allowables with progressive failure and probabilistic analyses
  - Validation on a few test cases and prediction on many cases
- **Reduced product development time**
  - Reduced testing time on allowables translates into earlier introduction of allowables into design cycle resulting in less redesign
  - Robust design capability results in designs requiring less redesign
- **Leveraging of traditional design**
  - Reliable and robust designs are achieved without weight penalty
  - Design for manufacturing via designs not sensitive to fabrication flaws saves time and costs
- **Problem solving capabilities unique to GENOA**
  - Determination of effects of certain flaws on design strength and stability are very difficult to obtain by test alone and require very accurate progressive failure analysis
  - Identifying damage composite evolution in each ply leads to designs that age and fail in predictable ways