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Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

2015 Technical Review

Michael Arce, Karen Harban, and Mark Tuttle
University of Washington

Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

- Motivation and Key Issues
  - Load-bearing discontinuous fiber composites (DFCs) are currently used in transport aircraft structures such as the Boeing 787
  - Certification achieved by testing large numbers of individual parts (certification by "point design")
  - Project goal is to transition to a certification process based on analysis supported by experimental testing

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Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

Technical Approach: HexMC (a DFC used on the B787) selected as a model material. HexMC prepreg consists of randomly-oriented "chips" of B-staged AS4-8552 (0.125x 8mm x 50mm). For this material, perform:

- Experimental studies of HexMC mechanical behaviors, starting with simple coupon-level specimens and progressing towards "complex" parts
- Study the effects of processing (e.g., impact of material flow during compression molding on stiffness and strength)
- Develop stochastic dtructural analysis methods (aka "probabilistic" or "Monte-Carlo" analyses)
- Compare measurements with analytical-numerical predictions

Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

Current Researchers (University of Washington):

- Prof. Mark Tuttle (PI)
- Michael Arce and Karen Harban, MSME Students

Additional Past Participants (University of Washington):

- Prof. Paolo Feraboli
- Graduate students: Marco Ciccu, Tyler Cleveland, Brian Head, Marissa Morgan, Tory Shifman, Bonnie Wade

FAA Personnel:

- Lynn Pham (Tech Monitor), Larry Ilcewicz, Curt Davies

Industry Participation:

- Boeing: Bill Avery
- Hexcel: Bruno Boursier, David Barr, and Sanjay Sharma

Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

Major topics of earlier papers/presentations:

(original presentations available: http://depts.washington.edu/amtas/events/index.html)

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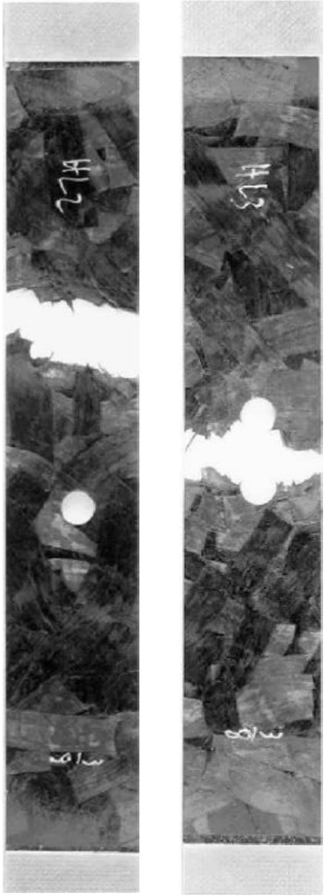
- HexMC coupon tests (e.g., UNT, OHT, UNC, OHC):
  - elastic and failure properties exhibit relatively high levels of scatter
  - HexMC is notch insensitive

- Documented by Feraboli et al:
  - (a) *J. Composite Materials*, Vol 42(19)
  - (b) *J. Reinf. Plastics and Composites*, Vol 28 (No 10)
  - (c) *Composites Part A*, Vol 40



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  - Tuttle/Shifman: JAMS '09 & '10, AMTAS Fall '09 and Spr '10

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- Modeling stiffness/strength via stochastic laminate analogy (SLA)
  Feraboli/Ciccu: JAMS '10 & '11, AMTAS Fall '10

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- Elastic bending stiffness of HexMC angle beams with non-symmetric cross-sections
  Feraboli et al: JAMS '11, Tuttle/Shifman: AMTAS Fall '10, JAMS '11

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- B-basis and B-Max measures of modulus (inferred from UW HexMC *coupon data*) used during FEM analyses of HexMC beams; predicted elastic stiffnesses bound both measurements and SLA predictions

  Tuttle/Head: AMTAS Fall '12 & ‘13

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  Tuttle/Head: AMTAS Fall '12 & '13

- Measurement/prediction of crippling/buckling/fracture of HexMC angle beams with symmetric cross-sections (FEM/SLA analyses and deterministic FEM with B-Basis and B-Max properties):
  Tuttle/Head/Arce: AMTAS Fall '13, JAMS'14

Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

Current Objective:

- To predict damage accumulation and final fracture of a HexMC intercostal when loaded as a simple cantilevered beam

Technical Approach:

- Model the intercostal using NASTRAN and the SLA approach
- Predict chip failures using the Tsai-Wu failure criterion
- Model damage accumulation using a simple "ply discount" scheme

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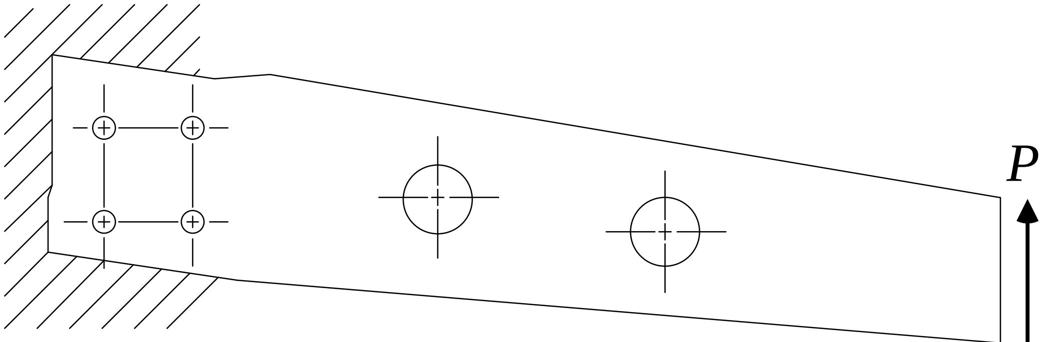
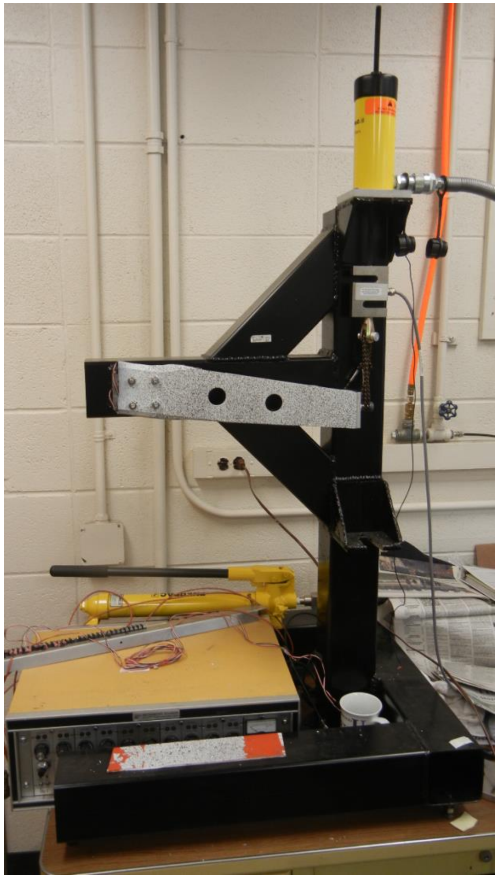
Two different experimental data bases are available for comparison to prediction:

1) Tests conducted at the UW (loaded end is free to rotate or displace in any direction)



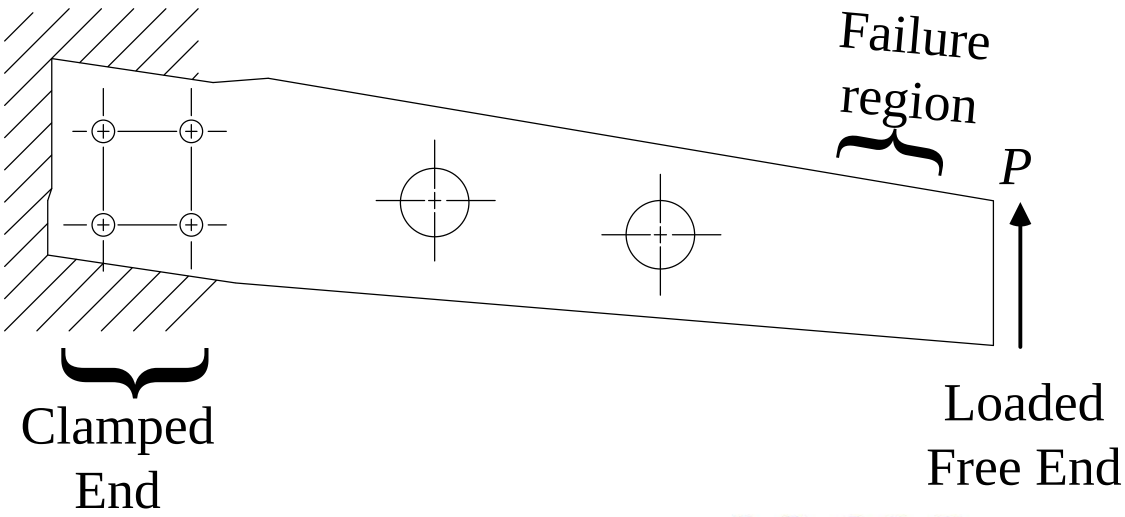


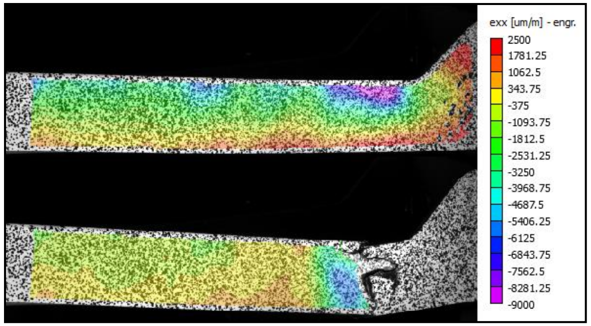
Certification of Discontinuous Composite Material Forms for Aircraft Structures: Stiffness and Strength Predictions

Two different experimental data bases are available for comparison to prediction:

1) Tests conducted at the UW:

- extensive end rotation
- all failure occurred along top of the (nominally) compressive flange





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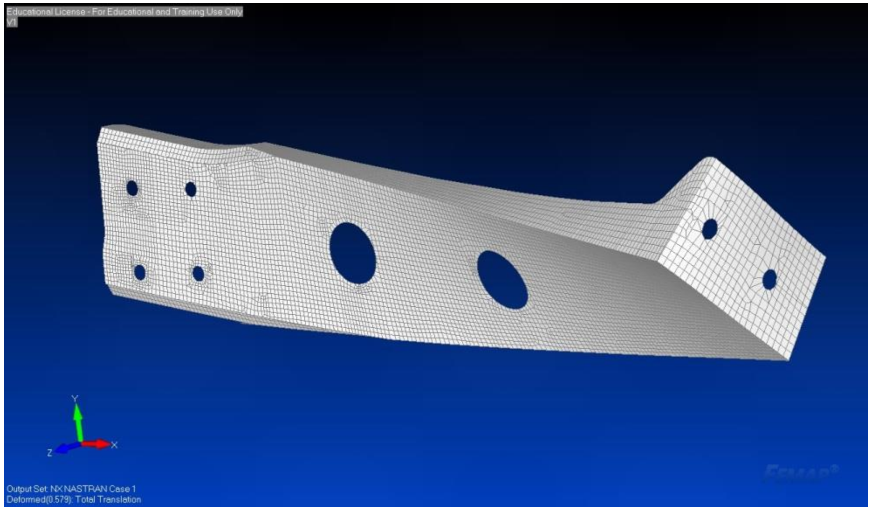

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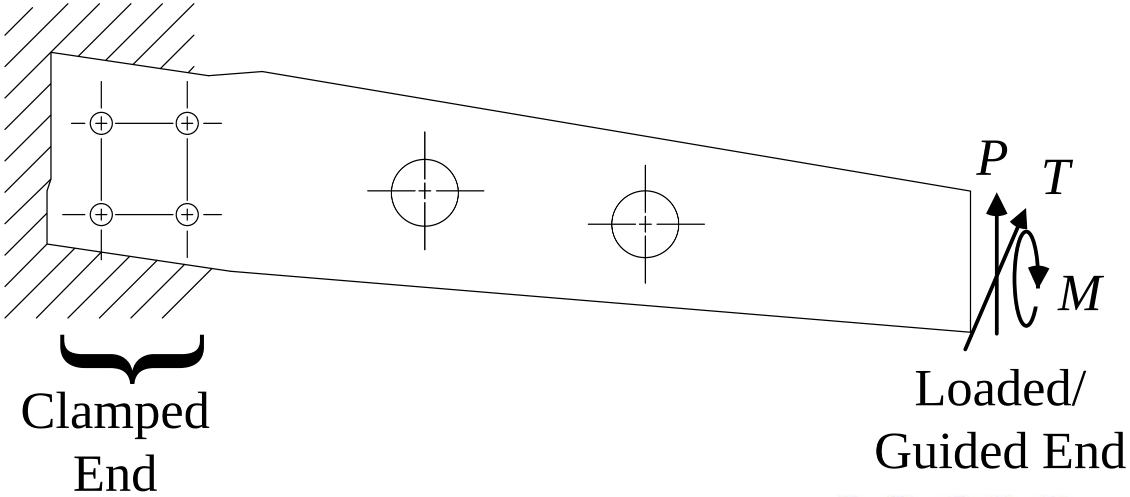
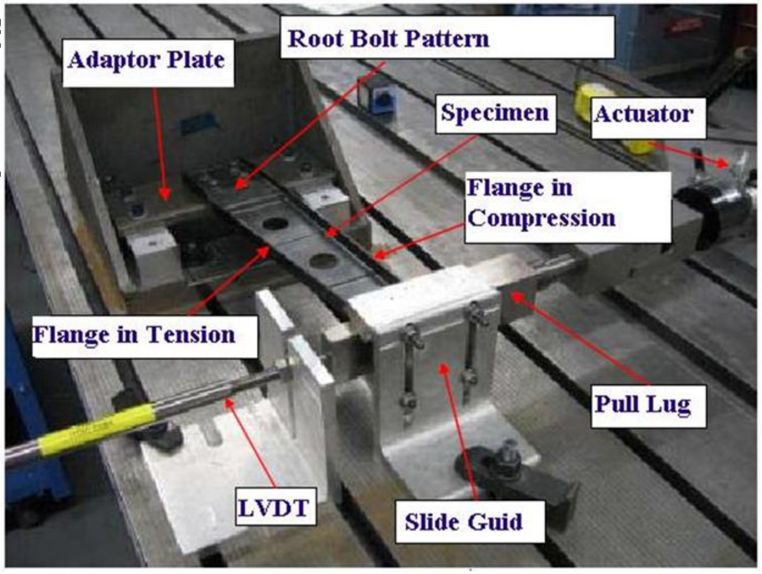
- Hexcel tests (guided end cannot rotate or displace out-of-plane reaction forces T and M were not measured; data proprietar





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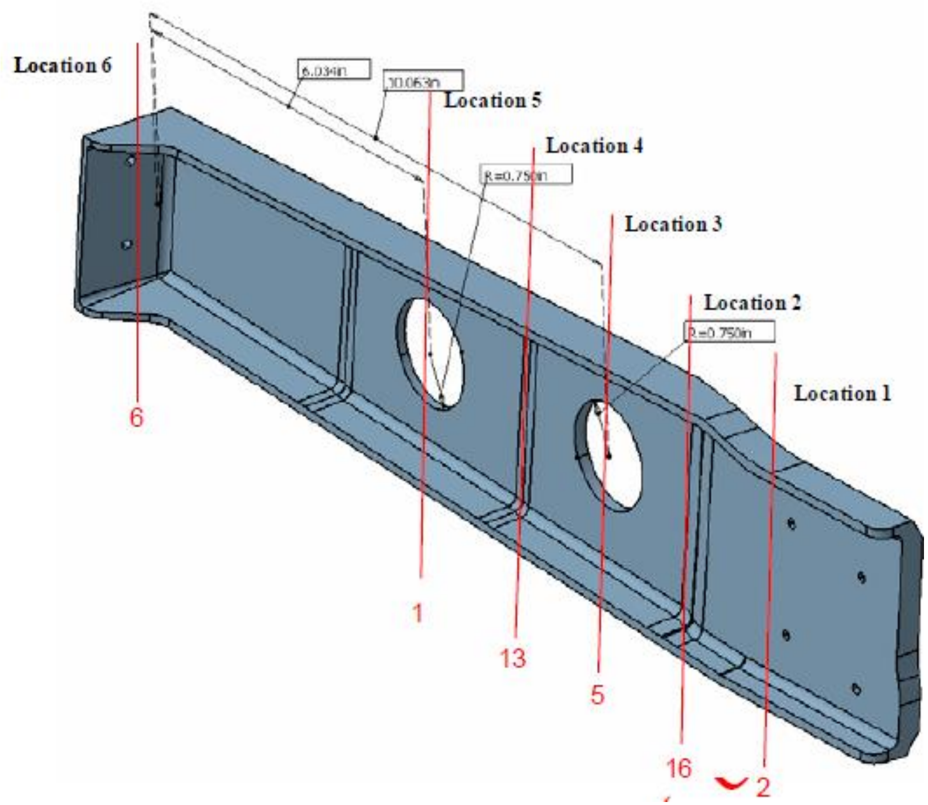
- Hexcel BCs resulted in widely dispersed failures… six distinct failure regions identified



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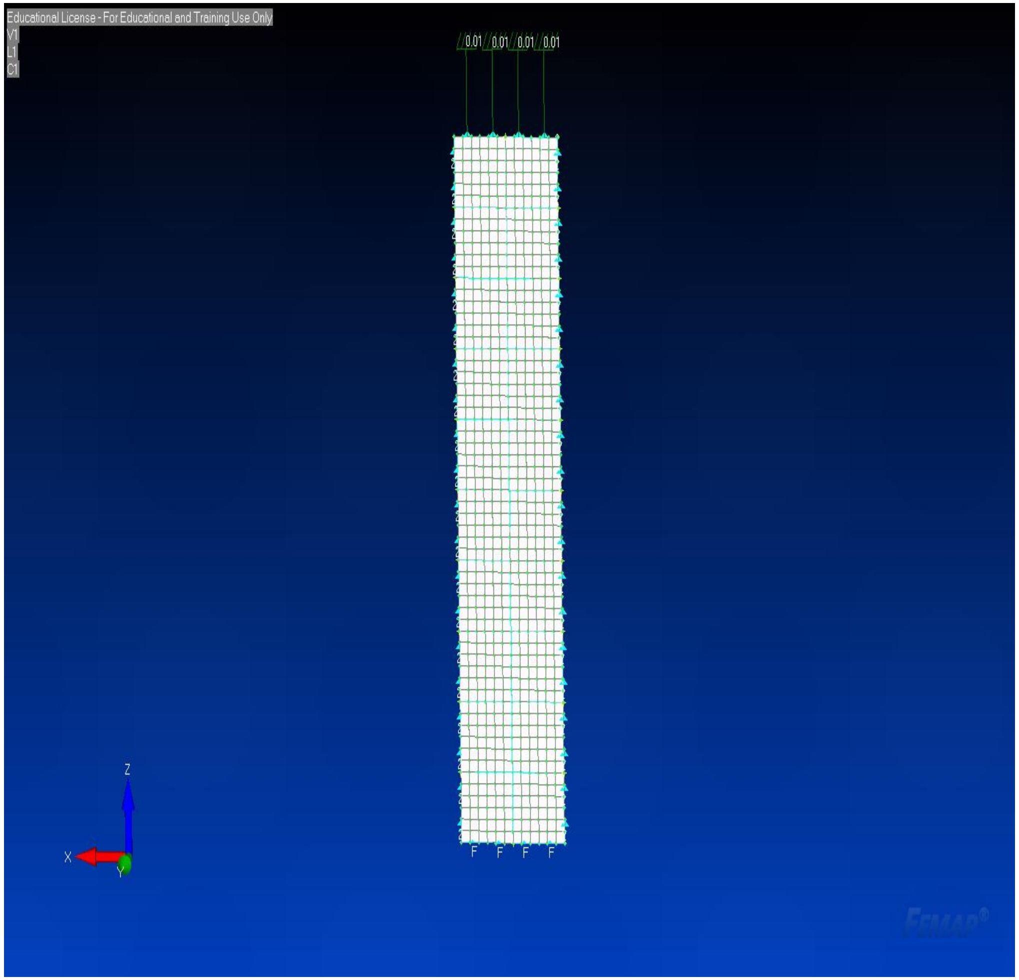
Stochastic Laminate Analogy (SLA)

Summary:

- Divide the structure to be modeled into Random Laminate Volume Elements (RLVEs)
- Assign randomly-selected and nonsymmetric stacking sequence to each RLVE :
  - fiber angles in one RLVE are independent of neighboring RLVEs
  - number of plies = number of through-thickness chips, reflecting local part thickness
- Further divide all RLVEs into “traditional” finite-element mesh

Stochastic Laminate Analogy (SLA)

Example: HexMC tensile coupon



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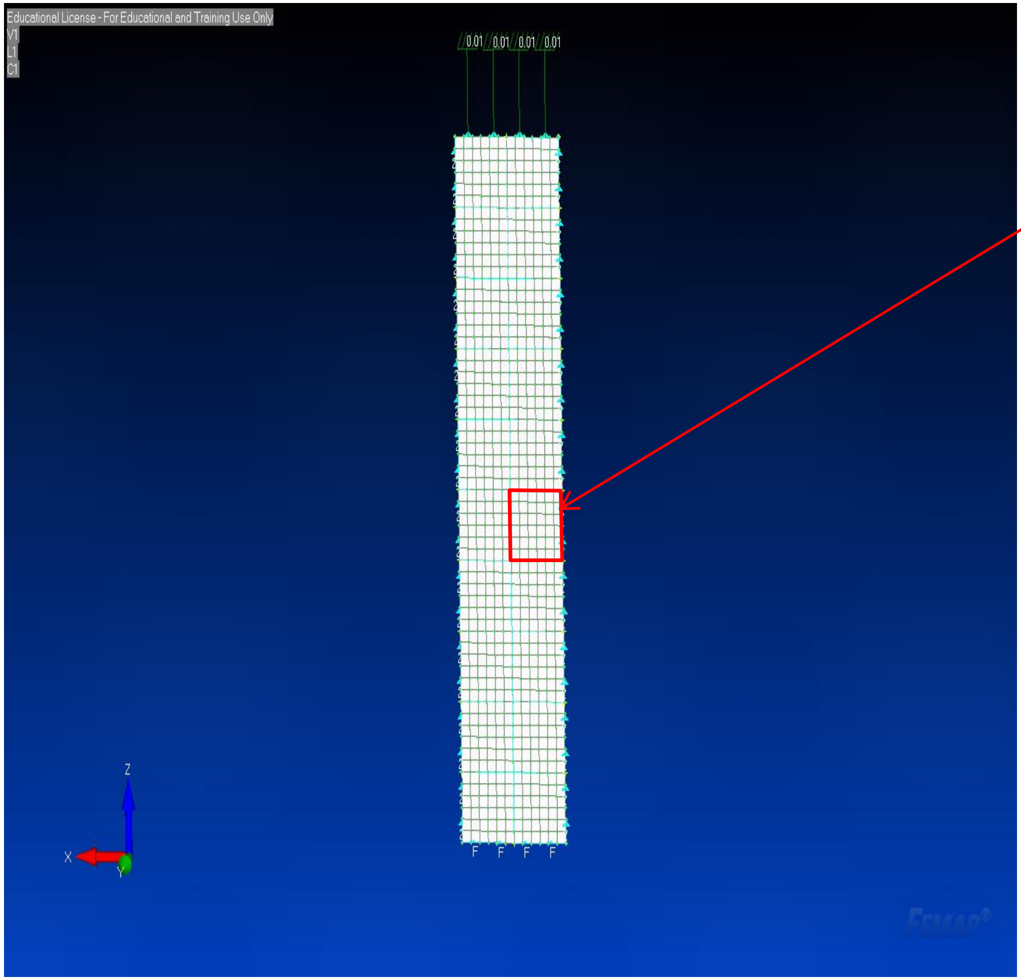

One of 20 RLVEs

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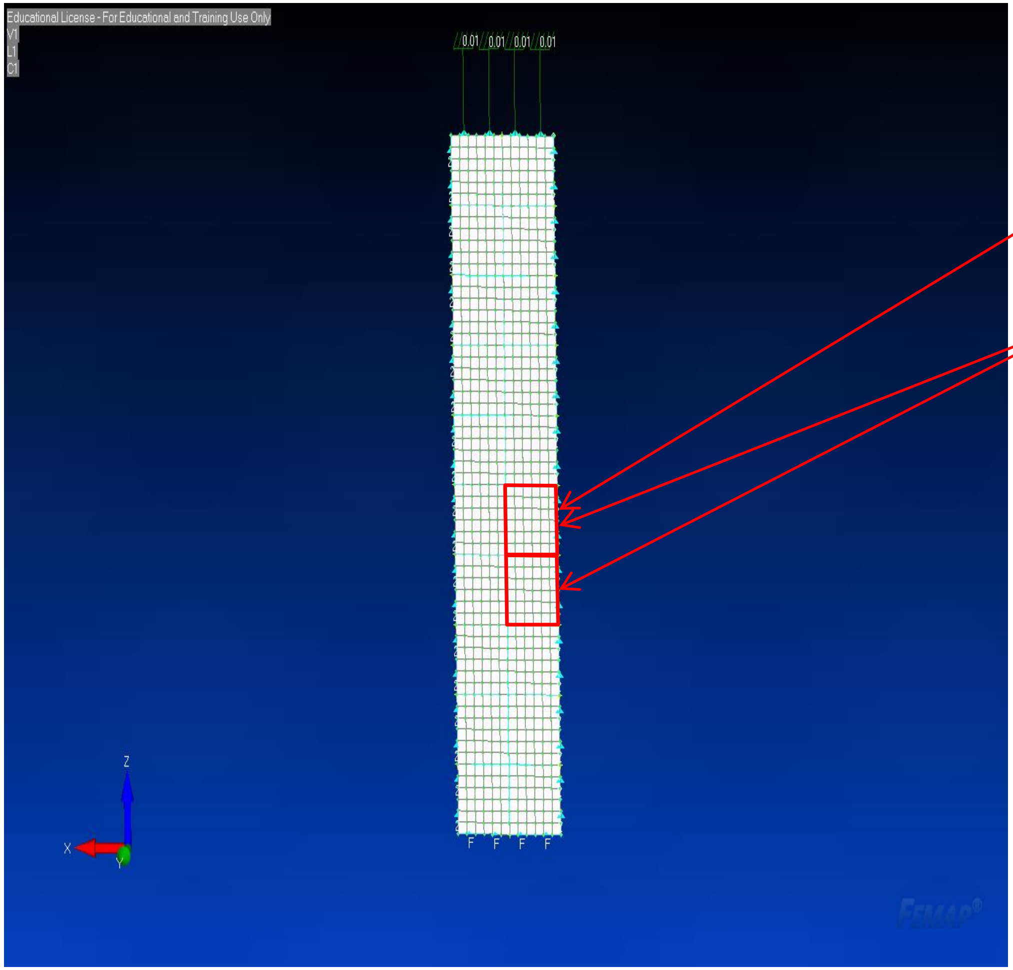

One of 20 RLVEs

Random stacking sequence differs in neighboring RLVEs

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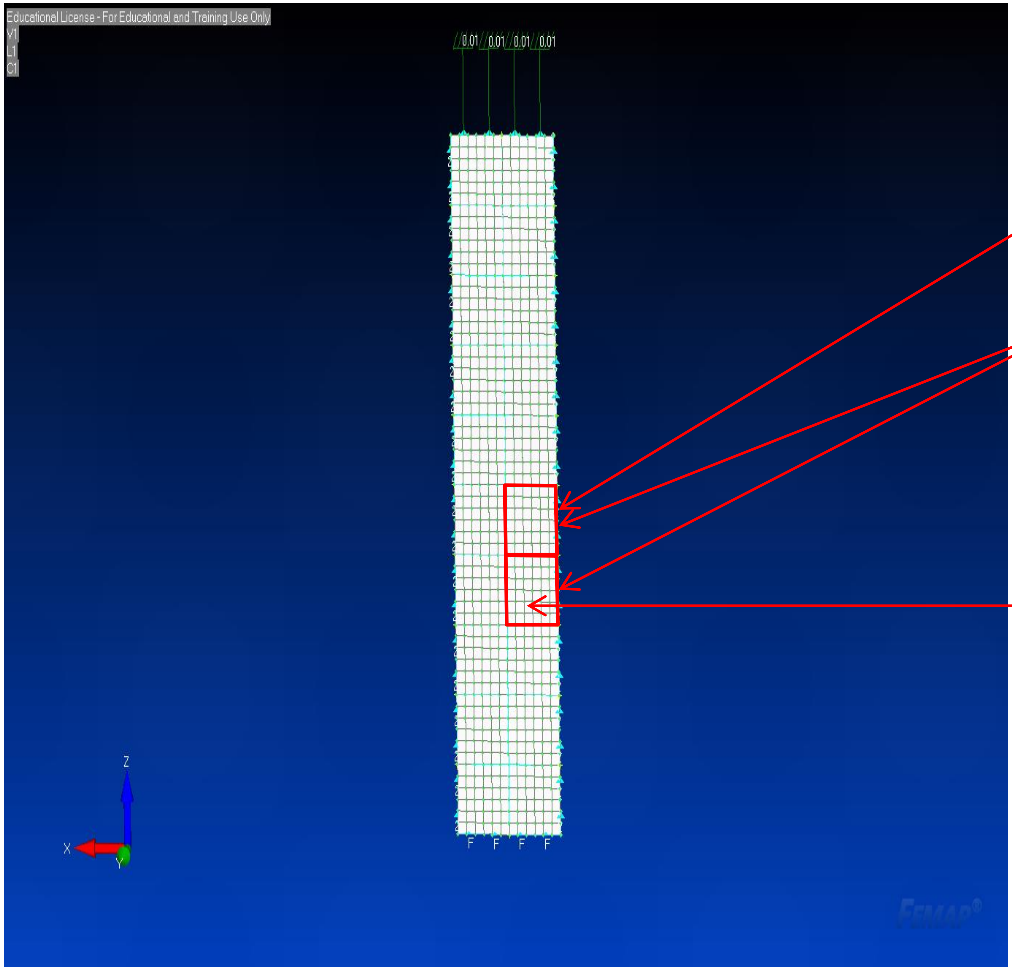

- One of 20 RLVEs
- Random stacking sequence differs in neighboring RLVEs
- Each RLVE divided into 6 x 6 = 36 finite elements (720 elements used in model)

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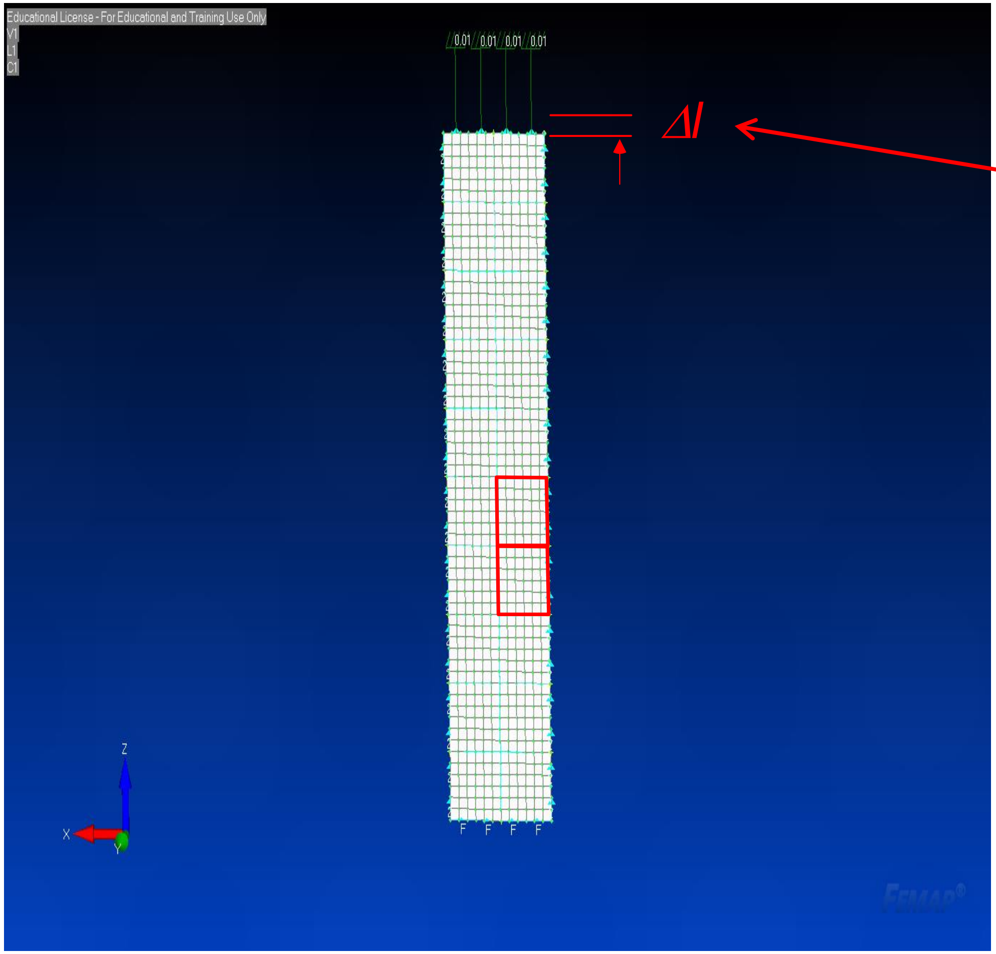

To predict tensile modulus:

(a) enforce uniform end displacement:

$$\varepsilon_{axial}\Big|_{nom} = \frac{\Delta l}{l}$$

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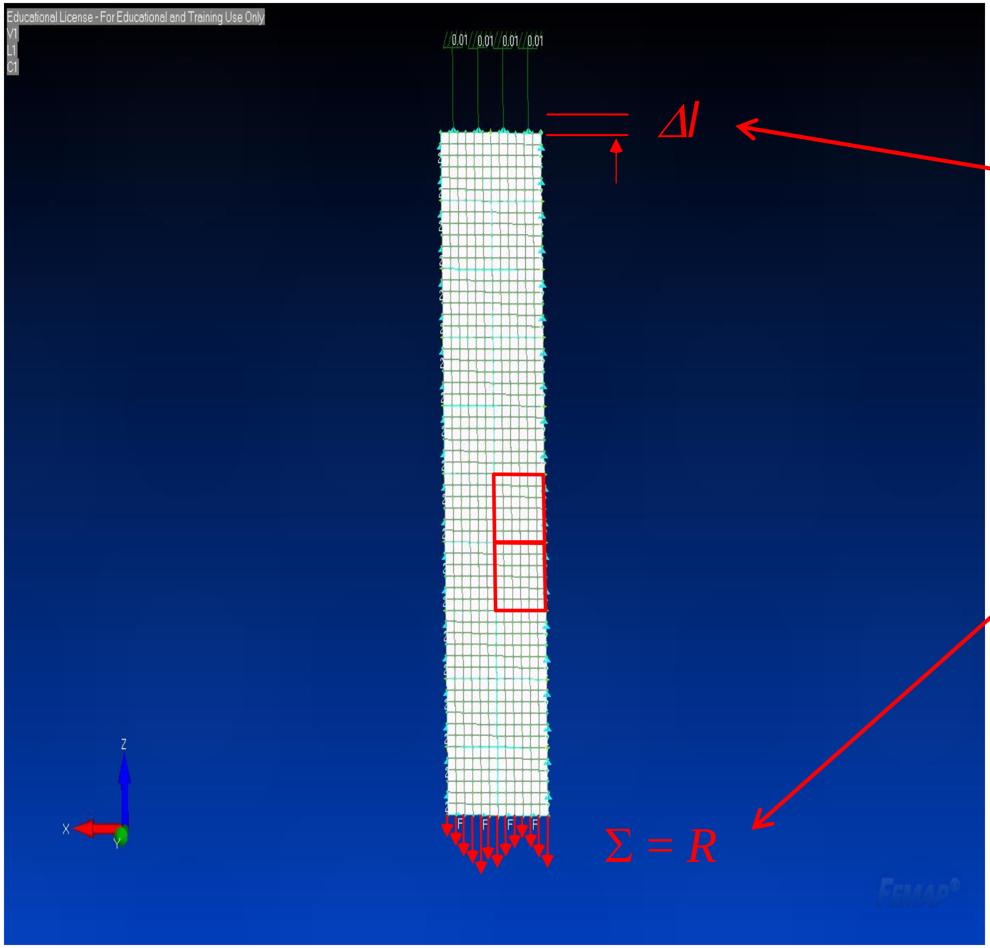

To predict tensile modulus:

(a) enforce uniform end displacement:

$$\varepsilon_{axial}\Big|_{nom} = \frac{\Delta l}{l}$$

(b) monitor total reaction force R at fixed end:

$$\sigma_{axial}\Big|_{nom} = \frac{R}{A}$$

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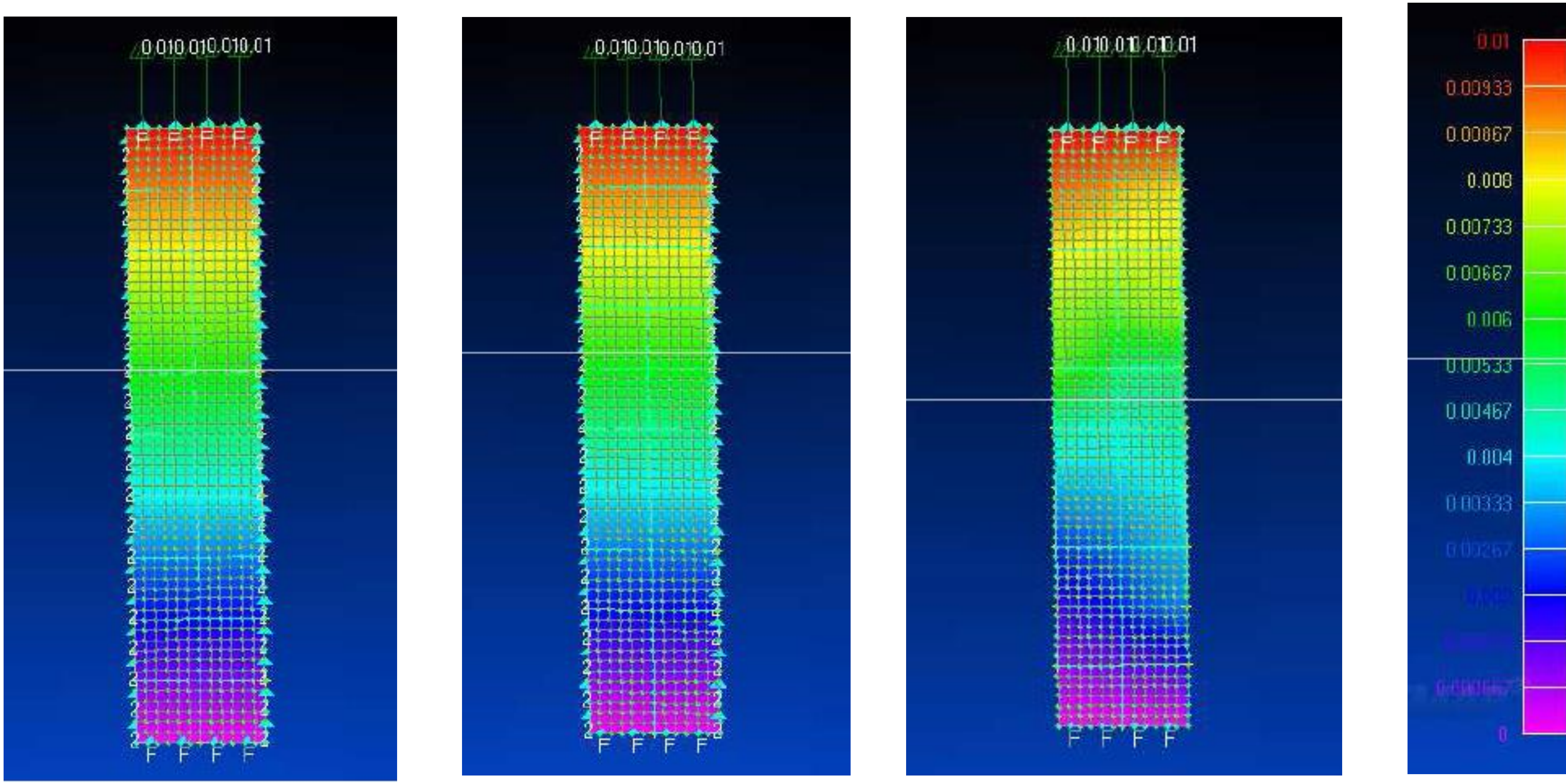
Stochastic Laminate Analogy (SLA)

Predicted displacement contour plots



All 90º RLVEs

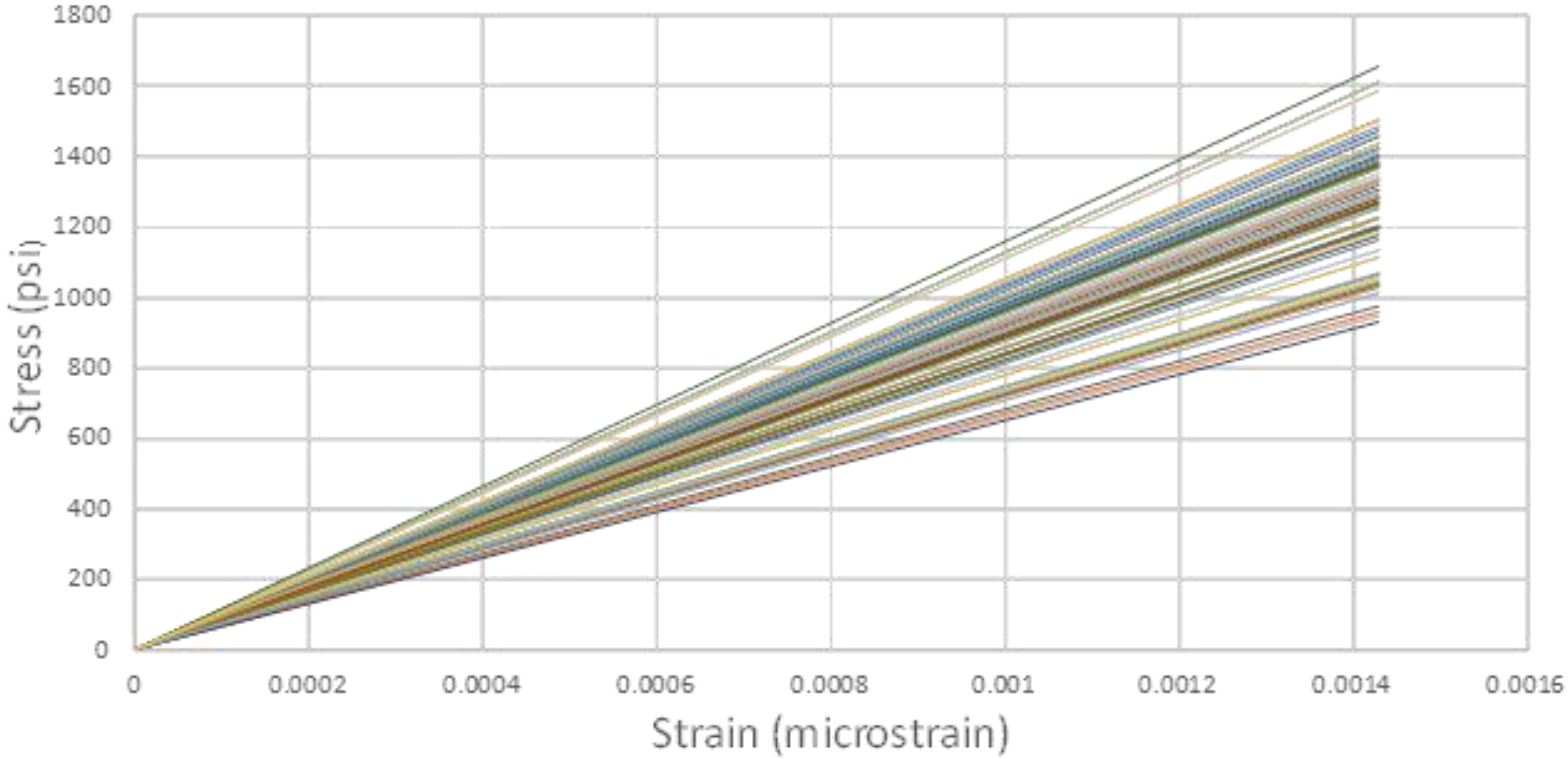
All 0º RLVEs

Random RLVEs

Stochastic Laminate Analogy (SLA)

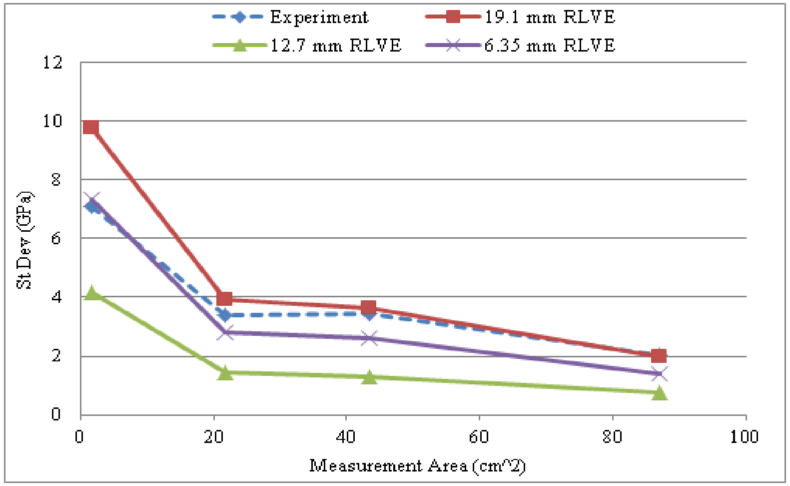
Predicted Young's Modulus

(Based on recommended RLVE dimensions ~19 mm =~ 0.76 in)

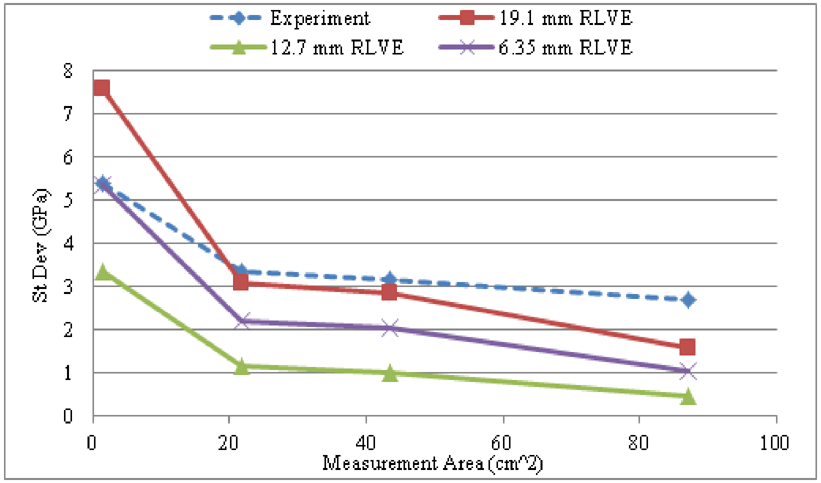


Stochastic Laminate Analogy (SLA)

- Recommended RLVE size established by matching standard deviation of predicted modulus vs modulus measured using DIC…best match for RLVE size ~0.76 in (19.1 mm)



0.097 in (2.5 mm) thick specimens

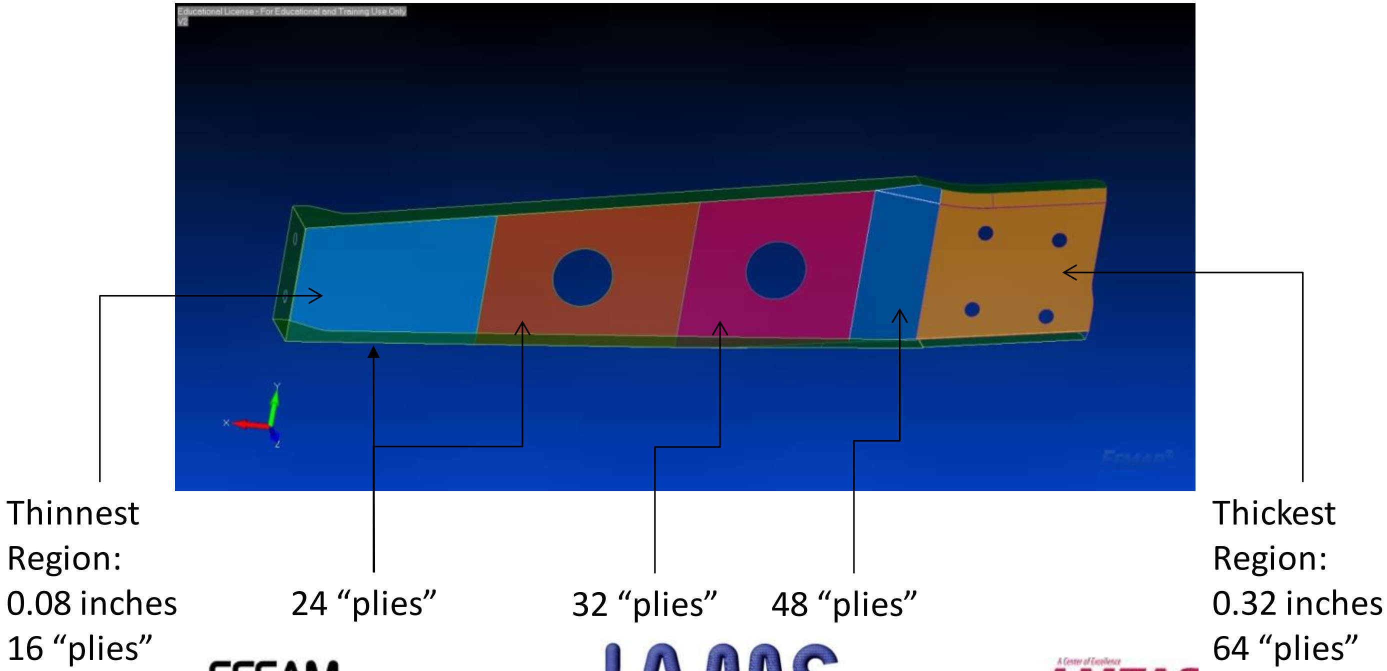


0.19 in (4.9 mm) thick specimens

Stochastic Laminate Analogy (SLA)

Applied to the HexMC intercostal

- Hexcel provided a solid model of the intercostal
- NASTRAN mesh created using midsurfaces generated from the solid model
- Laminated shell elements used; different PCOMP cards used to represent differing thicknesses



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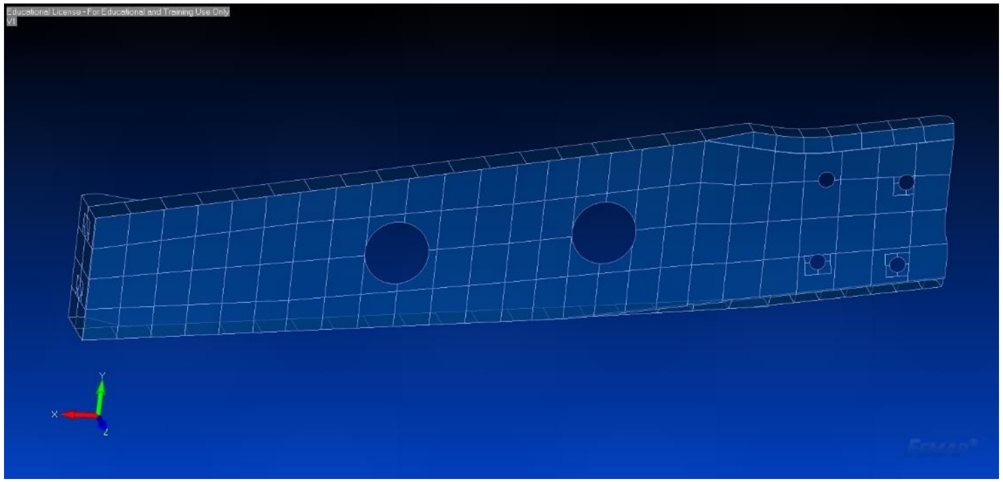
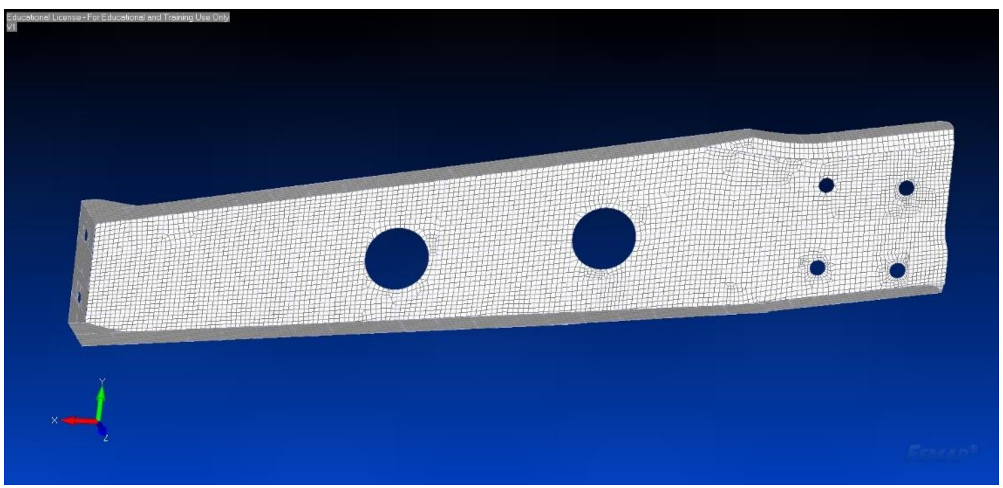


181 RLVEs were defined



FE mesh based on:

- 9235 nodes
- 8915 elements

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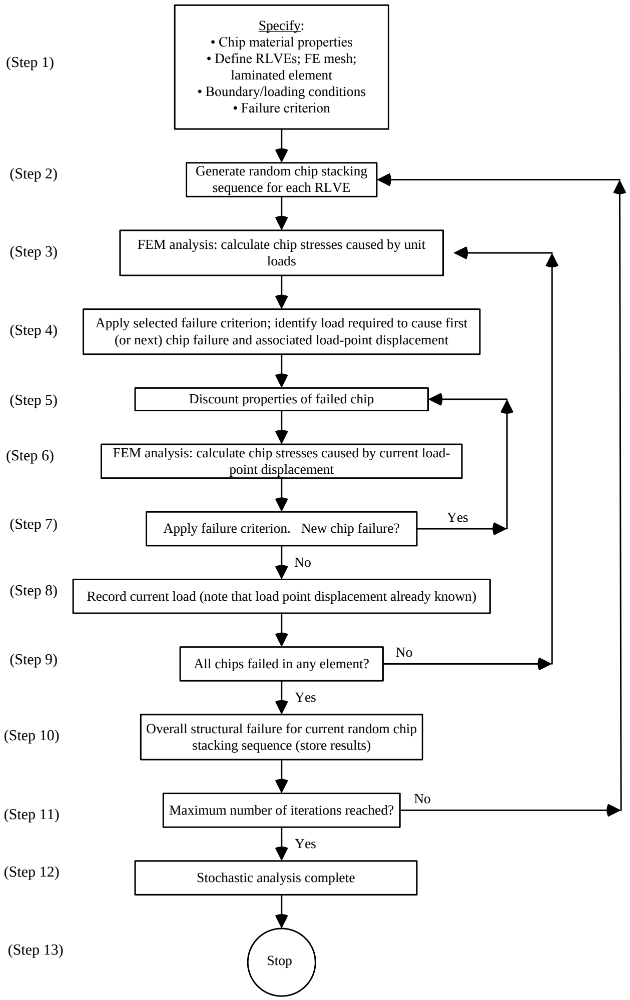
Modeling Damage Accumulation Using the Ply Discount Scheme



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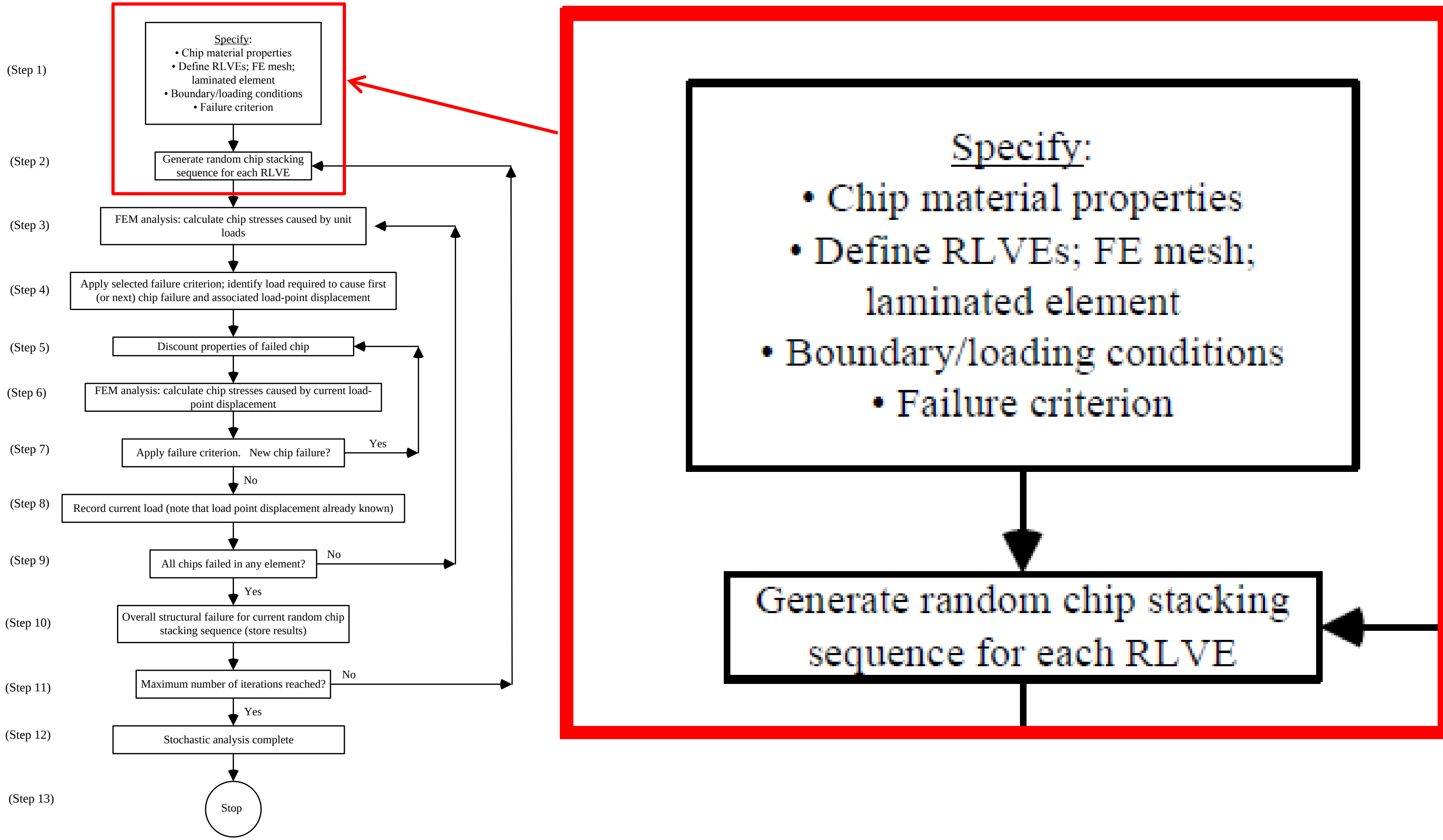

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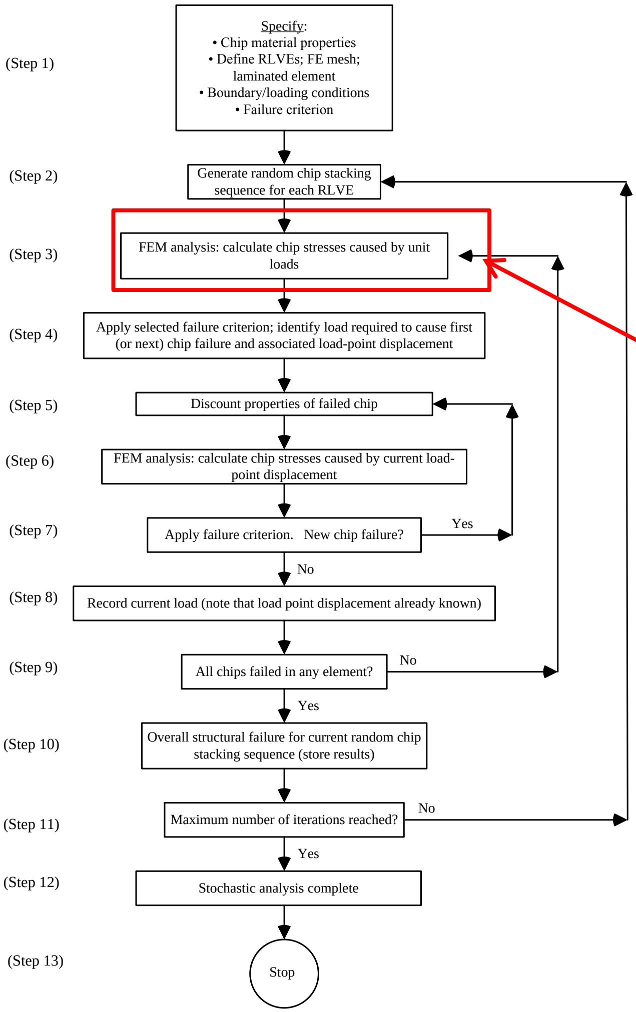

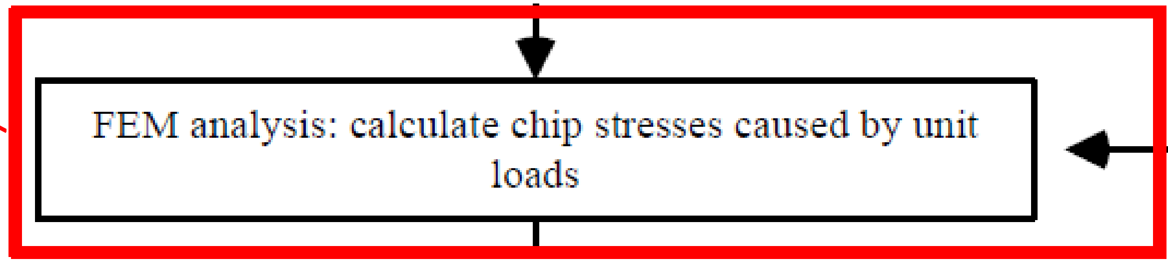

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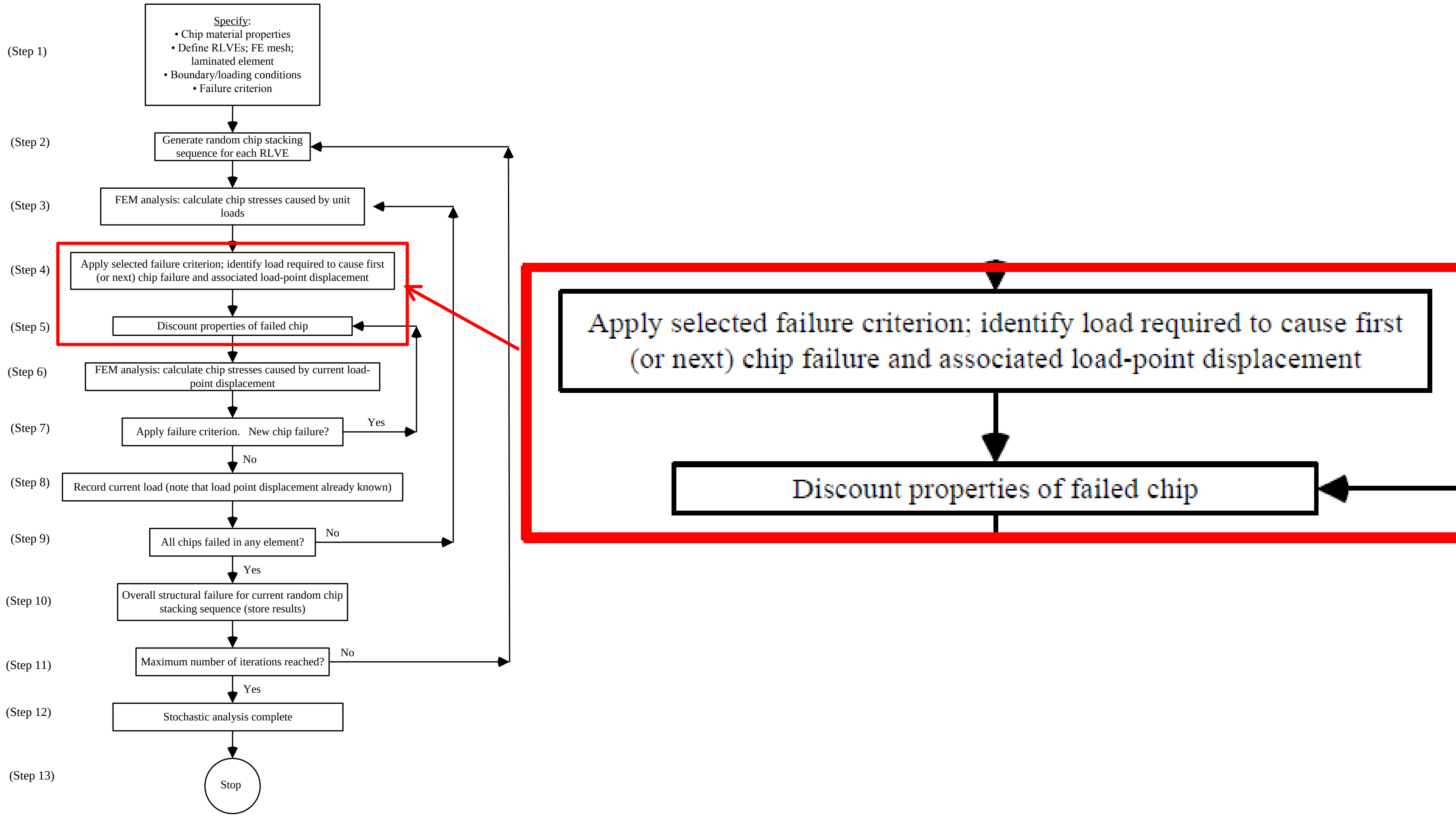

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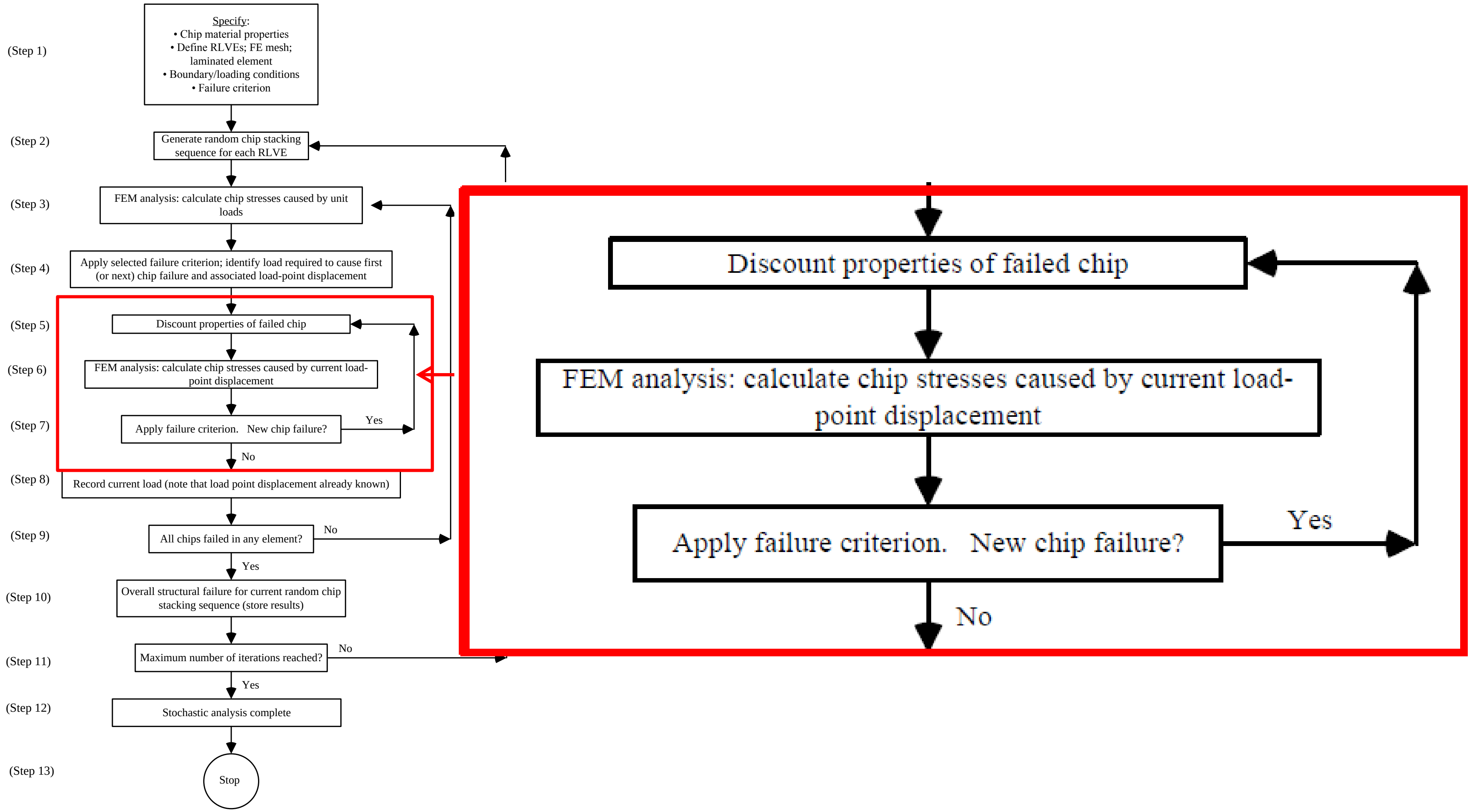

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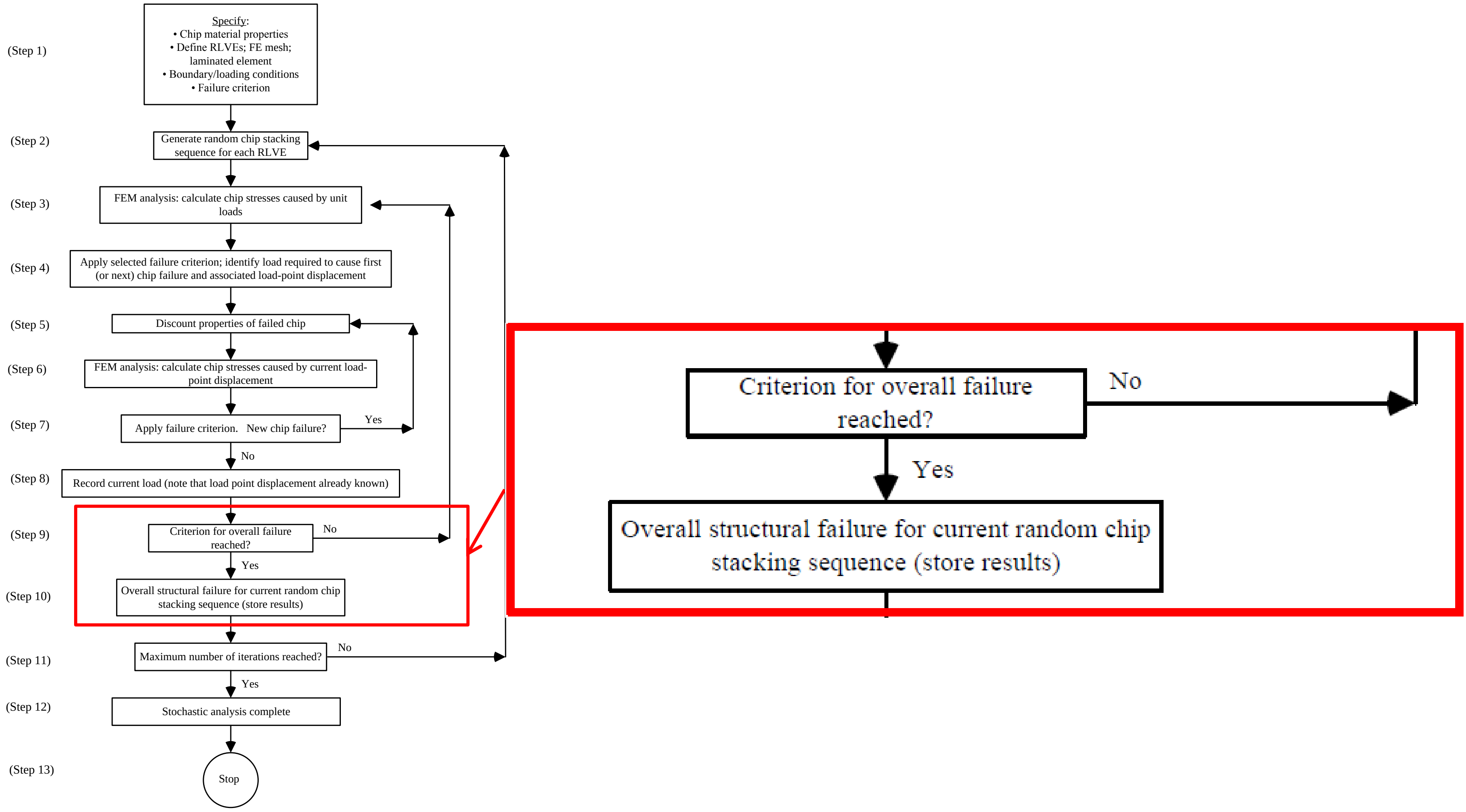

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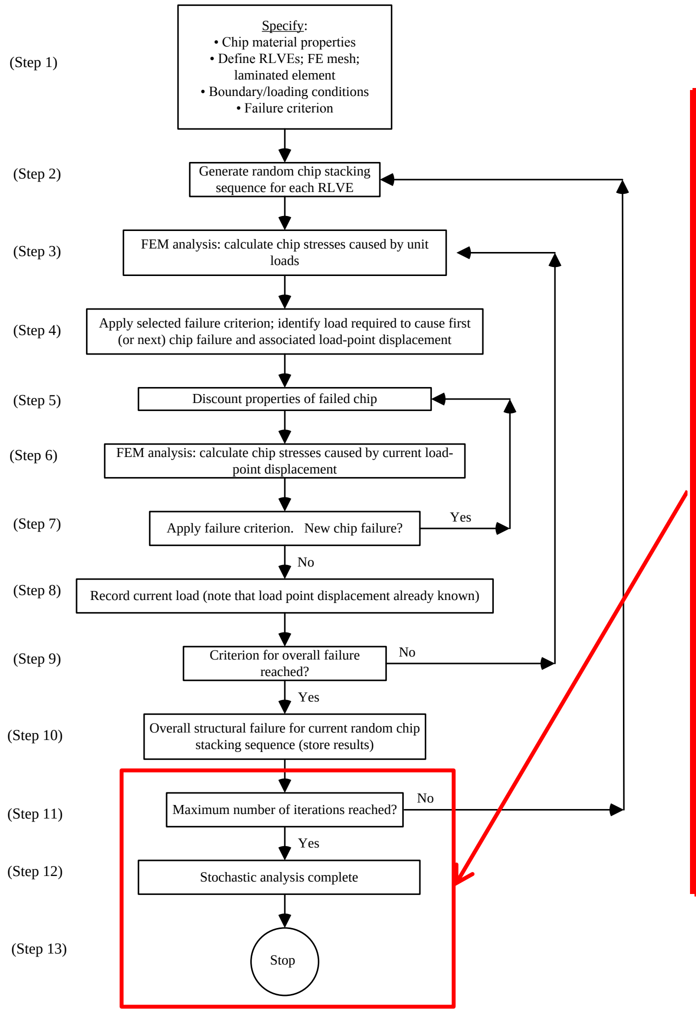

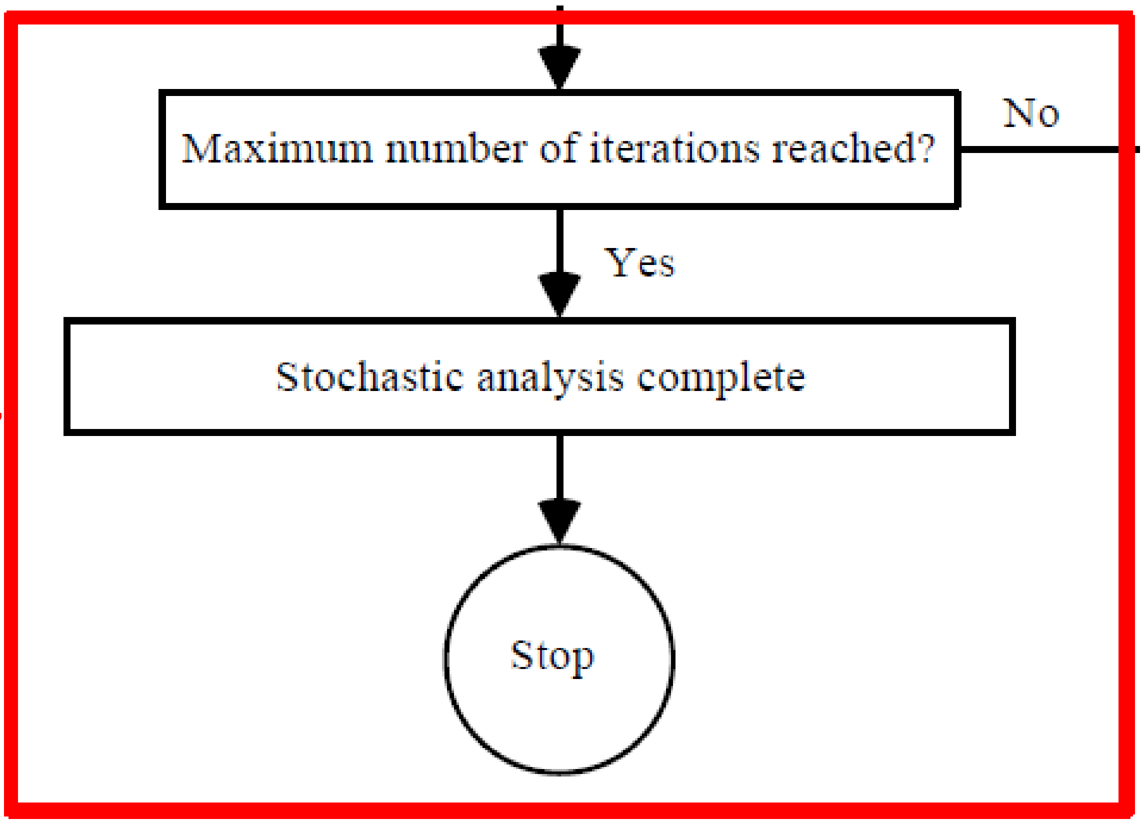

Modeling Damage Accumulation Using the Ply Discount Scheme

Three different criterion for overall structural failure have been explored:

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- Define final fracture when all plies/chips in a selected number of elements have failed … *arbitrarily selected 10 elements*

- Define final fracture when overall stiffness has been reduced by some percentage (10%, say) …. *highest computational expense*

Material Properties

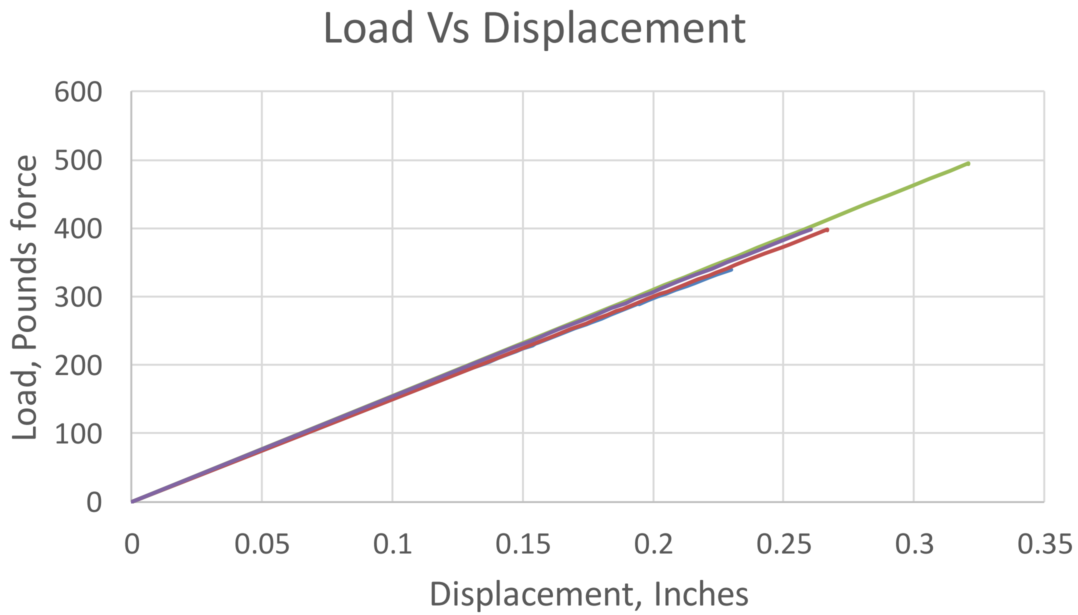
Chips properties are assumed to be equivalent to those of unidirectional AS4/8552*:

E_{11}, (tensile, Msi)	E_{22}, (tensile, Msi)	ν_{12} (tensile)	G_{12} (Msi)	0º Strength (ksi)		90º Strength (ksi)		In-Plane Shear Strength (ksi)
				Tensile	Comp	Tensile	Comp	
19.1	1.34	0.302	0.70	299	215	9.27	38.38	13.28

*Marlett, K., "Hexcel 8552 AS4 Unidirectional Materials Property Data Report", Nov 2011. Available online at: http://www.niar.wichita.edu/coe/ncamphexcel.asp

Intercostal failure Predictions: UW BCs
Fracture Criterion: All plies in a single element failed

Analysis	Number of Ply - Chip Failures	Load at Final Fracture	Analysis Time
1	942	339.62	10 H, 40 M
2	765	397.41	8 H, 45 M
3	872	494.21	9 H, 10 M
4	620	397.85	7 H, 10 M



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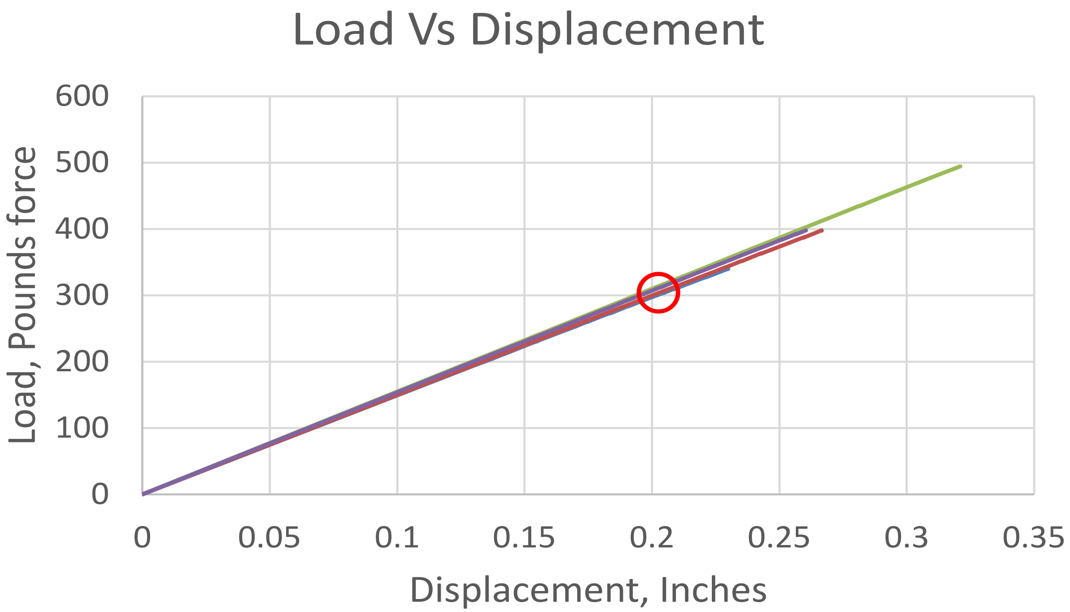

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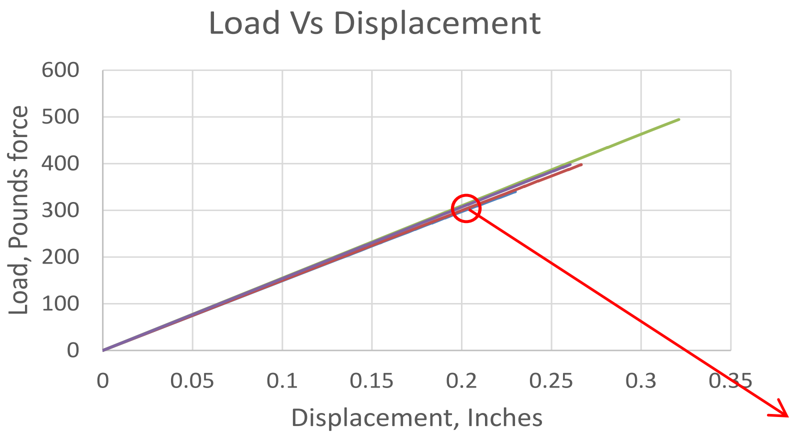

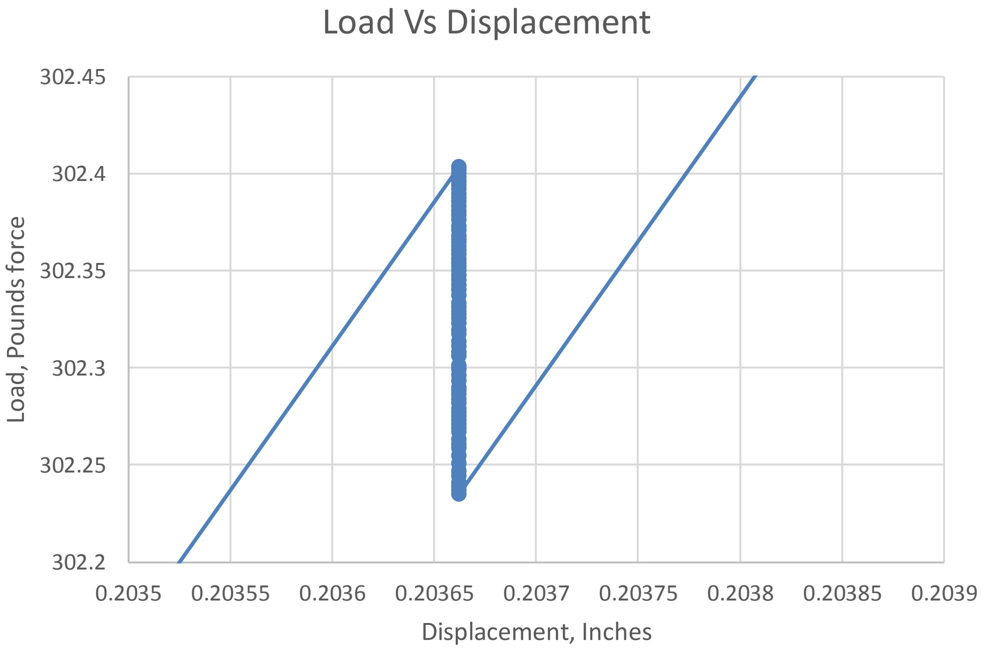

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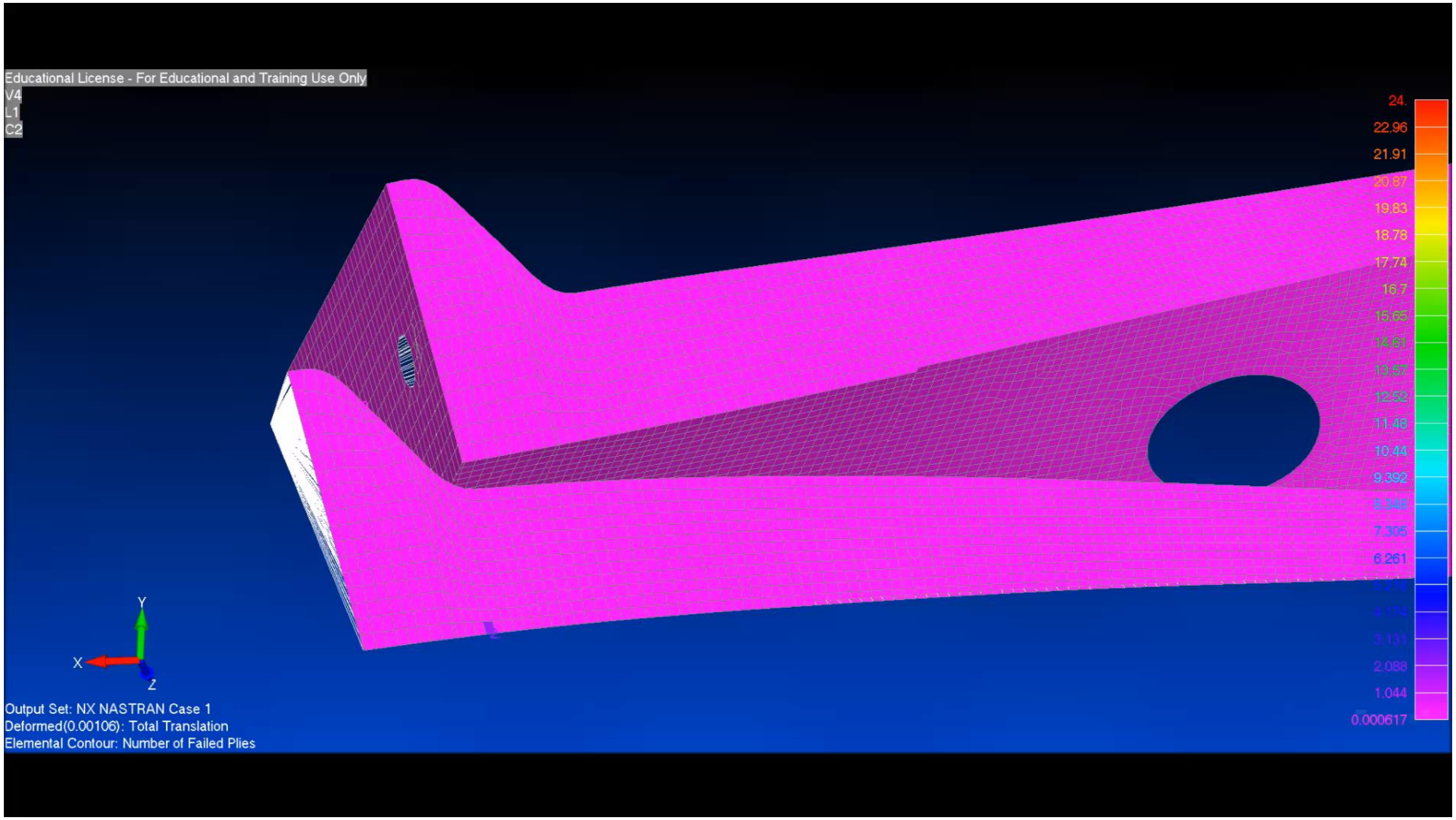

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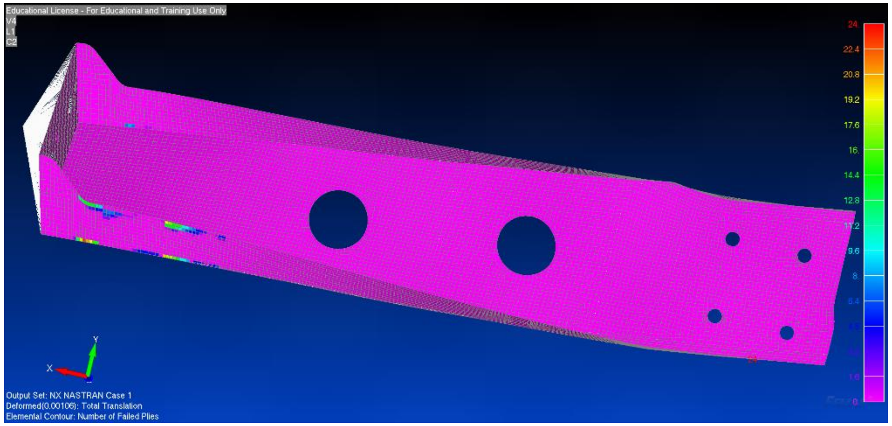
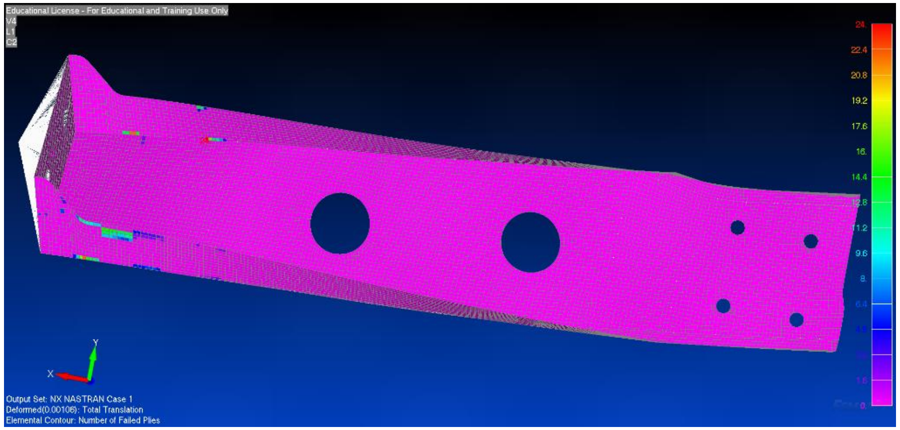
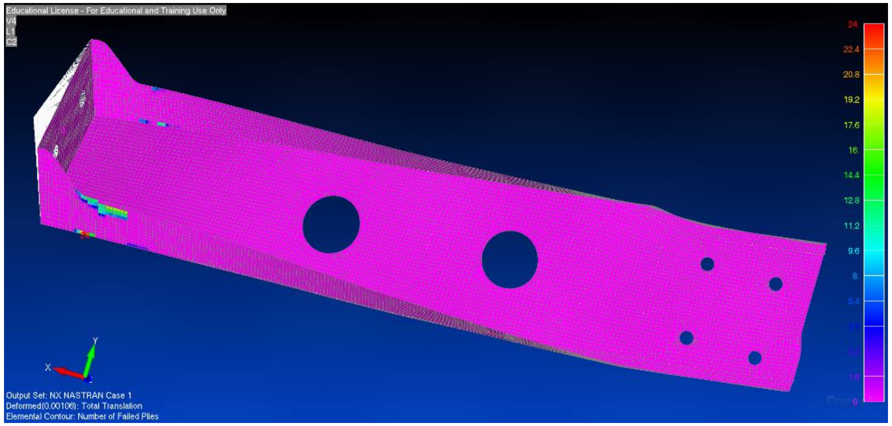
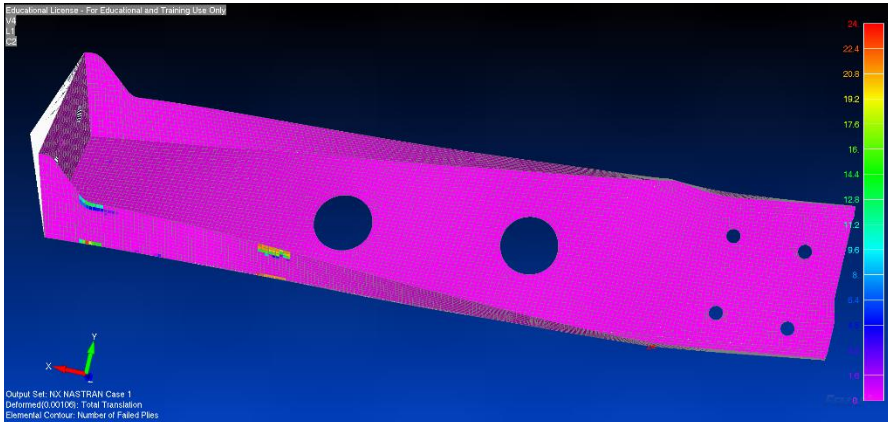
Intercostal failure Predictions: UW BCs

Fracture Criterion: All plies in a single element failed









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Intercostal failure Predictions: Hexcel BCs

Fracture Criterion: All plies in a single element failed

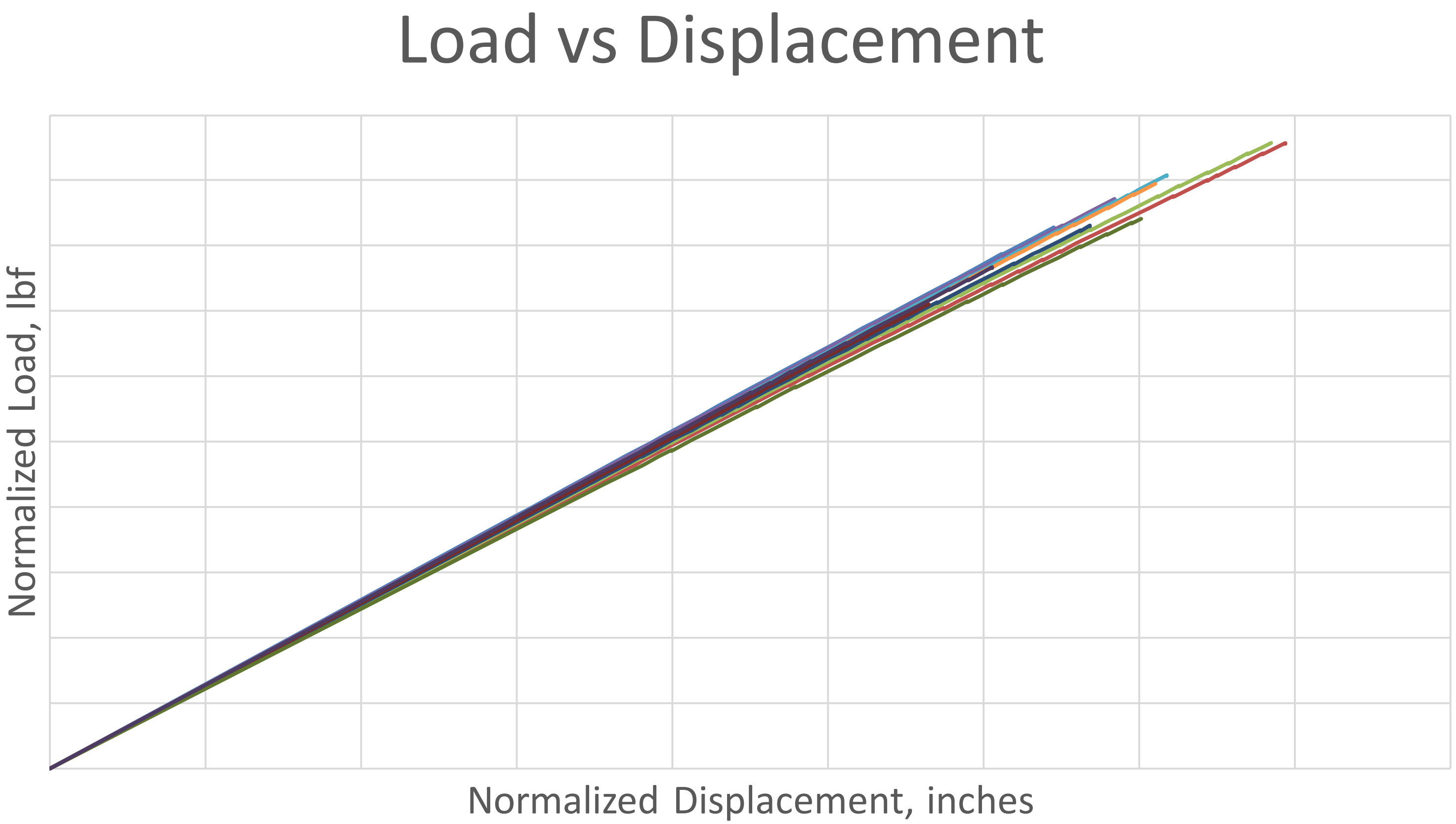
Normalized failure loads

Analysis	Number of Ply Failures	Load at Final Fracture	Time
1	1079	0.864332	5 H, 40 M
2	3900	0.998955	20 H, 40 M
3	3514	1	18 H, 50 M
4	1555	0.909943	8 H, 35 M
5	1787	0.947572	9 H, 50 M
6	1699	0.934449	9 H, 20 M
7	1621	0.867419	9 H, 5 M
8	792	0.742157	4 H, 45 M
9	2315	0.878562	12 H, 35 M
10	1240	0.800165	7 H, 20 M

Intercostal failure Predictions: Hexcel BCs

Fracture Criterion: All plies in a single element failed

Normalized failure loads



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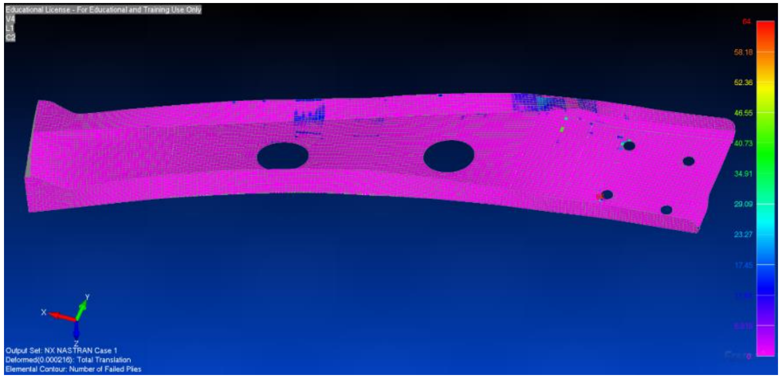
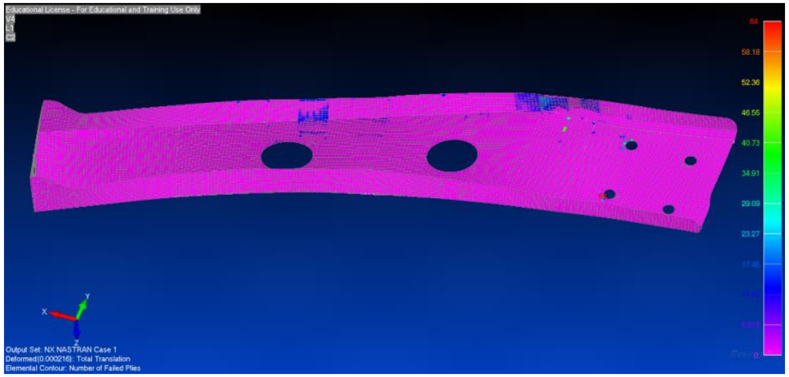
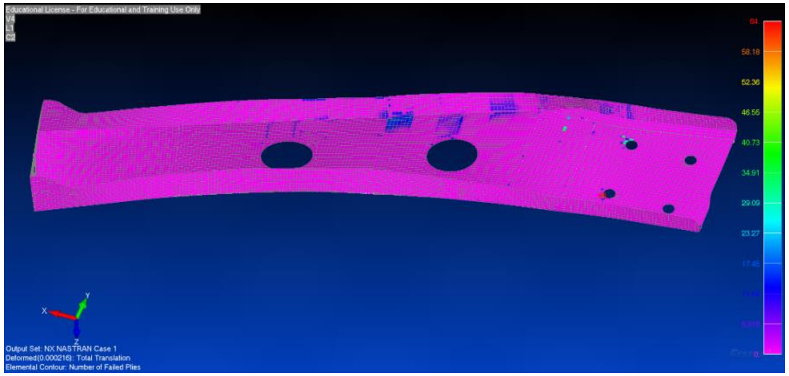
Intercostal failure Predictions: Hexcel BCs

Fracture Criterion: All plies in a single element failed

Normalized failure loads







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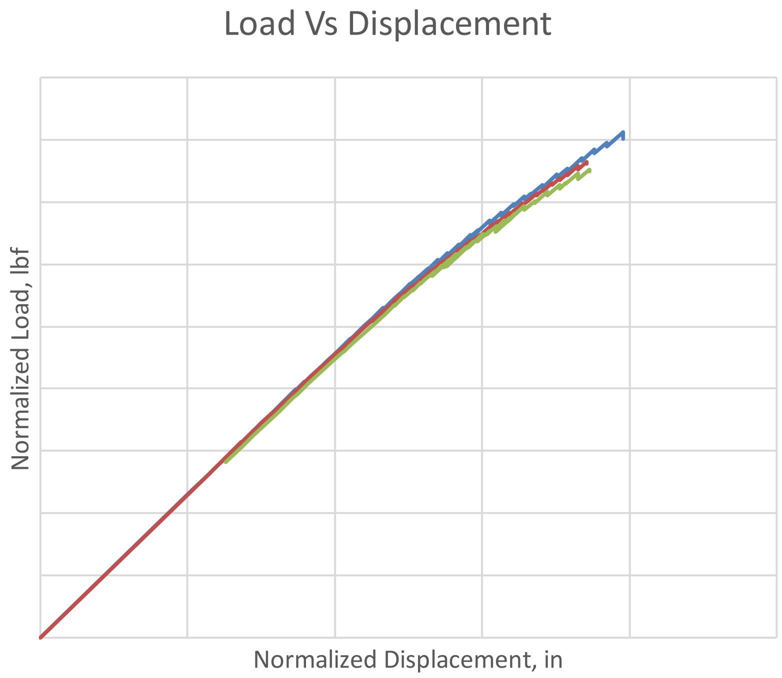
Intercostal failure Predictions: Hexcel BCs

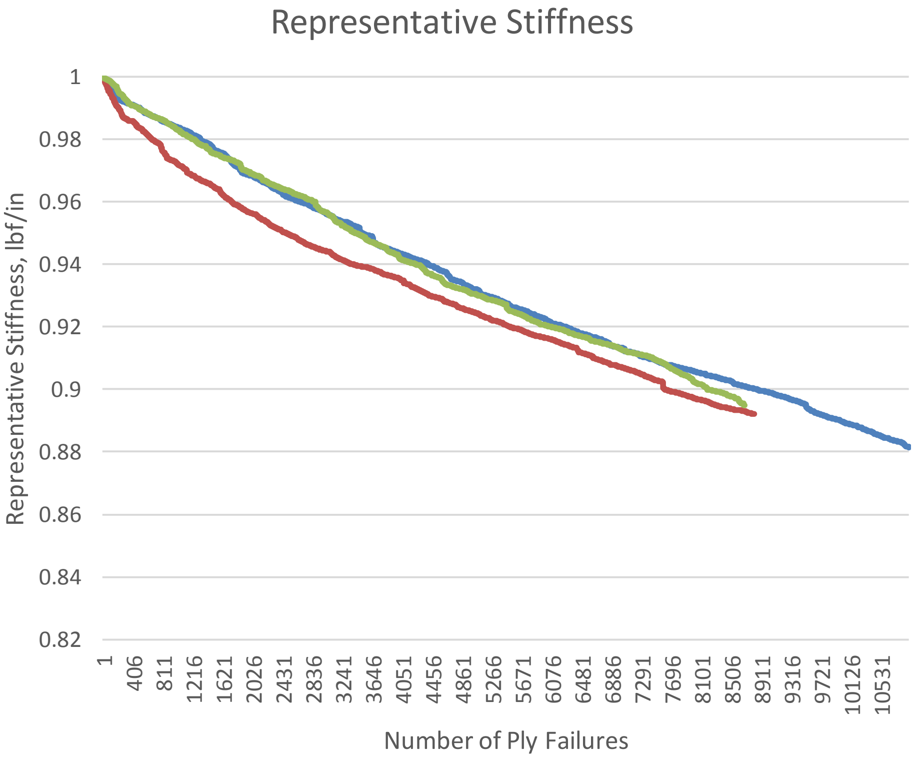
- Fracture criterion based on 90% stiffness reduction is computationally expensive

Analysis	Number of Ply Failures	Load at Final Failure	Time
1	10872	1	49 hrs 30 min
2	8766	0.949042	41 hrs 20 min
3	8641	0.934321	44 hrs, 20 min

Intercostal failure Predictions: Hexcel BCs

- Fracture criterion based on 90% stiffness reduction predicts clearly nonlinear behavior





Summary

- The Stochastic Laminate Analogy (SLA) has been combined with a simple ply discount scheme to predict:
  - Initial elastic stiffness
  - Damage accumulation
  - Final Fracture

  of a HexMC intercostal loaded as a cantilevered beam
- Two boundary conditions were considered
- Results are very promising, however
- A complete stochastic analysis involving dozens/hundreds of analyses is computationally very expensive.
- Additional FE analyses currently being performed

Benefit to Aviation

Results of this study will ultimately help to establish methods to certify DFC aircraft parts by analysis supported by experimental measurements

Thank you!

Questions?

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Convergence Study - Intercostal

Final mesh (element) size is 0.078 in, following software recommendation