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Failure of Notched Laminates Under Out-of-Plane Bending, Phase VI

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Motivation, Objective, and Approach

- Motivation and Key Issues

  Develop analysis techniques useful in design of composite aircraft structures under out-of-plane loading (bending and shear)

- Objective

  Determine failure modes and evaluate capabilities of current models to predict failure

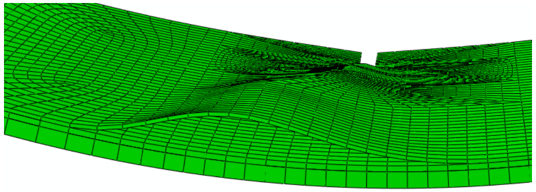
- Approach
  - Experiments: Mode 3 fracture
  - Modeling: Progressive damage development and delamination (Abaqus) under Mode 3 fracture

Out-of-Plane Shear Mode III Bending

- Principal Investigators & Researchers
  - John Parmigiani (PI); OSU faculty
  - I. Hyder, N. Atanasov; OSU grad students
- FAA Technical Monitor
  - Curt Davies
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Gerry Mabson, Boeing (technical advisor)
  - Tom Walker, NSE Composites (technical advisor)

Project Overview

- Phase I (2007-08)
  - Out-of-plane bending experiments w/composite plates
  - Abaqus modeling with progressive damage
- Phase II (2008-09)
  - Abaqus modeling with buckling delamination added
  - Sensitivity study of (generic) material property values
- Phase III (2009-10)
  - Abaqus modeling w/ more delamination interfaces



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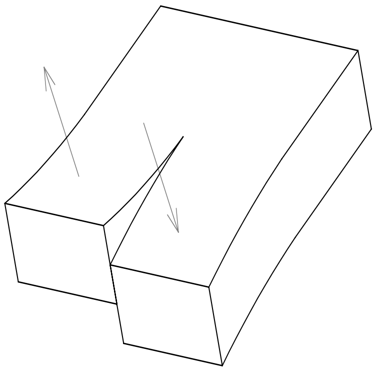
Project Overview

- Phase IV (2010-11)
  - Further study of additional delamination interfaces for out-of-plane bending and initiating vs. propagating toughness
  - Feasibility of Abaqus/Explicit and XFEM for future work
  - Sensitivity study using Boeing mat'l property values
- Phase V (2011-12)
  - Complete Out-of-plane shear (mode III) experiments & begin preliminary Abaqus modeling
  - Evaluate the Abaqus plug-in Helius:MCT (Firehole Composites) for modeling progressive damage in composites and applicability to Out-of-plane bending

Project Overview

- Phase VI (2012-13)
  - Evaluation of out-of-plane shear (mode III) modeling with built in capabilities of Abaqus Standard
  - Evaluation of plug-in Helius: MCT (Firehole Composites) for mode III shear
  - Evaluation for Abaqus Explicit for mode III shear



Project Overview

- Phase VII (2013-14)
  - Report of methods and results for Phase VI
  - Exploring the effectiveness of solid vs. continuum shell elements in modeling Mode III
  - Improving Abaqus/Explicit Modeling of Mode III shear
  - Sensitivity study using Boeing material property values with Helius: MCT, original values inaccurate?
  - Sensitivity study using Boeing material property values with Abaqus/Standard, original values inaccurate?
  - Sensitivity study using published material property values and configurations with Abaqus/Standard to determine which properties are significant for Mode III shear

Today’s Topic

- Experimental results: Out-of-plane shear
- Evaluation of Abaqus Standard results
- Evaluation of Helius: MCT results
- Evaluation of Abaqus Explicit results
- Current work with Mode III

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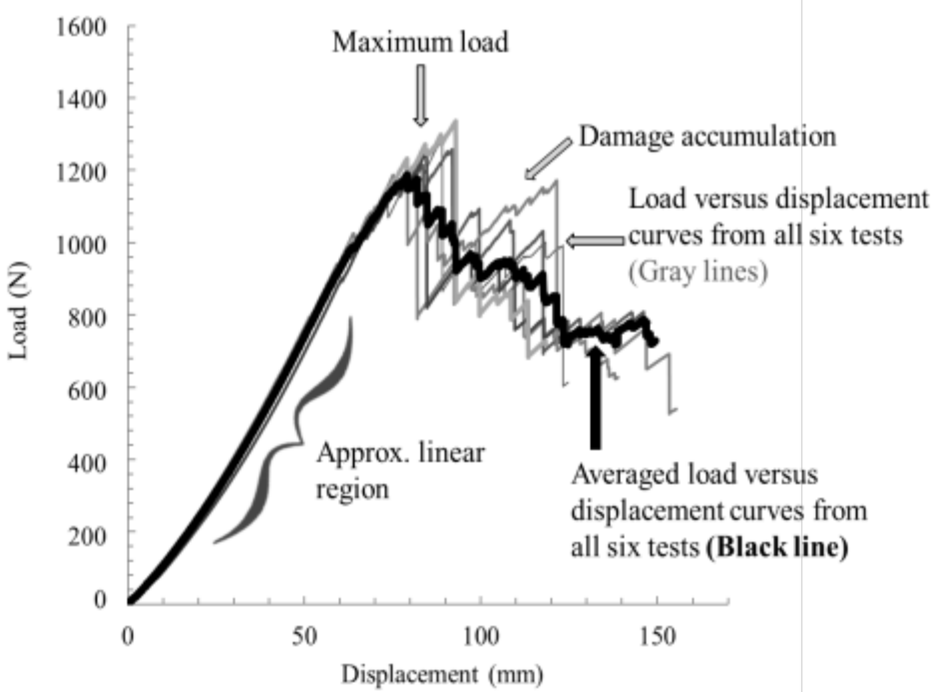
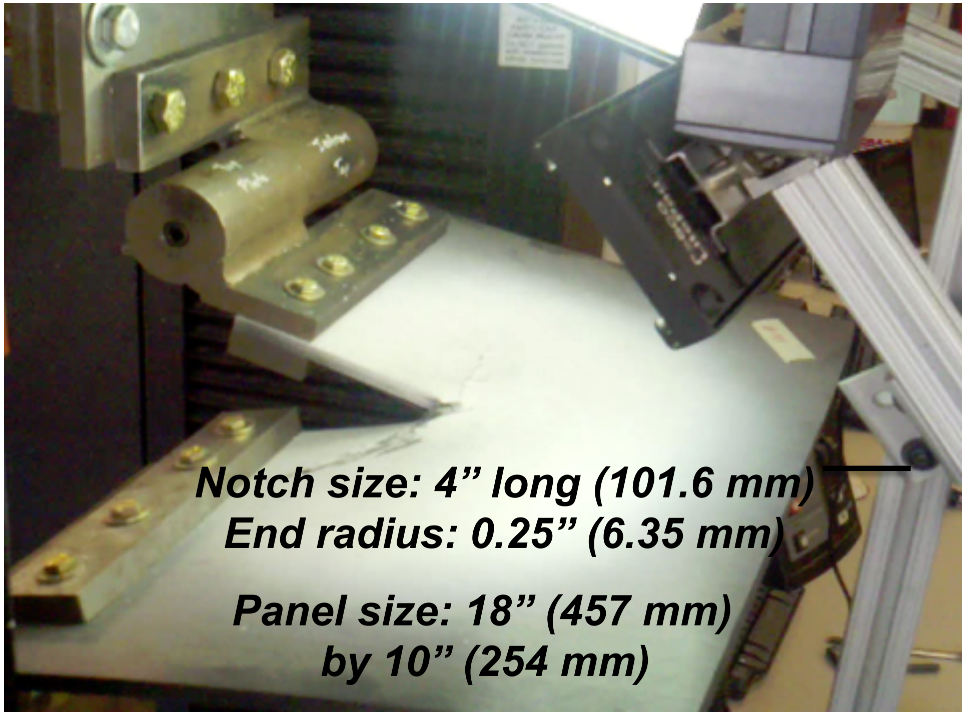
Experimental Results Out-of-Plane Shear





- Edge-notched CF panels displaced to maximum load
- 20 and 40 lamina thick panels with three lay ups: 10%, 30%, & 50% 0° plies
- Metrics: Applied displacement and applied load

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- Experimental results: Out-of-plane shear
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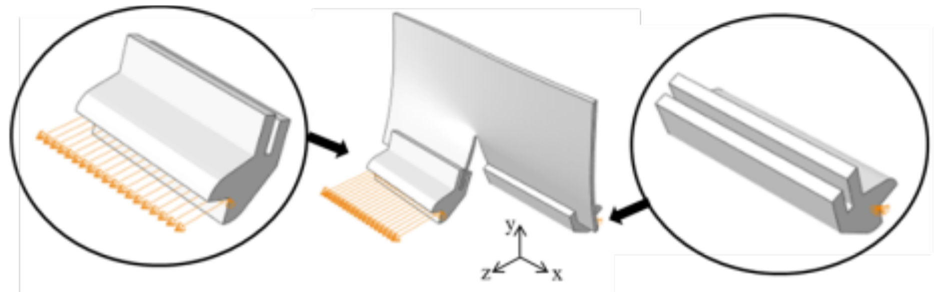
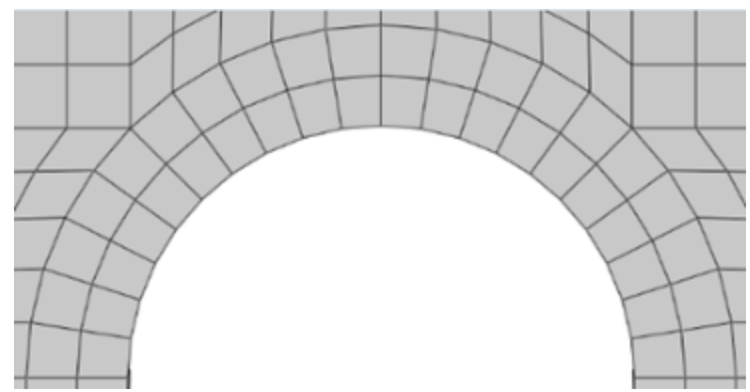
Evaluation of Abaqus Standard: Computational Model

- Solver basics:
  - Uses Newton-Raphson Technique to iterate to a converge solution for each time increment
  - Static equilibrium: $[K][U] = [R]$
- Uses Hashin failure criteria
- Quasi-static analysis and non-linear geometry turned on
- Panel: Continuum shell, reduced integration elements (SC8R)
- Grips: Continuum, 3-D, 8 node, reduced integration element (C3D8R)
- Boundary conditions implemented by grips
- Mesh Selection – 20 elements around notch tip, based on a linear elastic convergence study
- Implemented viscous regularization
- Hourglass stiffness scaling based on a converged value

Grip allowed to displace in z-axis and allowed to rotate about x-axis

Grip is fixed, but allowed to rotate about x-axis





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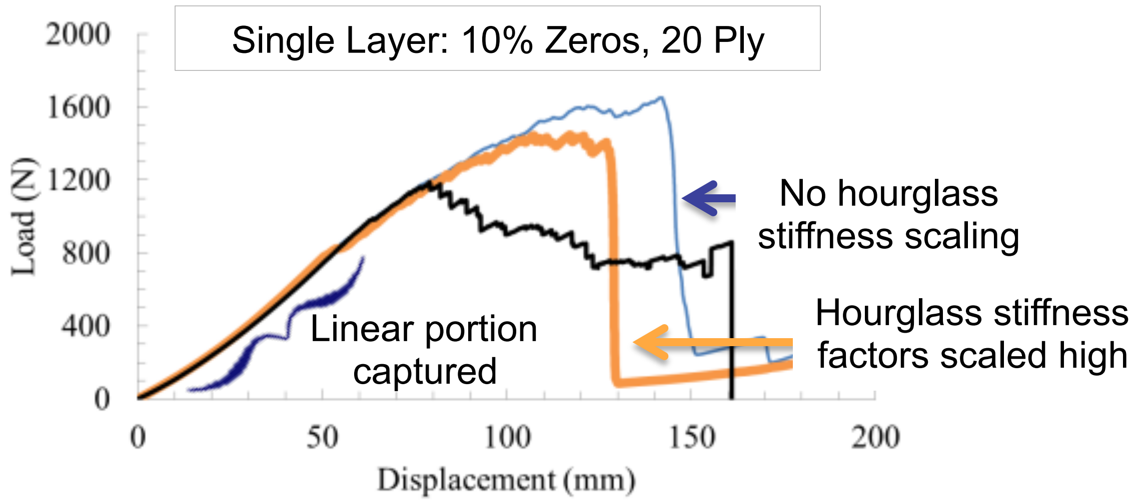
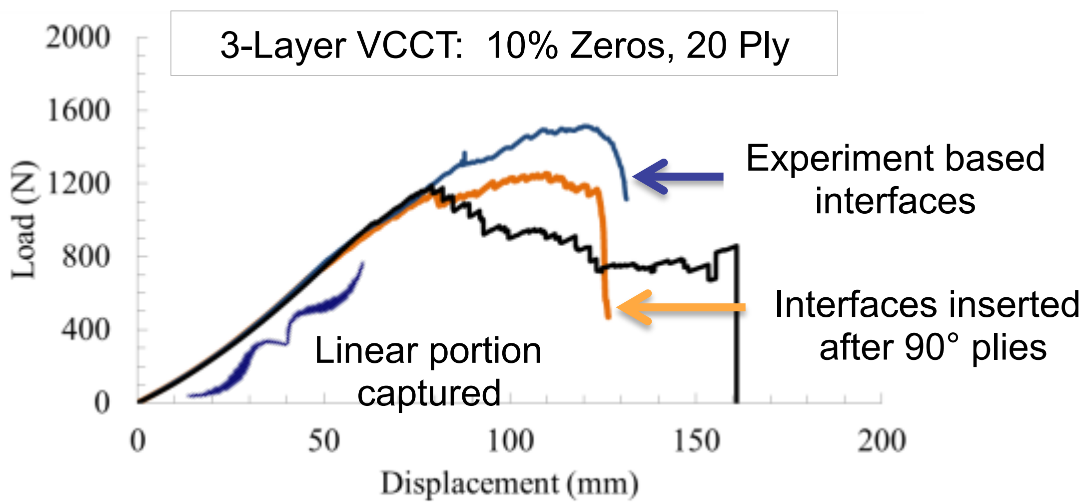
Evaluation of Abaqus Standard: Single Element Layer and 3 Element Layer Delamination with VCCT Results





- All models effectively captured linear region
- FE models have stiffness factors scaled high
- FE material response is similar, but 3-layer VCCT models capture experiment behavior better
- Not all models revealed a clear max

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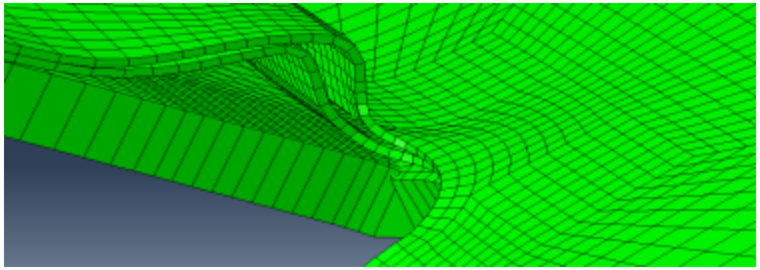
Evaluation of Abaqus Standard: Summary of Results

- Benefit: Standard predicts max load within 20% of experiments
- Major Challenges:
  - Implicit analysis fails to converge without excessive stiffness factors
  - After the use of excessive stiffness factors, some models still fail to converge
- Suggestion:
  - Accuracy can be improved by changing VCCT interfaces – but no rational for it
  - Modify convergence parameters

	% Zero	FEA % Difference from Average Experimental Maximum Load					
		1 Element Layer - No Scaled Stiffness Factors (SSF)	1 Element Layer - with SSF	2 Element Layer VCCT with SSF - Interface from Experiments	2 Element Layer VCCT with SSF - Interface before 90° plies	3 Element Layer VCCT with SSF - Interface from Experiments	3 Element Layer VCCT with SSF - Interface before 90° plies
20 PLY	10%	31%	15%	25%	20%	20%	**-1%**
	30%	DNC	19%	21%	21%	DNC	**18%**
	50%	**-16%**	**-16%**	-23%	-23%	DNC	DNC
40 PLY	10%	45%	22%	DNC	18%	DNC	**17%**
	30%	DNC	3%	**-2%**	-7%	42%	22%
	50%	**-3%**	-5%	-4%	-4%	DNC	DNC



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Today's Topics

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Evaluation of Abaqus/Standard with Helius:MCT

- Helius:MCT was utilized for its recognized convergence capabilities and fast solver algorithm for out-of-plane bending
- Solver basics: analyzes the composite based on its constituents as well as a whole:

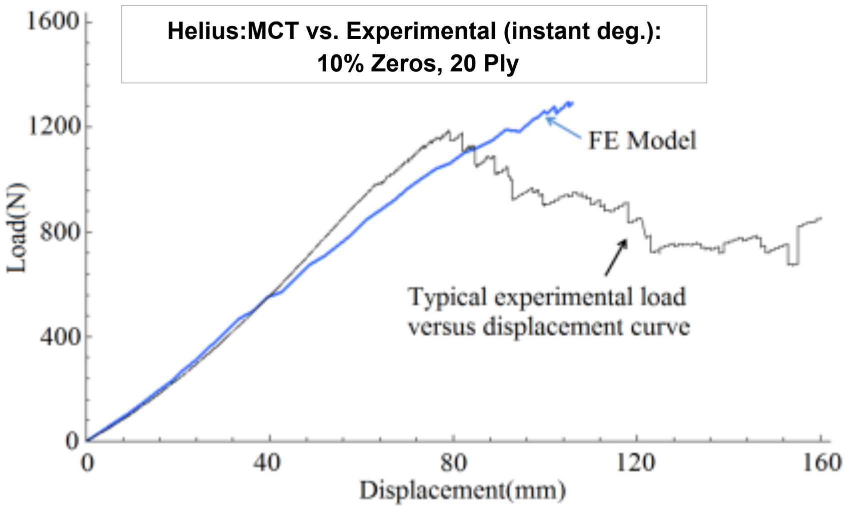
Volume fractions

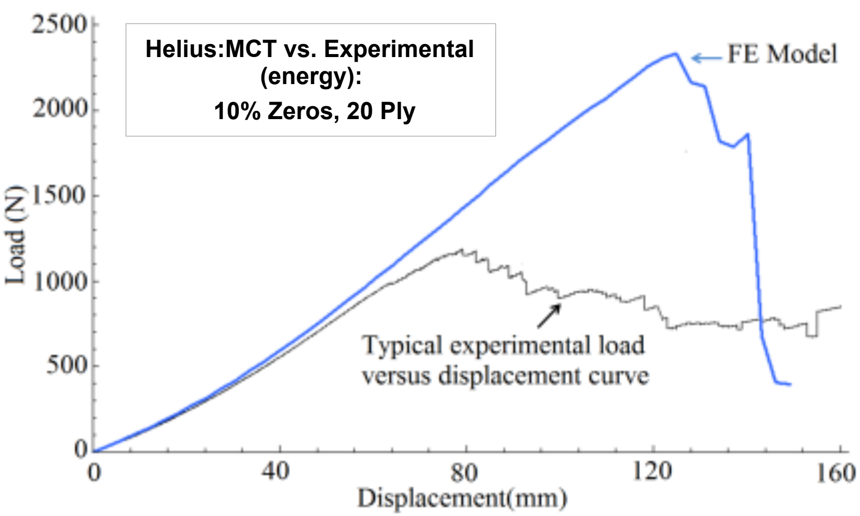
$$\sigma^c = \phi_f \sigma^f + \phi_m \sigma^m$$

Average stress of composite, fiber, and matrix respectively

- Method:
  - Adapt input file to include Helius:MCT solver
  - Use default parameters, instant degradation parameters, energy degradation parameters
  - Apply cohesive zones (CZ)

Evaluation of Abaqus/Standard with Helius:MCT Results





- Representative of all trials and configurations, including with CZ
- Benefits:fast solver: runtime < 10hrs
- Major challenges:
  - Convergence
  - Accuracy in certain situations
- Suggestions
  - Shows promise if convergence occurs, try different energy parameters or degradation values
  - Possible changes may occur in the future to better the solver: Autodesk ownership

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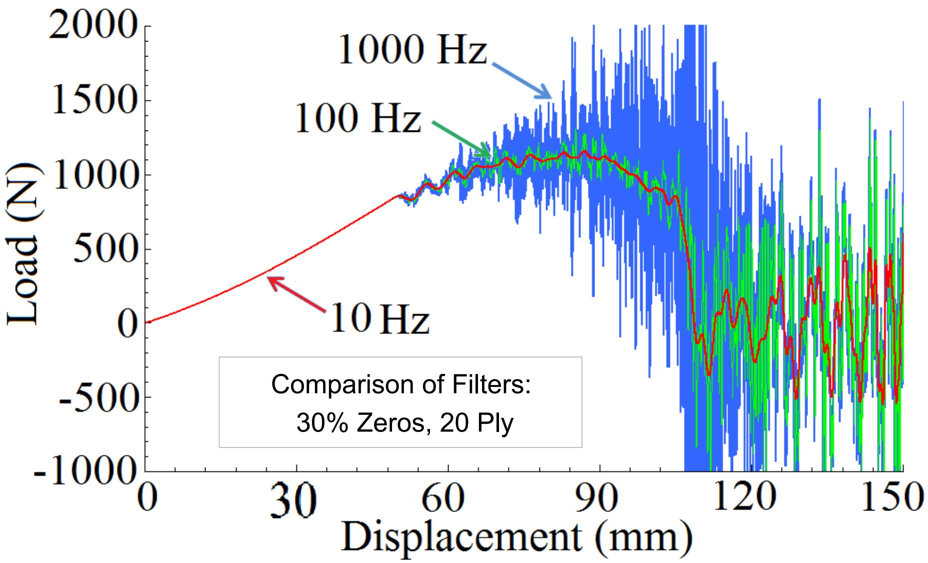
Abaqus/Explicit Analysis : Solver Basics and Implementation of Filtering

- Why use explicit: implementation of element deletion and better convergence
- Solver basics:
  - Analysis uses an explicit, dynamic solver: $[M][\ddot{U}] + [C][\dot{U}] + [K][U] = [R]$
  - Central difference method for enhanced convergence: hope to overcome the issues present in Abaqus/Standard
  - Hashin damage criteria



- Benefits: convergence in most cases
- Major challenges:
  - Extreme amounts of noise
  - Extremely long runtime
  - Difficult to determine cut-off frequency
  - Large amounts of data, 10+ Gb ODB
- Suggestions
  - Filtering the data
  - Implementing more layers

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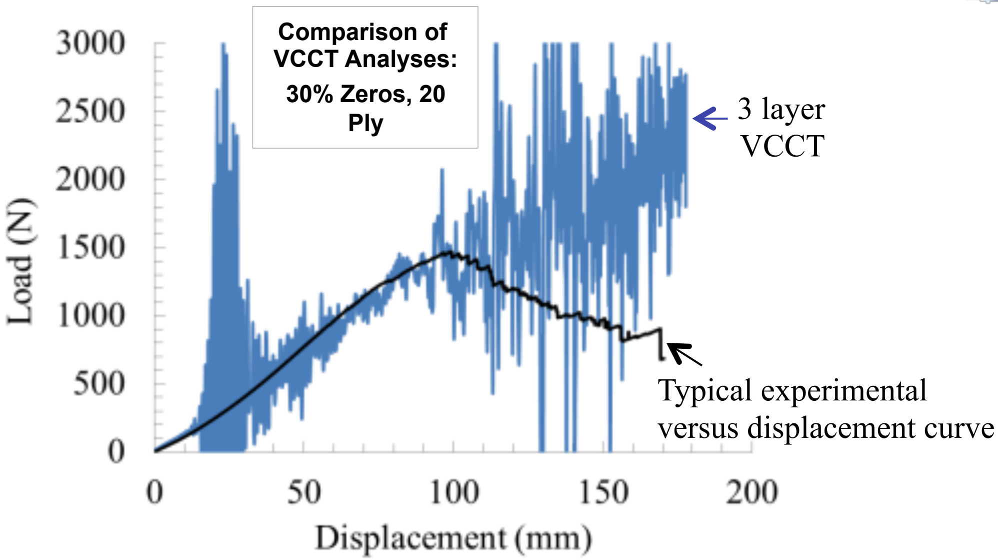
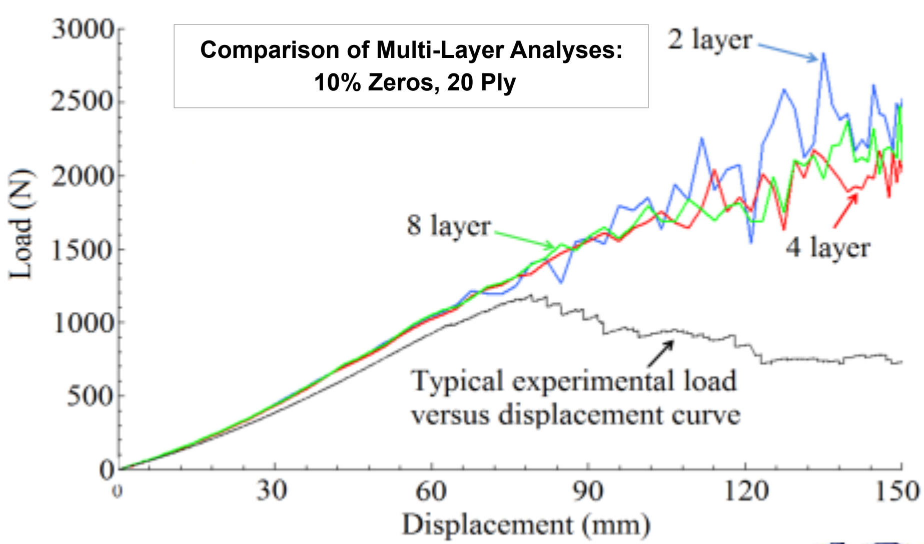
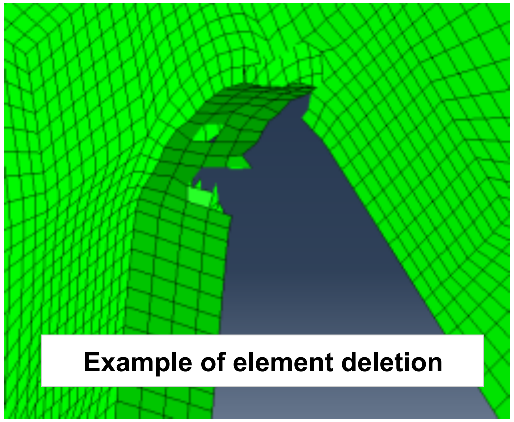
Abaqus/Explicit Analysis: Implementation of Multiple Layers and VCCT



- Benefits: eliminate distorted elements
- Major Challenges:
  - Convergence
  - Extremely long run times
- Suggestion: not much can be gained overall from implementing multiple layers





Example of element deletion

Summary of Phase VI

- With Standard, it is possible to get max load predictions <20 % of experiments, however with major issues
  - Requires scaling convergence factors which produces excessively stiff elements
  - Some solutions still may not converge
- Helius: MCT has severe convergence issues
- Explicit can converge and can handle element deformation but other issues exist
  - Noisy solutions with damage
  - Extremely long run time
- Recommendations - Going beyond the built-in capabilities of Abaqus and Helius:MCT
  - Create a user defined element that can more effectively handle deformation
  - Create a user defined progressive damage criterion based on Tsai Wu, Tsai-Wu has shown to be more effective then Hashin Damage

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Current Work with Mode III

- Report of methods and results for Phase VI
- Exploring the effectiveness of solid vs. shell elements in modeling Mode III
- Improving Abaqus/Explicit Modeling of Mode III shear
- Sensitivity study using Boeing material property values with Helius: MCT
- Sensitivity study using Boeing material property values with Abaqus/Standard
- Sensitivity study using published material property values and configurations with Abaqus/Standard to determine which property values are most significant

Current Work with Mode III

- ~~Report of methods and results for Phase VI~~
- ~~Exploring the effectiveness of solid vs. shell elements in modeling Mode III~~
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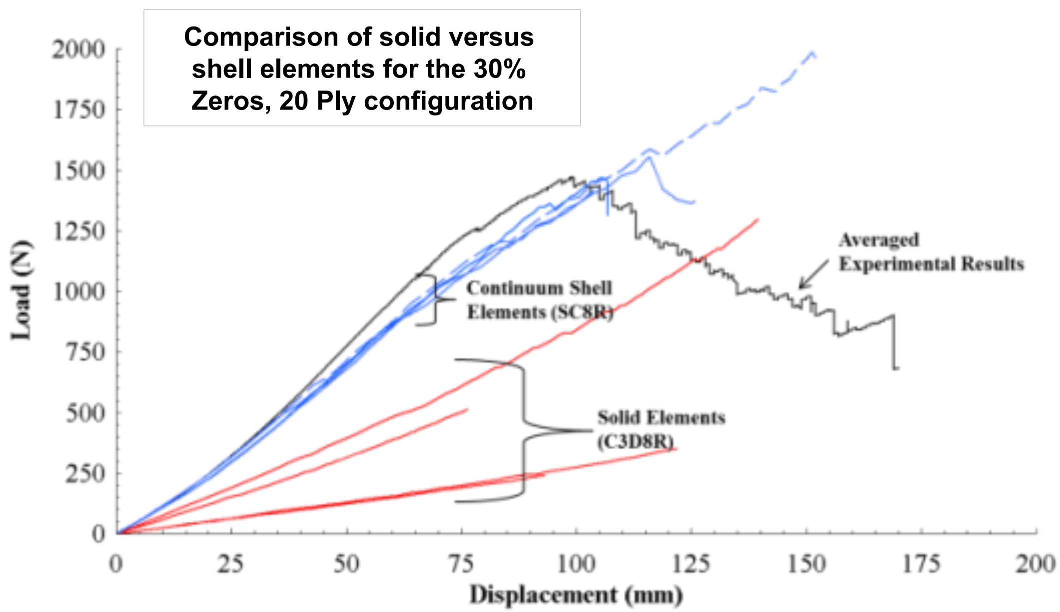
Solid vs. Shell Elements

- Important change: Helius:MCT (Firehole Composites) → Simulation Composite Analysis (SCA) [Autodesk]
- Only shell elements can be used with Hashin criteria in Abaqus/ Standard and Explicit
- Shell vs. solid elements were only compared within SCA
- Drastic difference in behavior and increased scatter with solid elements



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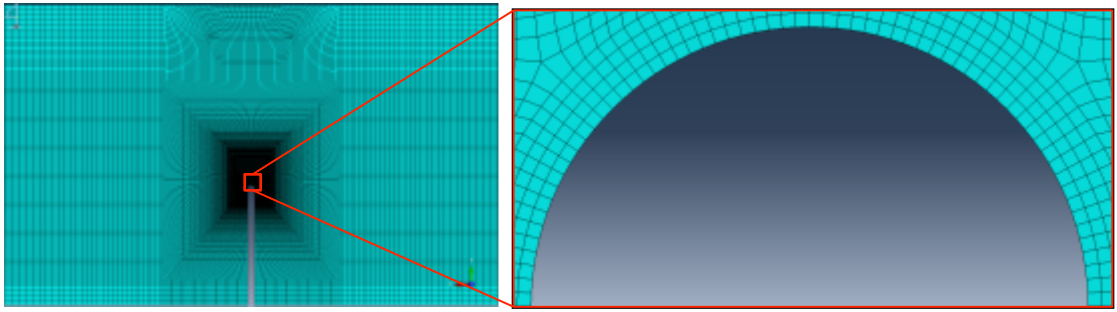
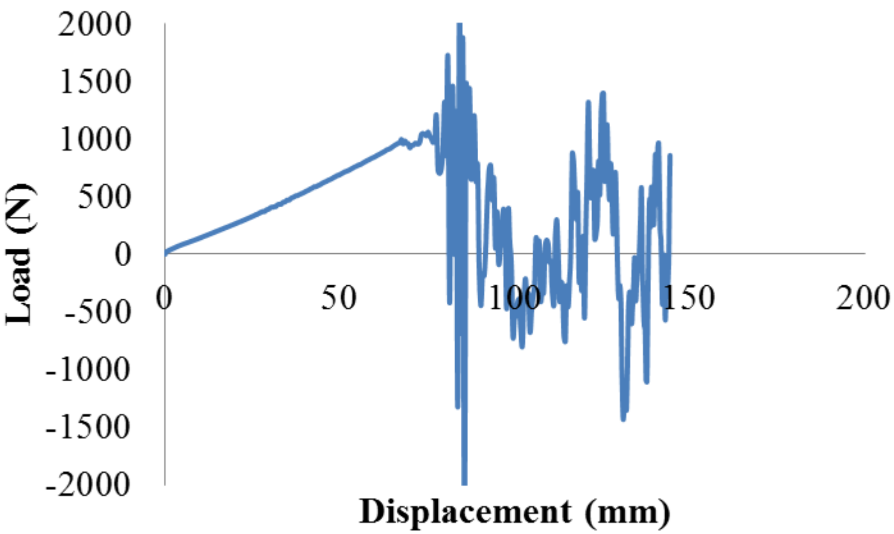
Possible Improvements for Abaqus/Explicit

- Attempted to increase in-plane mesh density: 64 elements around notch tip
  - Noise still occurred
  - Noise less evident only because fewer frames were extracted from .odb files
  - If more frames were extracted, more noise would be evident
- Introduce damping into the system?
- Determine a better mesh and work with existing filtering techniques?





SCA Sensitivity Study

******Hashin and Energy Parameters may not be accurate*

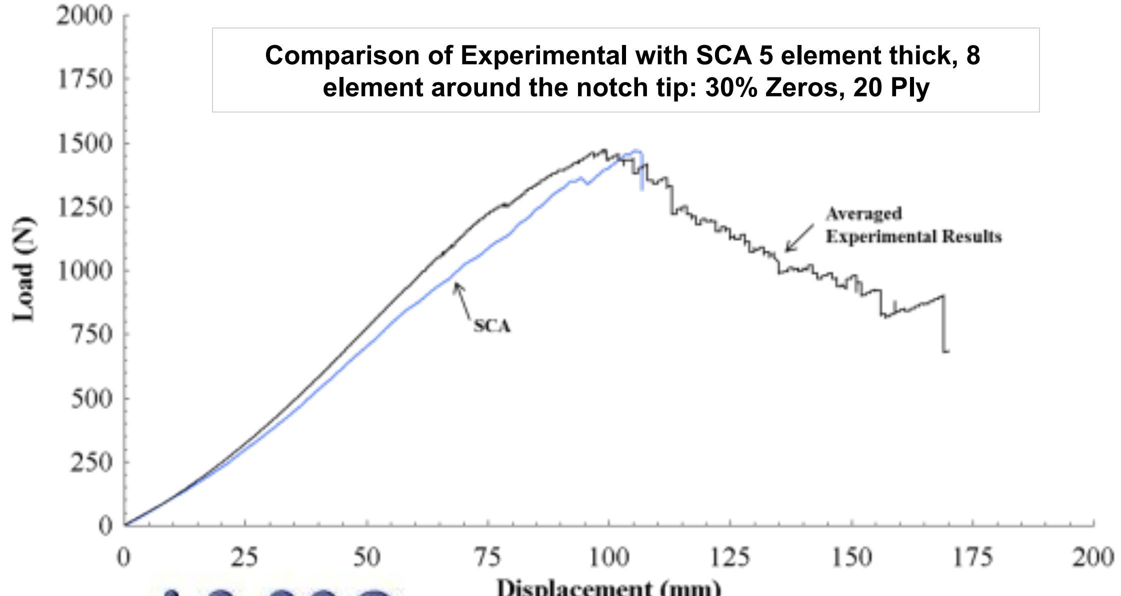
Percent differences from experimental for different configurations with varied instant degradation parameters

Combination	% Difference
20 plies thick - 10% Zeros	5.7
20 plies thick - 30% Zeros	9.8
20 plies thick - 50% Zeros	30.9
40 plies thick - 10% Zeros	4.3
40 plies thick - 30% Zeros	11.0
40 plies thick - 50% Zeros	18.9
Average	13.4

Parameters used in the 2^k factorial

Mesh Density	8, 20
Elements through thickness	1,5
Energy Degradation	Based on Study (2x)
Element Type	C3D8R & SC8R

- Variation of material parameters – obtained maximum loads for each configurations with variations of instant degradation factors
- 2^k factorial using instant degradation factors w/ 20 plies thick - 30% Zeros configuration – no maximum load obtained with solid elements. Obtained maximum load within 2 percent using 5 elements through the thickness and 8 elements around the notch tip; also, damage propagation is similar to damage in experimental panels.



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SCA Sensitivity Study

- 2^k factorial using energy degradation factors – same results as solid vs. shell element investigation for the solid element models within the study. On-going study to determine the effect of number of elements through the thickness and energy parameters. However, it appears that using energy degradation also has limits: convergence issues still exist.

Parameters used in the 2^k factorial

Mesh Density	8, 20
Elements through thickness	1,5
Energy Degradation Factors	Given & 1/4 of given
Element Type	C3D8R & SC8R

- Conclusion: more elements = lower probability of convergence, convergence is highly dependent on degradation factors which may be different for each configuration, ultimate problem is excessive element deformation

Sensitivity Studies with Abaqus/Standard

- Sensitivity study using Boeing material property values with Abaqus/ Standard
  - 2^{10-4} fractional factorial for a 1/16 fraction, resolution IV design
  - Vary Hashin and energy parameters ± 20%
  - Ideal future outcome: determine which material properties have the greatest effect with the Boeing configurations and what combination of varied properties yields the lowest deviation when compared to experimental outcomes
- Sensitivity study using published material property values and configurations with Abaqus/Standard
  - Will use simpler configurations, as compared to Boeing layups, and fewer plies through the thickness: 8-10 plies thick with all 0ºs, 90ºs, ±45º lamina orientations, this may provide for clearer results
  - A variety of loading scenarios will be investigated: Mode III, compression, etc.
  - Ideal future outcome: define loadings and layups that isolate the Hashin and energy parameters leading to an ASTM standard for determination of these properties.

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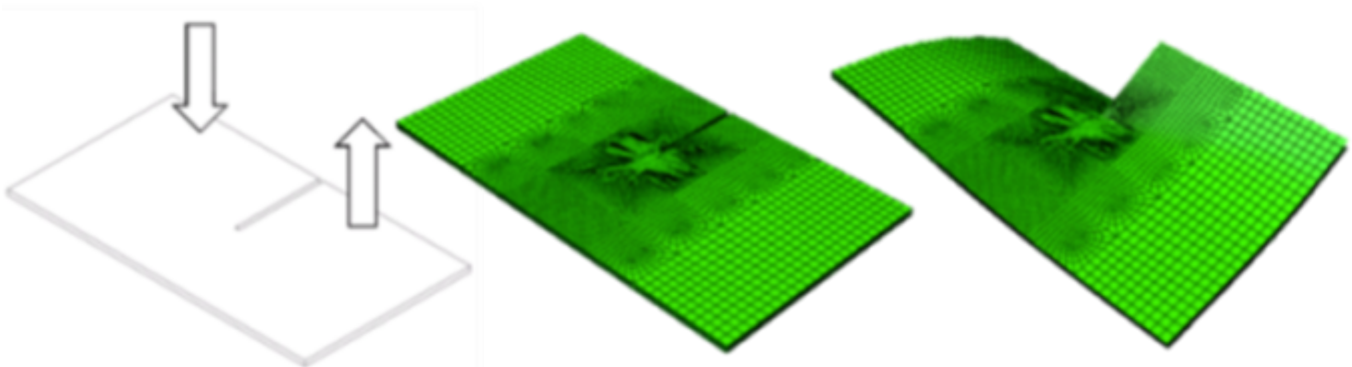
Questions?



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Out-of-Plane Shear: Summary of Experimental Results

- **Maximum applied load (failure load)**

	Max Force per Test [kN]						
Layup (#plies / % zero degree)	1	2	3	4	5	6	**MEAN**
40/50%	5.552	5.345	5.122	6.103	5.395	5.321	**5.473**
40/30%	5.342	5.363	6.061	5.616	6.176	5.690	**5.708**
40/10%	3.891	4.161	4.112	4.016	4.277	4.148	**4.101**
20/50%	1.751	1.859	1.929	1.691	1.740	1.801	**1.795**
20/30%	1.484	1.541	1.541	1.456	1.527	1.638	**1.531**
20/10%	1.290	1.215	1.258	1.254	1.198	1.336	**1.259**

Why Continuum Shell Elements vs. Solid Elements

- Solid elements can be laminated but max order of variation of the displacement is quadratic
  - Hence strain variation is at most linear
  - Insufficient to model variation of strain through thickness of laminate
- Potential Solution: stack solid elements at one element per lamina
  - In-plane dimensions can not be > 10x thickness
  - Requires a really fine mesh
- Alternate Solution: Use continuum shell elements
  - Does not have the same problems as a solid element
  - Can have multiple plies through the thickness
  - Also can be stacked for using with grips and delamination
  - Laminate stacking sequence was constructed using Composite Layup in Abaqus – define material property per ply
- MOST IMPORTANTLY: Abaqus built-in limits Hashin Damage to elements with plane stress formulation, which include plane stress, shell, continuum shell, and membrane elements

Viscous Regularization Scheme

- The viscous regularization scheme helps a model come to a converged solution
- Viscous coefficient must be small with respect to the time increment, $t/\eta_i \to \infty$
- Four viscous coefficients for each damage mode that needs to be user specified

η_{fc}	Viscosity Coefficient for Fiber Compression
η_{ft}	Viscosity Coefficient for Fiber Tension
η_{mc}	Viscosity Coefficient for Matrix Compression
η_{mt}	Viscosity Coefficient for Matrix Tension

Viscous Regularization Scheme

- Models involving stiffness degradation may have convergence difficulties with implicit solvers
- For small time increments, viscous regularization allows the tangents stiffness matrix of a mat'l to be positive definite
  - Tangent stiffness matrix would be symmetric with positive eigenvalues
  - If matrix is singular and not positive definite, determinant of matrix would be zero
  - Results in dividing by zero during matrix inversion
- Technique defines a regularized damage variable, d_I^V and the rate at which the variable changes with time $\dot{d}_I^V$
  - User specifies the relaxation time of the viscous system η_I
  - d_I^V is utilized to calculate the damage response of the material

$$\dot{d}_I^V = 1/\eta_I (d_I - d_I^V)$$

- Viscous regularization scheme helps the model converge

Viscous Regularization Scheme Cont…

- How to determine $\eta_{ft}, \eta_{fc}, \eta_{mt}, \eta_{mc}$?
- Set terms terms to relatively high values to get model convergence
- For this study, $\eta_{ft} = \eta_{fc} = \eta_{mt} = \eta_{mc}$
- Parameters were decreased until maximum load prediction did not change dramatically
- This yielded a starting point in determining appropriate values for viscous coefficients

Scaling Hourglass Stiffness

- Default hourglass stiffness was scaled to prevent severe element deformation
- Pure stiffness approach was recommended for quasi-static analysis
- Three user defined scaling factors

Factor	Description	Typical Range
	Hour glass stiffness scaling factor for displacement degree of freedom	0.2 - 3.0
	Hour glass stiffness scaling factor for rotational degree of freedom	0.2 - 3.0
	Hour glass stiffness scaling factor for out-of-plane displacement degree of freedom	0.2 - 3.0

Scaling Hourglass Stiffness

- Scaling $s{\uparrow}w$ caused solutions to fail prematurely
- Only scaled $s{\uparrow}s$ and $s{\uparrow}r$
- After scaling to the limits of the recommended value, not all stacking sequences converged
- After drastically increasing factors, convergence was achieved for most models
- Factors were selected based on a convergence study

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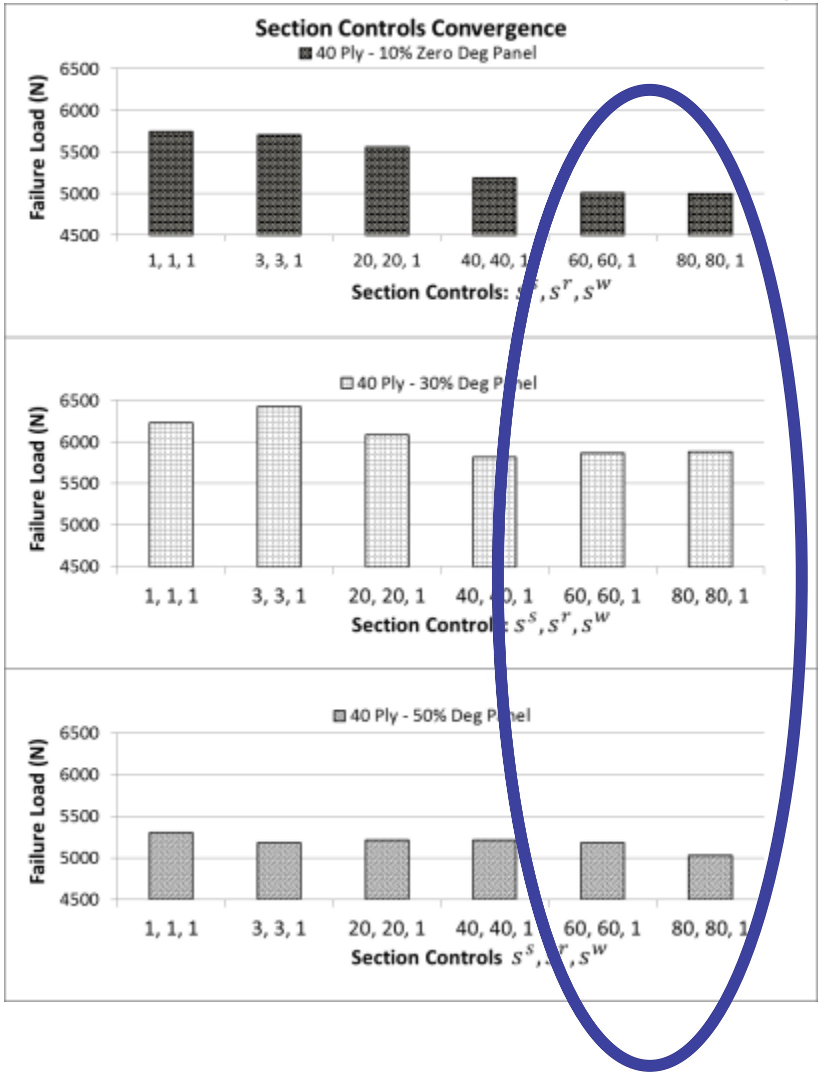
Scaling Hourglass Stiffness



- **Begin to see a converging trend at** $s^s=60, s^r=60, s^w=1$
- This **is consistent between the three stacking sequences**

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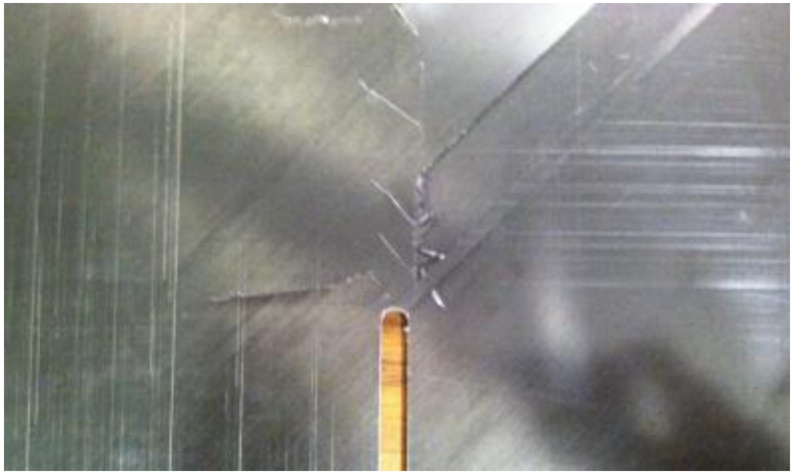
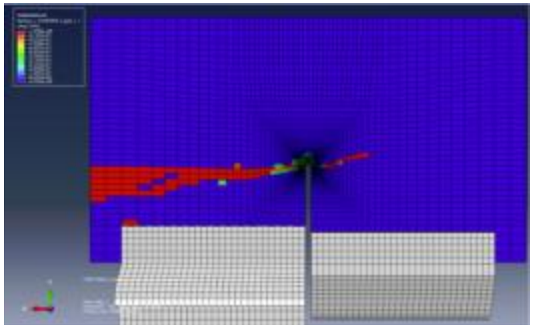
Abaqus/Standard Damage Path Model

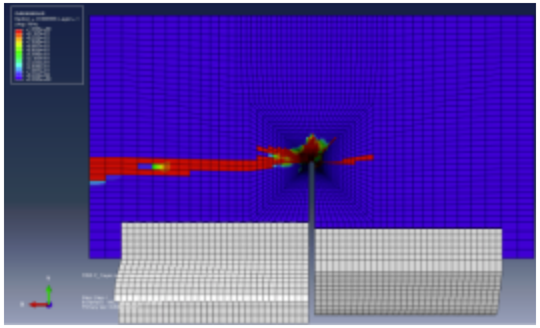
10% 0°– 20 ply



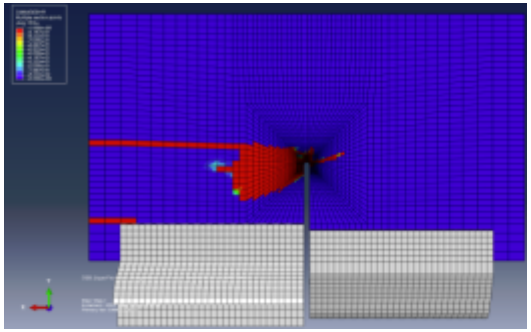
1 Layer – No SSF



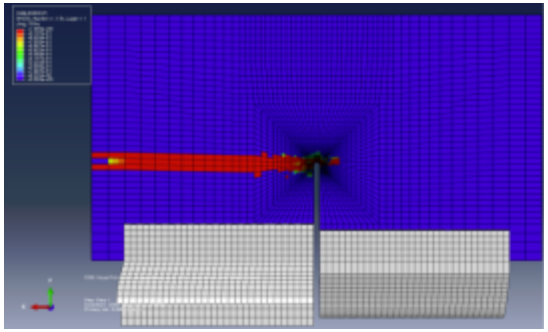
1 Layer – with SSF



2 Layer – VCCT



3 Layer – VCCT



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Results Table: Explicit and Helius:MCT

Energy (Given)				
Combo	**MCT (N)**	**Exp. (N)**	**% Diff**	**Converge**
F	2330.83	1188	65.0	Y
N	2377.34	1689	33.9	Y
P	2598.69	1472	55.4	Y
AN	9785.4	5111	62.8	N
FP	9278.33	4005	79.4	Y
AR	7394.08	5899	22.5	Y

Instant Degradation (Default)				
Combo	**MCT (N)**	**Exp. (N)**	**% Diff**	**Converge**
F	1254	1188	5.4	N
N	1514	1689	10.9	N
P	1624	1472	9.9	N
AN	5182	5111	1.4	N
FP	4817	4005	18.4	N
AR	6528	5899	10.1	N

Instant Degradation (Given)				
Combo	**MCT (N)**	**Exp. (N)**	**% Diff**	**Converge**
F	1296.9	1188	8.8	N
N	1184.99	1689	35.1	N
P	1388.43	1472	5.8	Y
AN	4989.86	5111	2.4	N
FP	5104.25	4005	24.1	N
AR	6528.27	5899	10.1	N

Cohesive Zones (Given - Instant)				
Combo	**MCT (N)**	**Exp. (N)**	**% Diff**	**Converge**
F	713	1188	50.0	N
N	996	1689	51.6	N
P	838	1472	54.8	N

Abaqus/Explicit: Filter				
Combo	**Explicit (N)**	**Exp. (N)**	**% Diff**	**Converge**
F	1291	1188	8.3	Y
N	928	1689	58.1	Y
P	1158	1472	23.8	Y

Legend: Y = Yes, N=No, Exp. = Experimental Values, MCT= Helius:MCT results

F= 10% zeros, 20 ply ; P = 30% zeros, 20 ply ; N=50% zeros, 20 ply ; FP = 10% zeros, 40 ply ; AR = 30% zeros, 40 ply ; AN = 50 % zeros, 40 ply

Helius:MCT Results – Boeing Parameters (Energy Degradation)

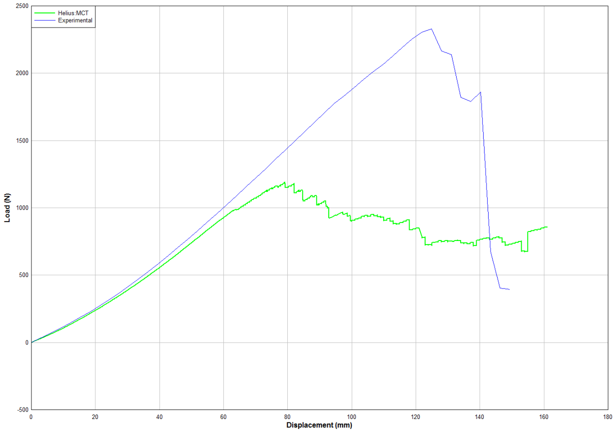

Fig 1. F Configuration

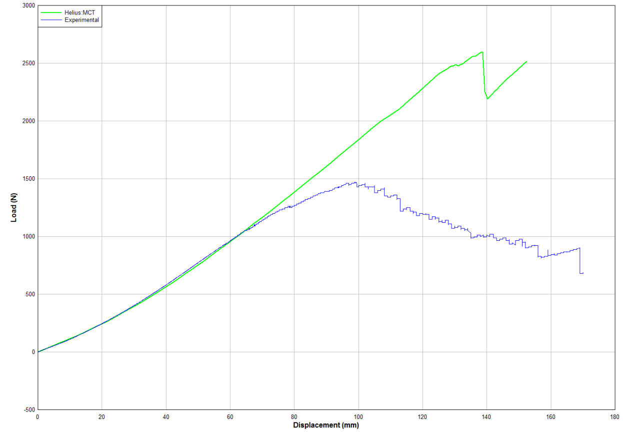

Fig 2. P Configuration

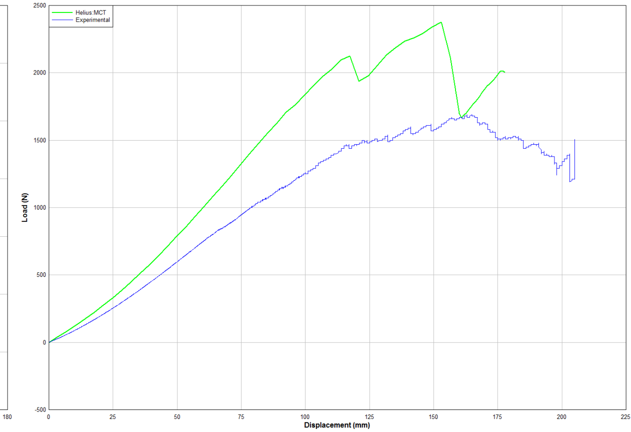

Fig 3. N Configuration

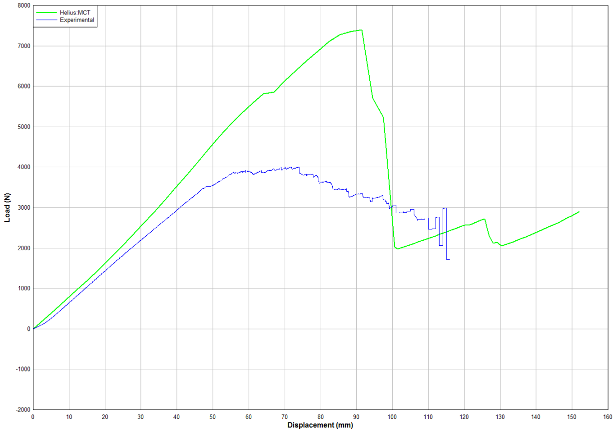

Fig 4. FP Configuration

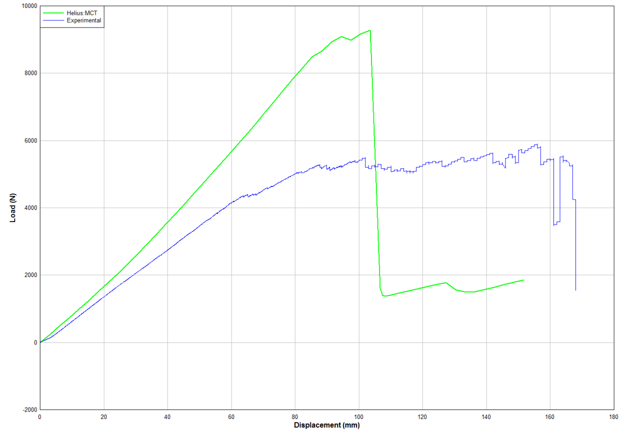

Fig 5. AR Configuration

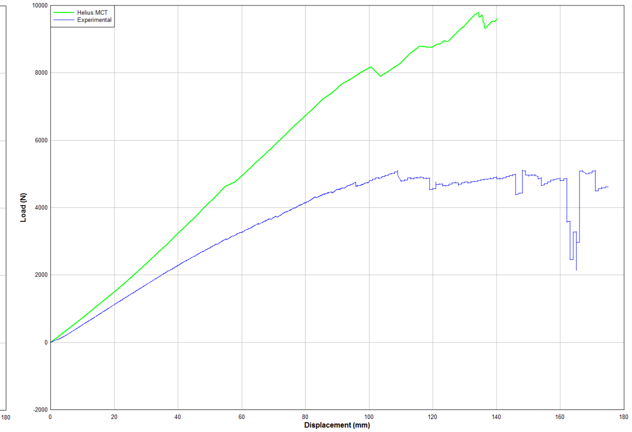

Fig 6. AN Configuration

Helius:MCT Results – Boeing Parameters (Energy Degradation)

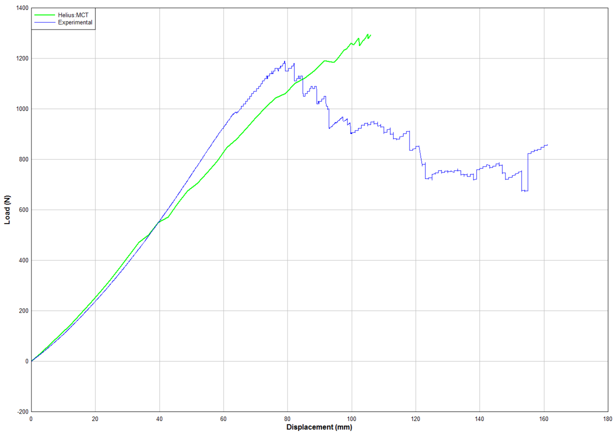

Fig 1. F Configuration

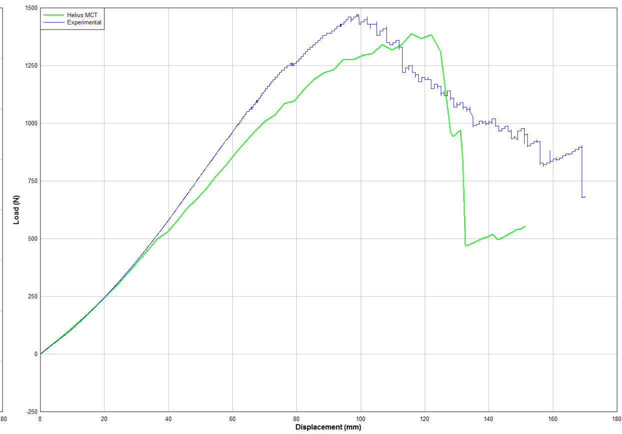

Fig 2. P Configuration

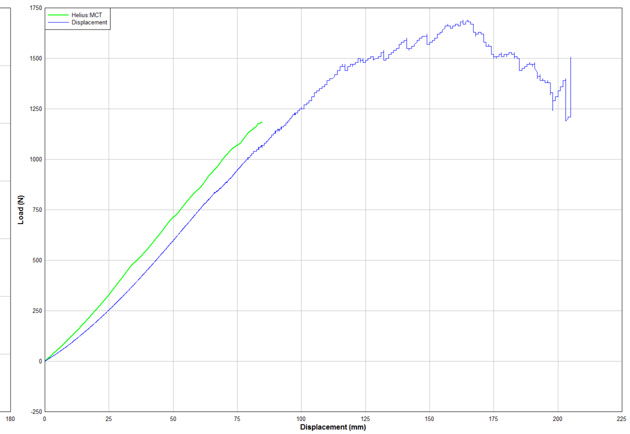

Fig 3. N Configuration

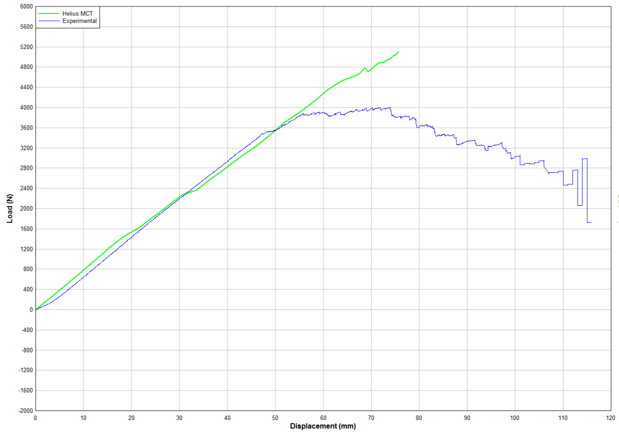

Fig 4. FP Configuration

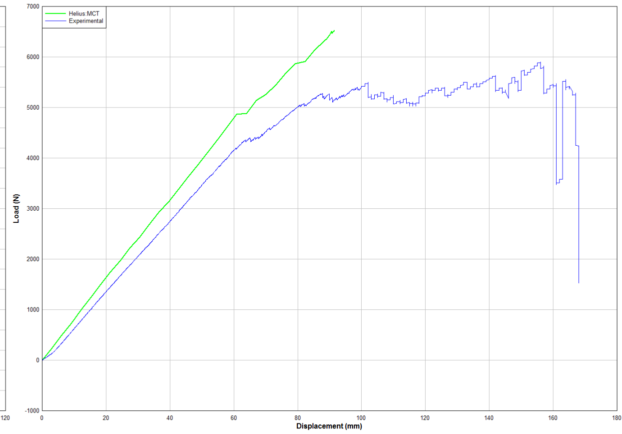

Fig 5. AR Configuration

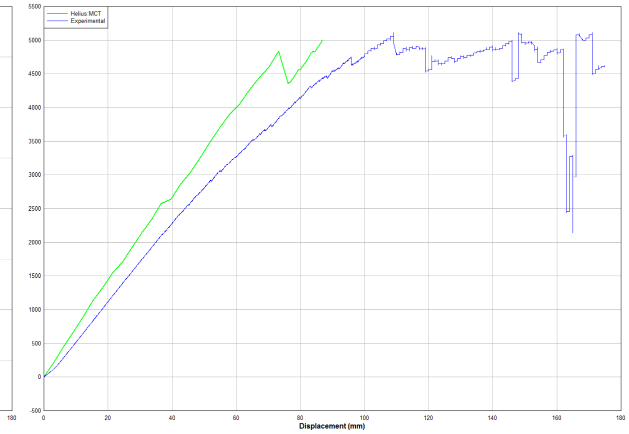

Fig 6. AN Configuration

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Helius:MCT Results – Default Parameters

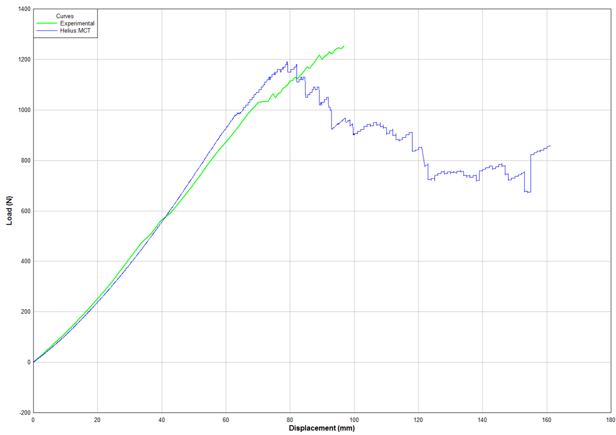

Fig 1. F Configuration

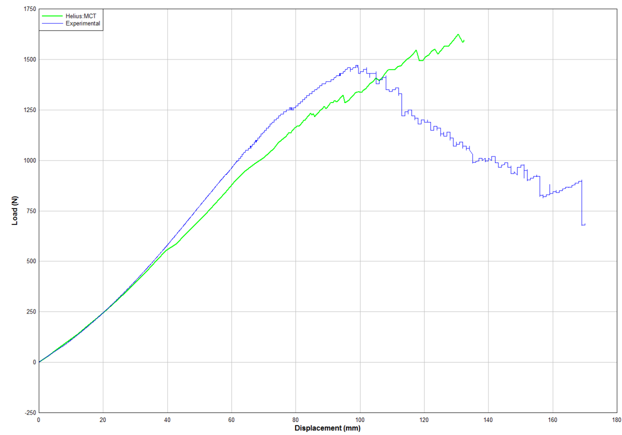

Fig 2. P Configuration

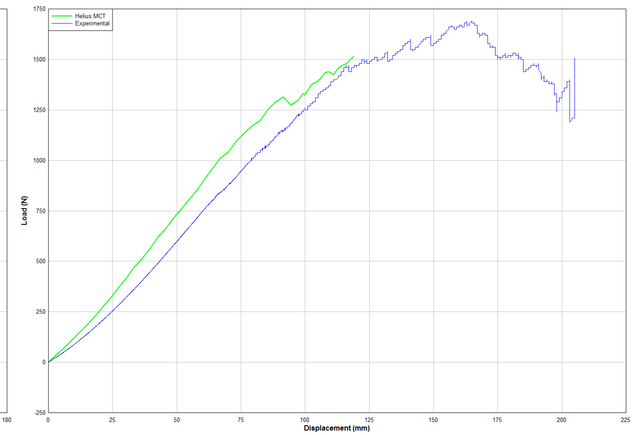

Fig 3. N Configuration

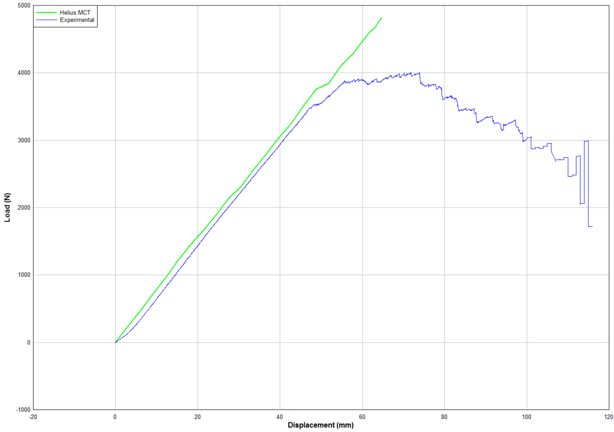

Fig 4. FP Configuration

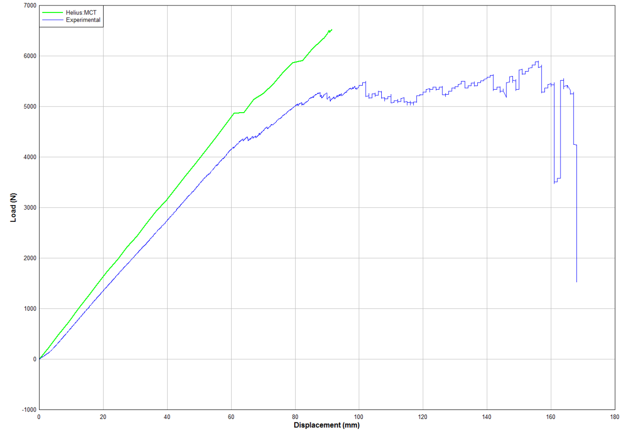

Fig 5. AR Configuration

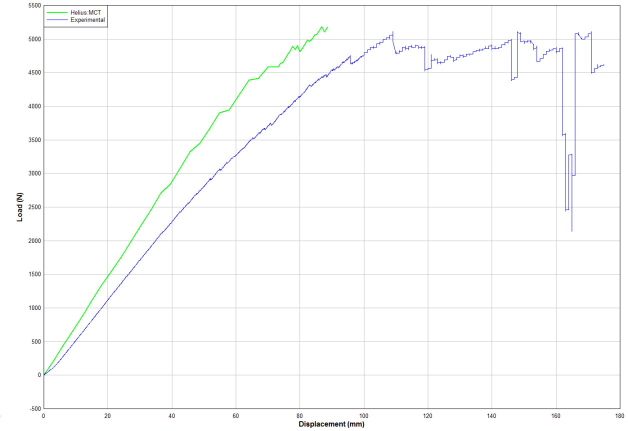

Fig 6. AN Configuration

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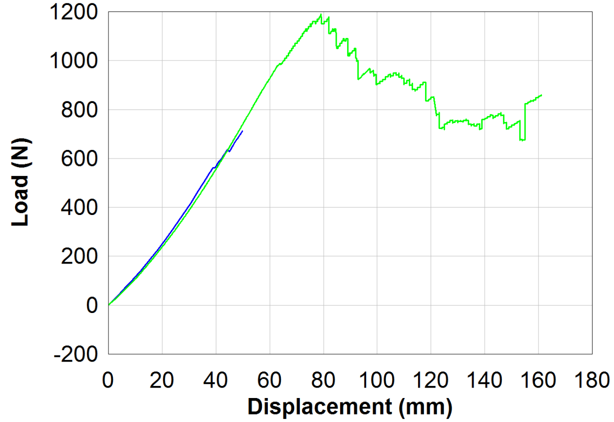
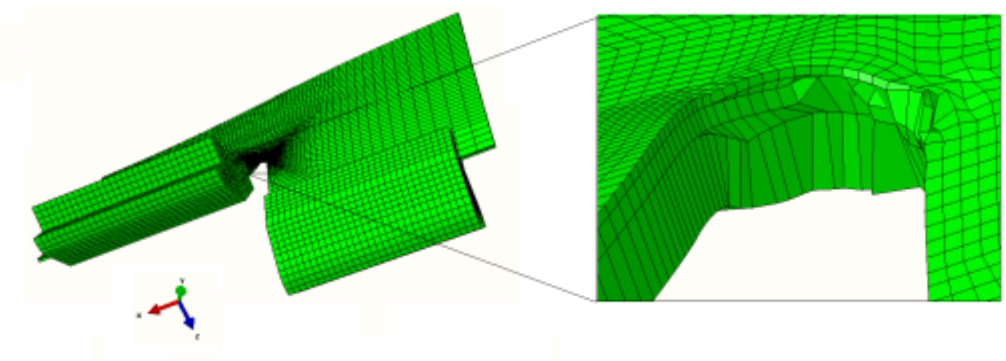
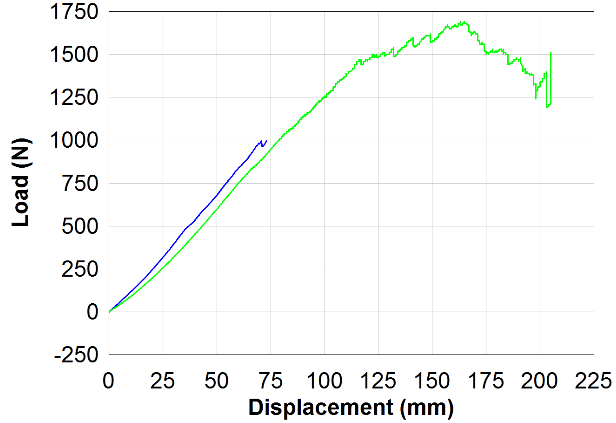
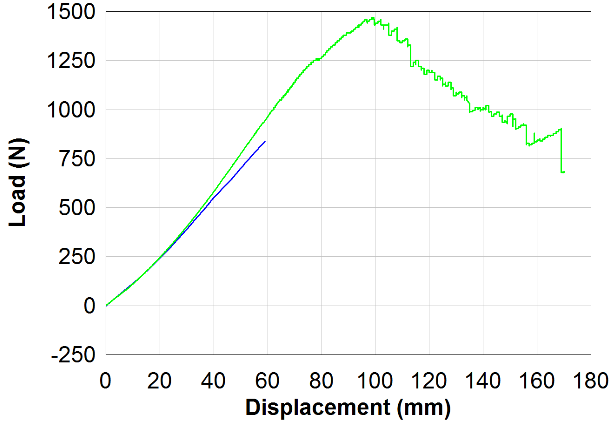
Cohesive Zones in Helius:MCT









- Cohesive zone runs do not converge
- Deformation in cohesive zone areas can be observed but it is difficult to discern if this deformation is delamination

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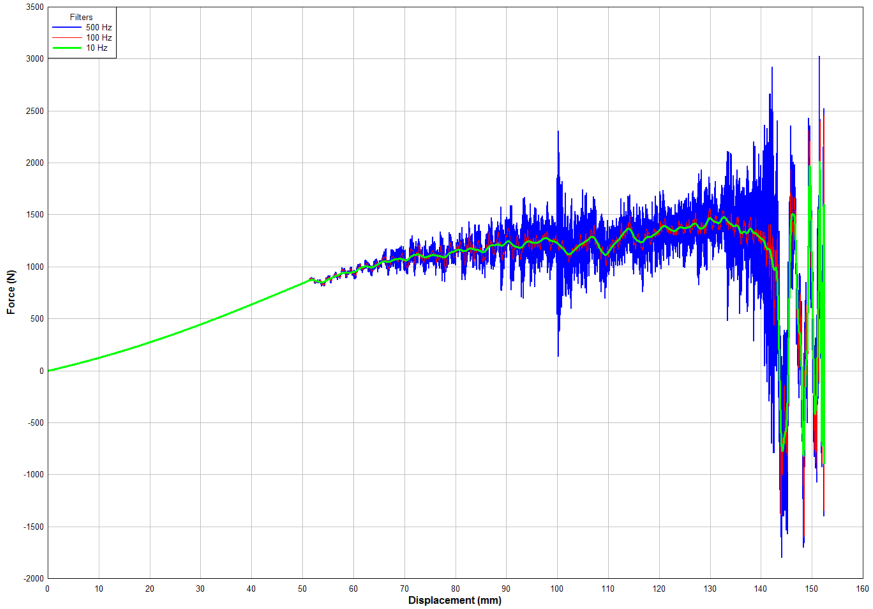
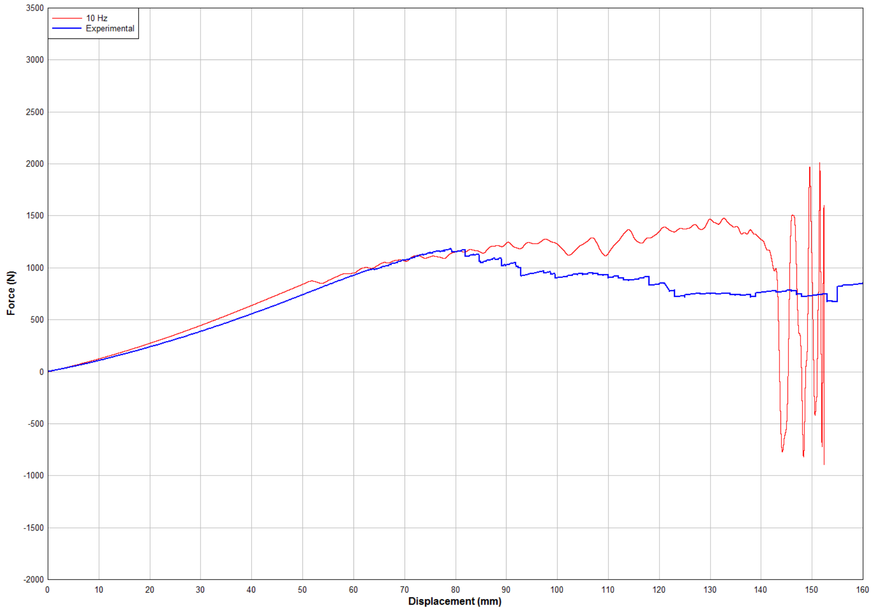
Filtering Results

*10% zeros, 20 plies



Application of filters with varying cut-off frequencies for F-configuration



10 Hz cut-off filter compared to experimental results for F-configuration

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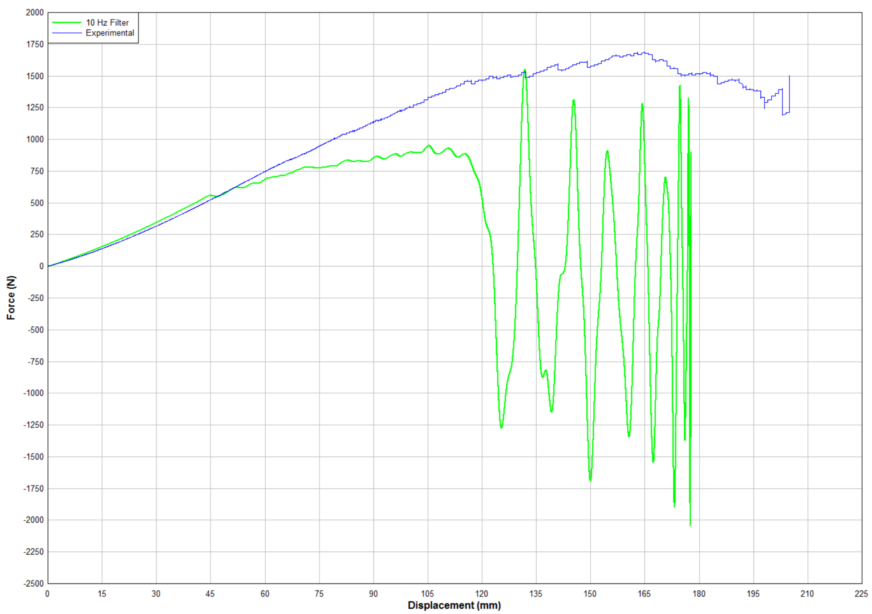
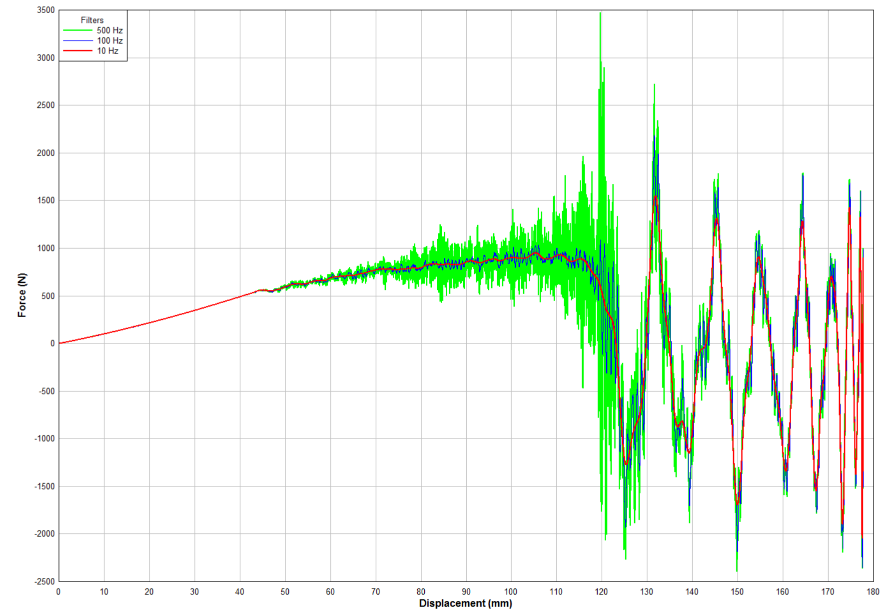
Filtering Results

*50% zeros, 20 plies

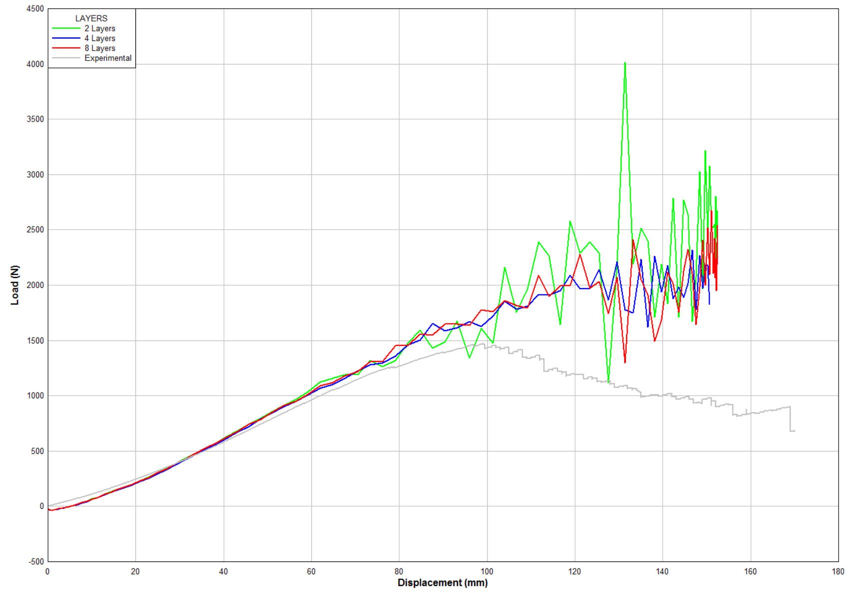


10 Hz cut-off filter compared to experimental results for N-configuration

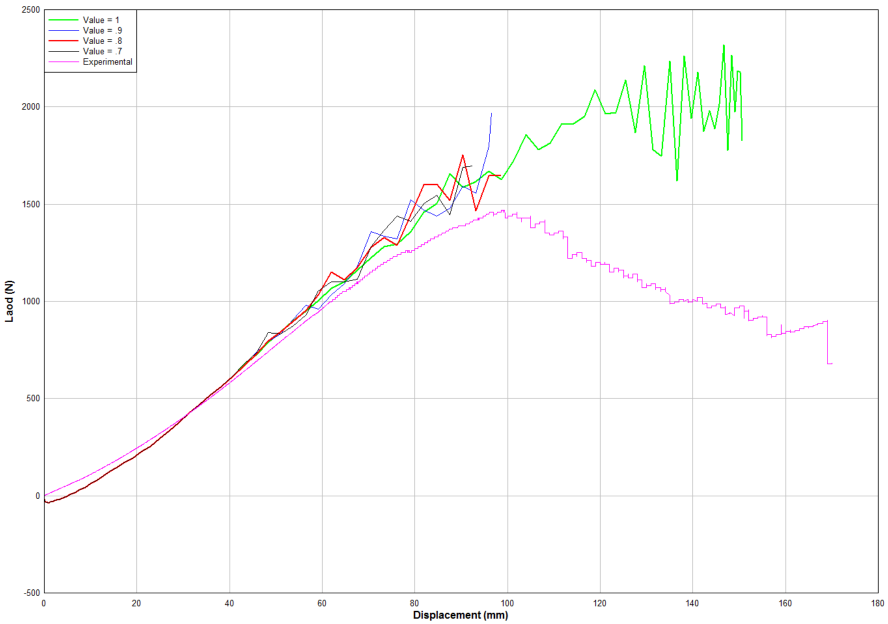


Application of filters with varying cut-off frequencies for N-configuration

More Multi-Layer Results



Multi-Layer Models : 30% zeros, 20 plies configuration



4 layer with varying degradation values: 30% zeros, 20 plies configuration

Abaqus/Explicit Solver Runtime

- Analyses are extremely long
  - the Explicit solver is only conditionally stable and requires an extremely small time step. Critical time step must considered:

$$\Delta t \leq \frac{2}{\omega_{max}} \leq \Delta t_{cr}$$

  - Need to maintain a Quasi-static state: $E_K \leq 0.1\, E_I$

Multi-Layer Run Time

Table 1. Run Times for Quasi-static models.

Layers (ct.)	Run Time (hr)
2	354
4	672
8	585

More on Damping

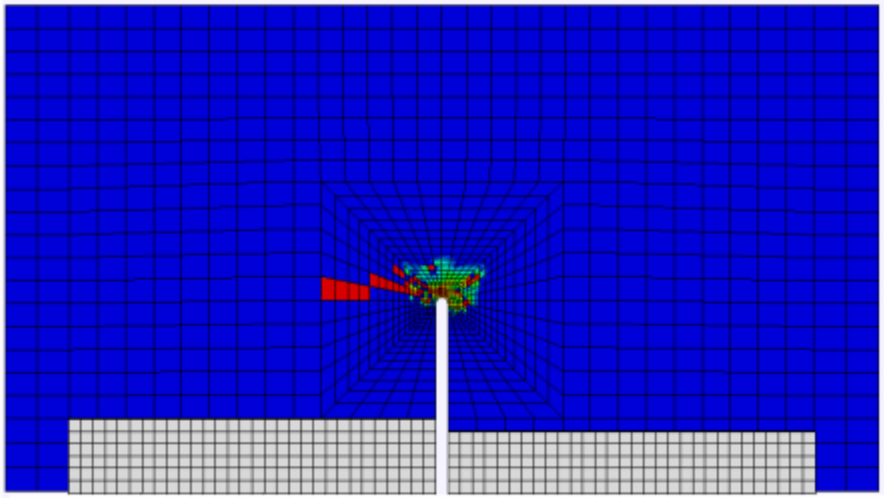
Introduce damping into the system?

- Rayleigh damping – meant to reflect physical damping in the material, used in steady-state dynamic analyses
  - Mass Proportional Damping – model moves through a viscous ether, so any motion causes damping
  - Stiffness Proportional Damping - can be thought of as damping associated with material itself
  - Caused excessively longer run times

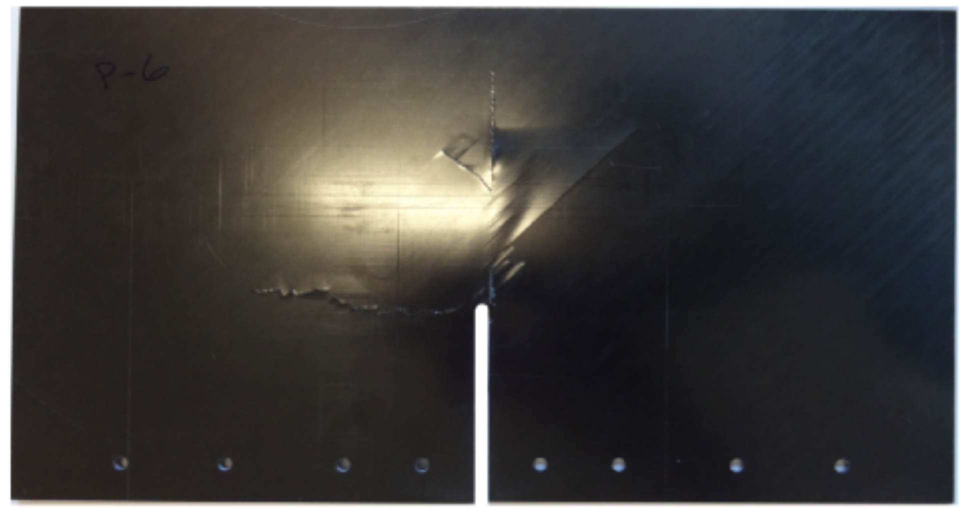
- Bulk viscosity damping – purpose is to improve speed of dynamic events, introduces a small amount of numerical damping to control high frequency oscillations
  - Linear bulk viscosity – used to damp ringing
  - Quadratic bulk viscosity – Only for solid continuum elements

Damage Propagation Using SCA

SCA Model versus Experimental Panel : 20 plies thick - 30% Zeros Configuration



8 el @ notch tip - 5 el through thickness



Experimental panel

* Damage propagation using instant degradation parameters; however, similar propagation is modeling with energy degradation parameters