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

Fall 2013 Meeting

Imran Hyder, Nasko Atanasov,

& John P. Parmigiani,
Oregon State University

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

- 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

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

- 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)

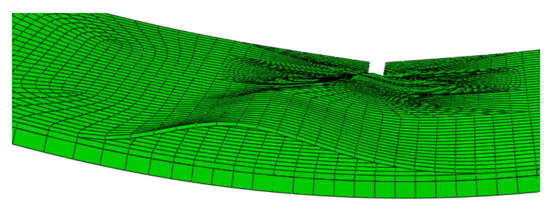
- Out-of-plane bending experiments w/composite plates
- Abaqus modeling with progressive damage

Phase II (2008-09)

- Abaqus modeling with buckling delamination added
- Sensitivity study of (generic) material property values

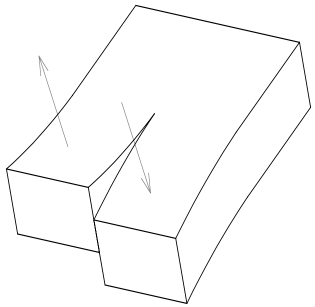
Phase III (2009-10)

- Abaqus modeling w/ more delamination interfaces



Project Overview

Phase IV (2010-11)

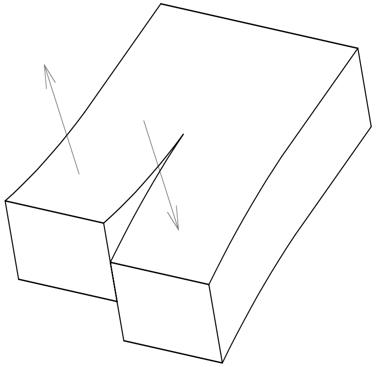


- Out-of-plane shear experiments
- Further study of additional delamination interfaces for out-of-plane bending
- Initiating vs. propagating toughness values for out-of-plane bending
- Feasibility of Abaqus/Explicit and XFEM for future work
- Sensitivity study using Boeing mat'l property values

Project Overview

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 use in modeling progressive damage in composites and applicability to this project – specifically for Out-of-plane bending



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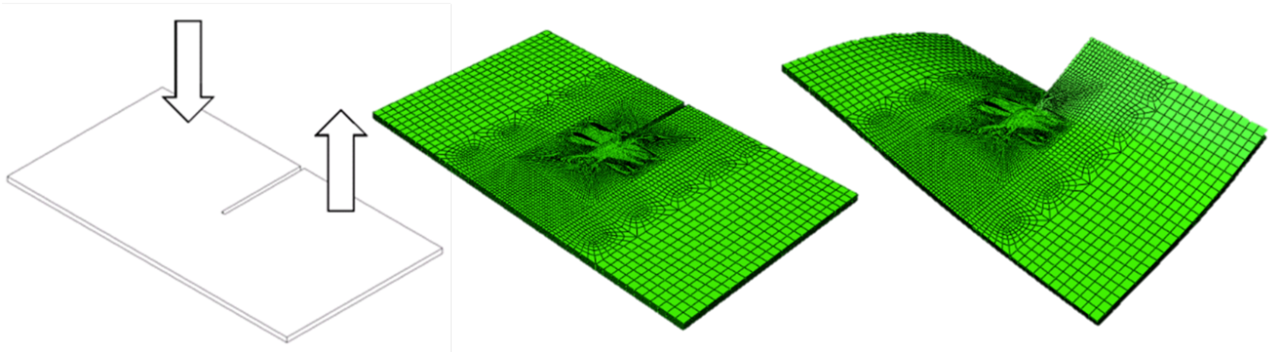
Project Overview

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



Today's Topics

- Experimental results: Out-of-plane shear
- Evaluation of Abaqus Standard results
- Evaluation of Helius: MCT results
- Evaluation of Abaqus Explicit results

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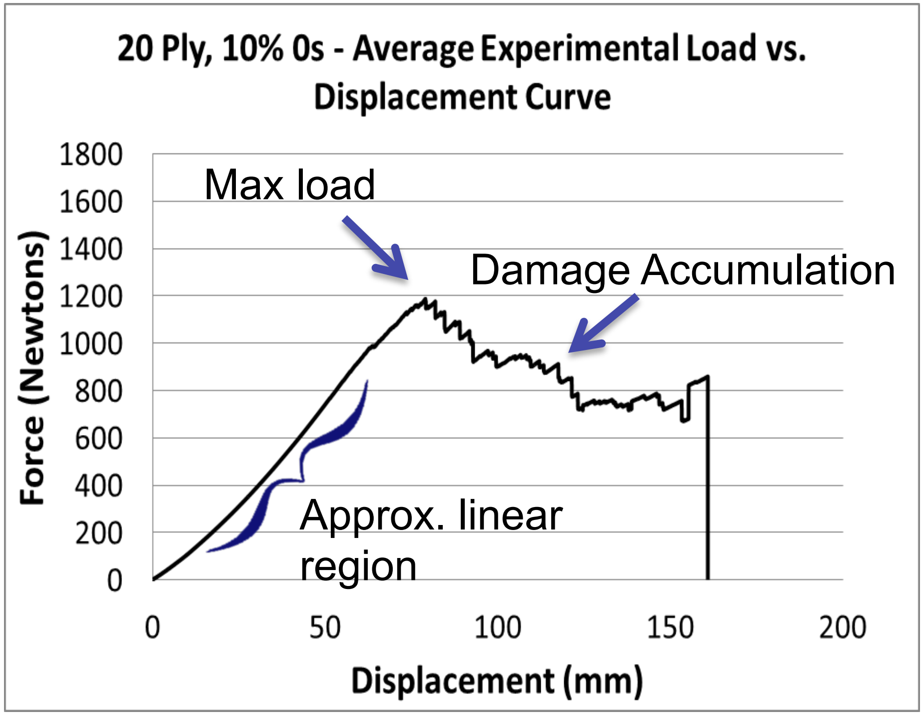
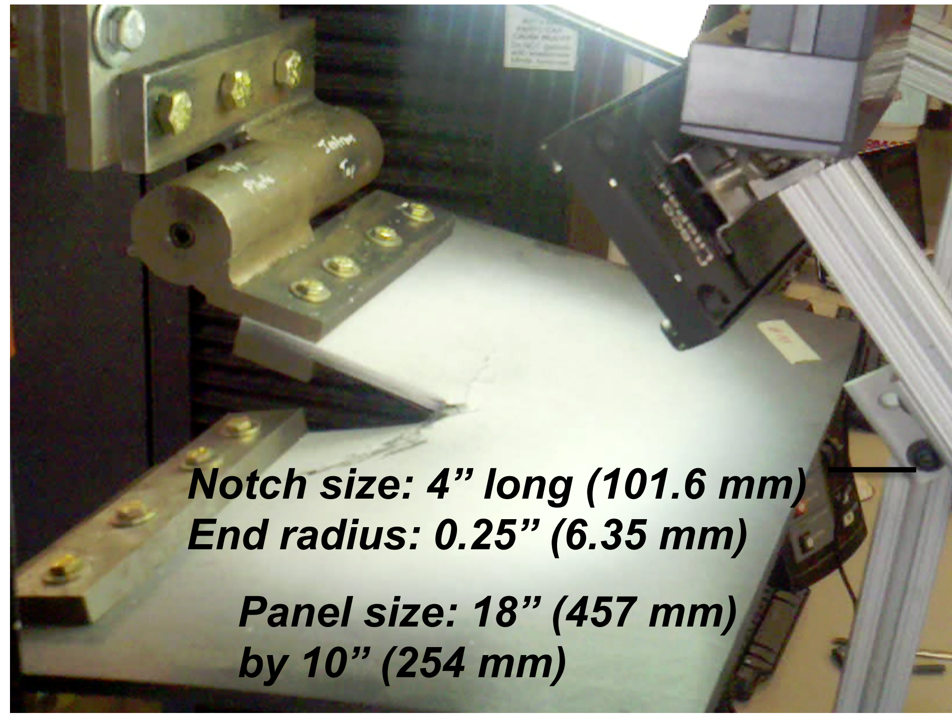
Out-of-Plane Shear: Summary of Experimental Results





- 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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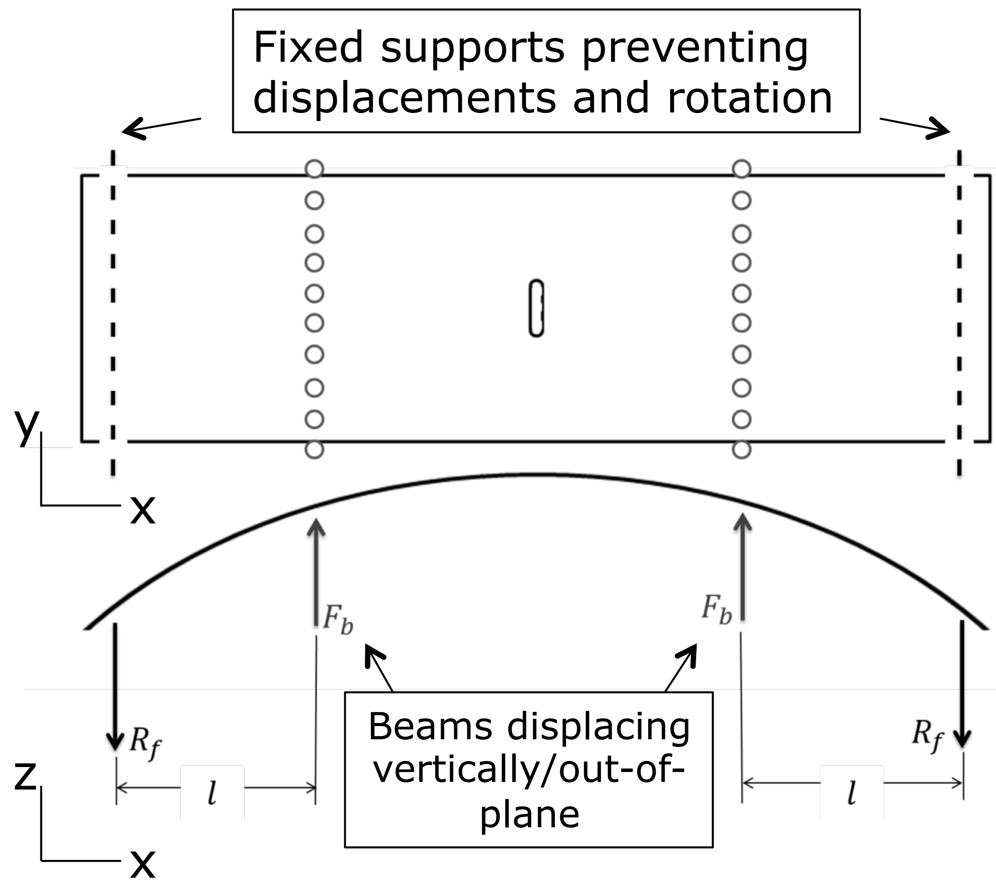
- Experimental results: Out-of-plane shear
- Evaluation of Abaqus Standard results
- Evaluation of Helius MCT results
- Evaluation of Abaqus Explicit results

Evaluation of Abaqus Standard: Previous Study with Out-of-plane Bending

- Selected mesh based on a linear elastic convergence study
- Created single layer and multilayer models
- VCCT interfaces around 0° plies for delamination (0°plies more critical)
- Agreed with experimental results within 10%
- Applied same procedure to Mode III/ Out-of-plane shear

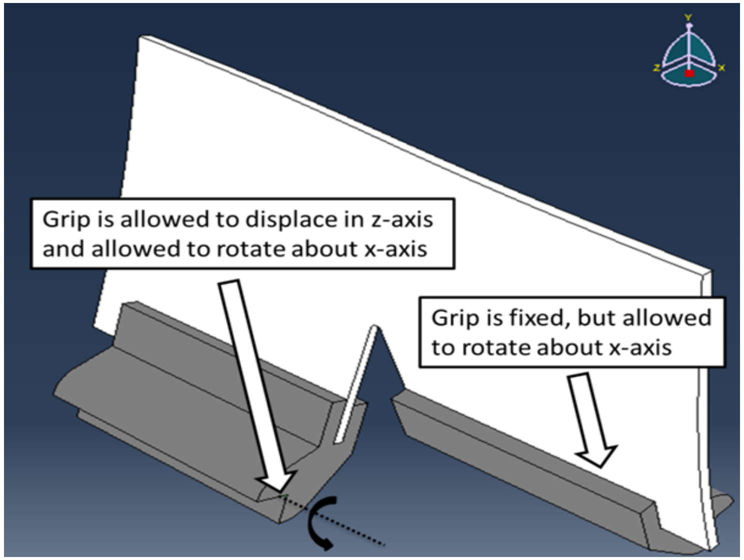


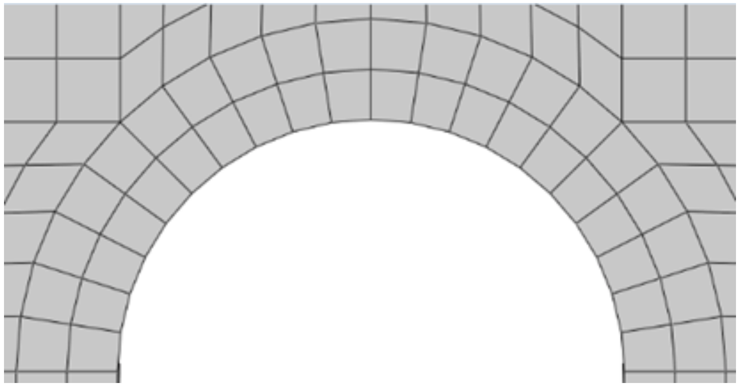
Evaluation of Abaqus Standard: Computational Model

- 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

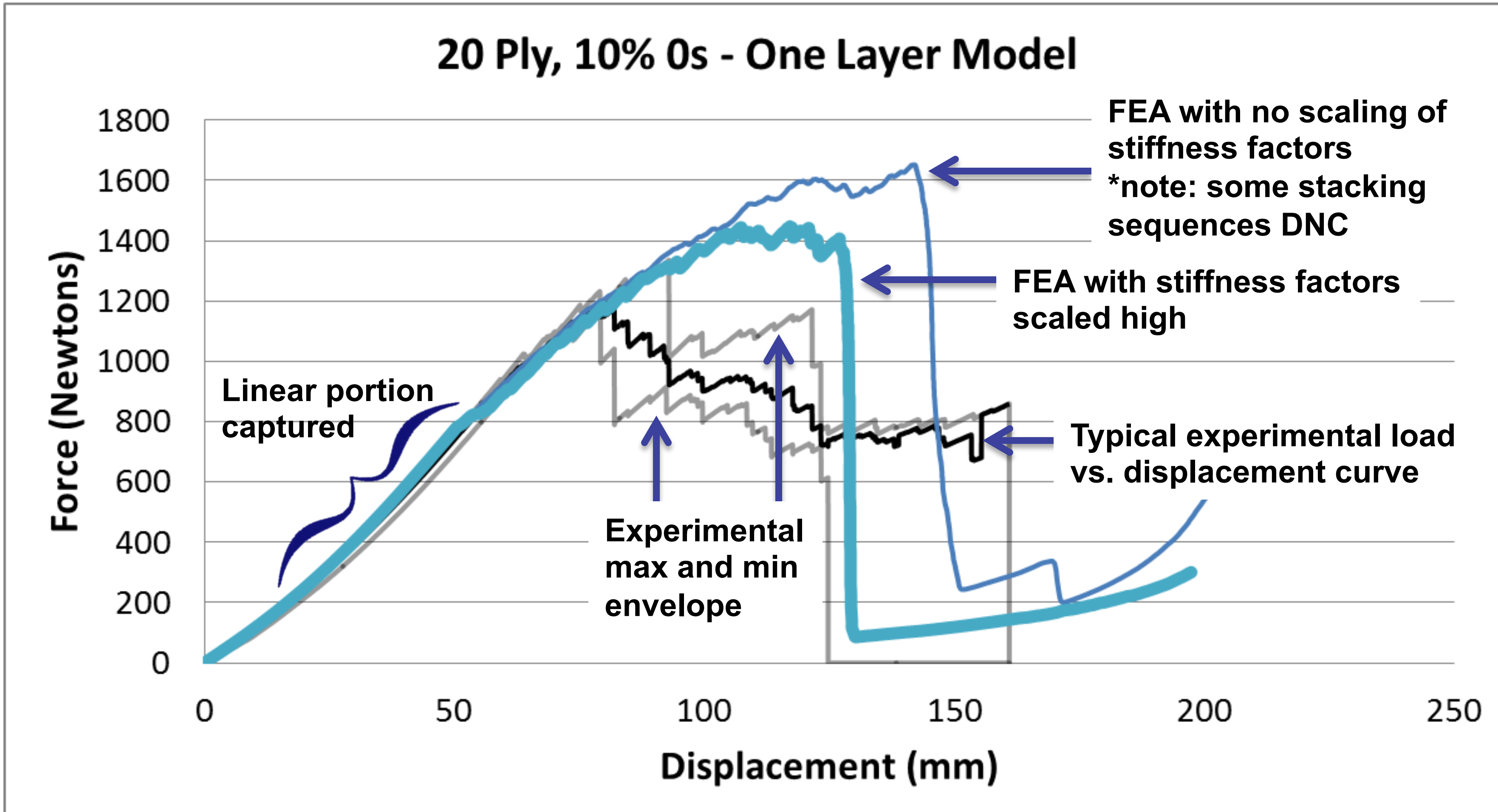




Evaluation of Abaqus Standard: Computational Model and Convergence Based Parameters

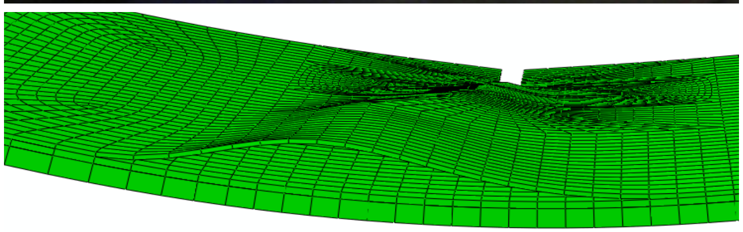
- Viscous Regularization Scheme (used in standard/explicit) helps with convergence
  - Viscosity coefficients for fiber compression (η_{fc}), fiber tension (η_{ft}), matrix tension (η_{mt}), and matrix compression (η_{mc})
  - Must be small with respect to the time increment, $t/\eta_{i} \rightarrow \infty$
  - Convergence trend at: $\eta_{ft} = \eta_{fc} = \eta_{mt} = \eta_{mc} = 0.0005$
- Hourglass stiffness scaled to prevent severe element deformation (Standard only)
  - Three hour glass scaling factors for displacement degree of freedom (s^{s}), rotational degree of freedom (s^{r}), and out-of-plane displacement degree of freedom (s^{w})
  - Scaling to recommended values $(0.2 \leq s^{s}, s^{r}, s^{w} \leq 3.0)$ didn't yield converged solutions for some stacking sequences in Standard
  - Needed to drastically increase factors, most models and stacking sequences converged

Evaluation of Abaqus Standard: Single Element Layer Results



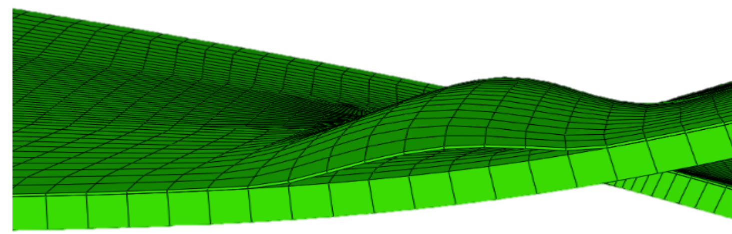
Evaluation of Abaqus Standard: Where to Insert VCCT Interfaces

Out-of-plane Bending



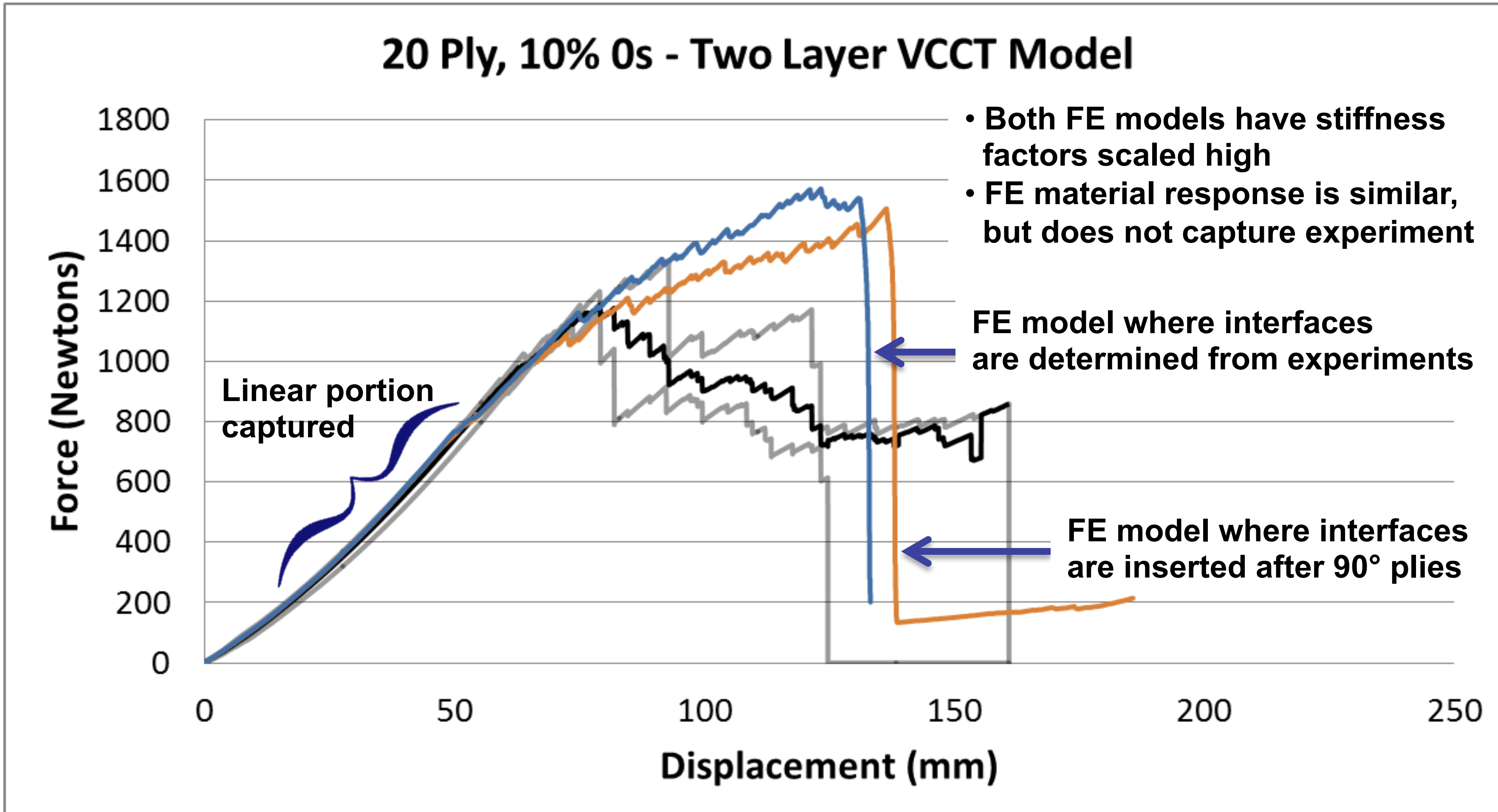
- 0° fibers going from left to right
- 0°plies would be most likely buckle/ delaminate (experimentally verified)
- VCCT interfaces around 0° plies for delamination (0°plies more critical)

Out-of-plane Shear

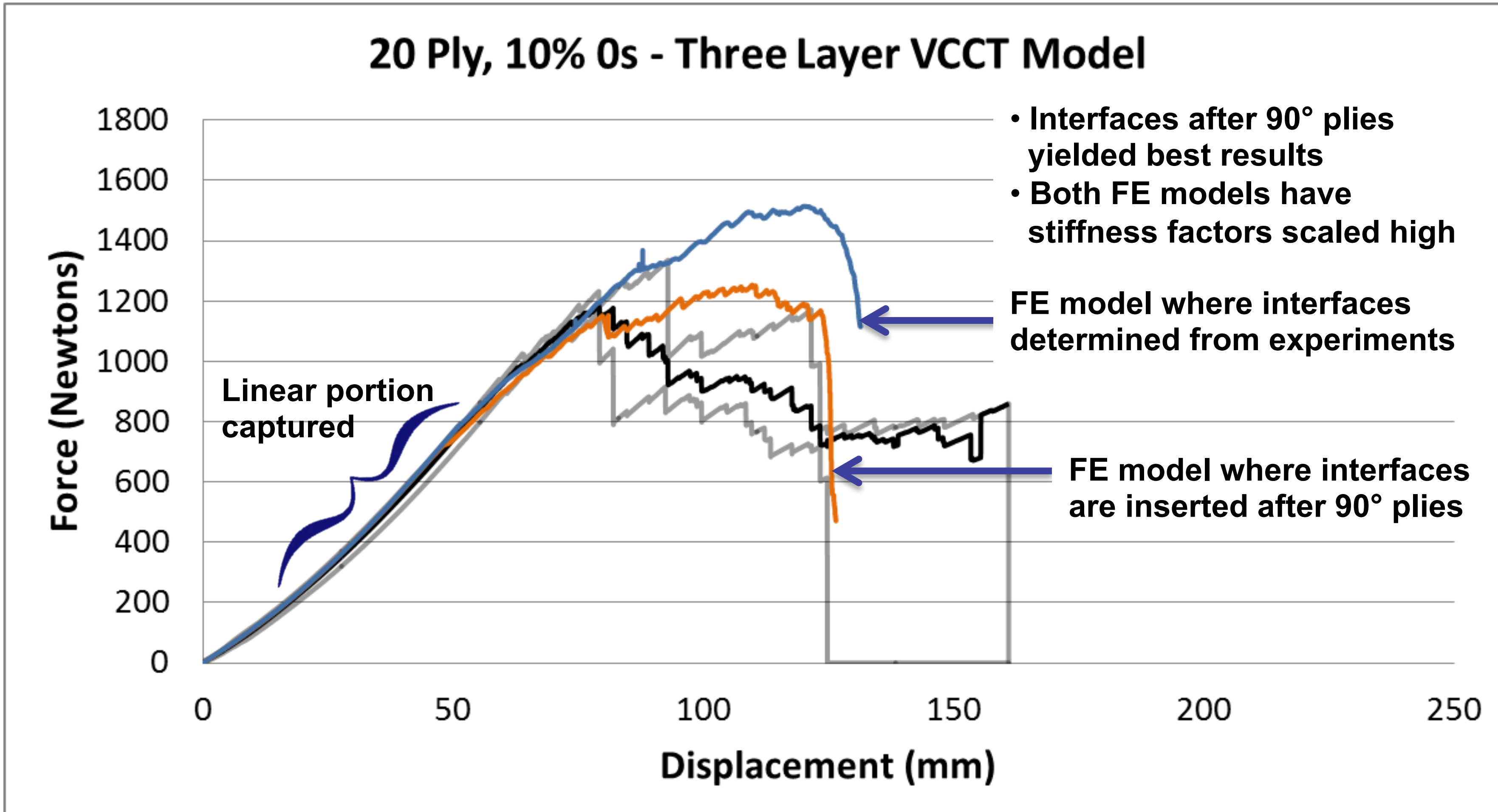


- 90° fibers going from left to right
- 90°plies deemed likely to buckle/delaminate
- Delamination observed around 90°plies, but delamination on other interfaces observed as well
- Put VCCT interfaces after 90° plies and after experimentally observed delamination

Evaluation of Abaqus Standard: Two Element Layer Delamination via VCCT Results



Evaluation of Abaqus Standard: Three Element Layer Delamination via VCCT Results

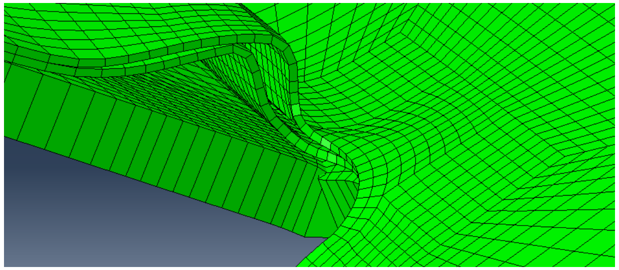


- Interfaces after 90° plies yielded best results
- Both FE models have stiffness factors scaled high

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

		FEA % Difference from Average Experimental Maximum Load					
	% Zero	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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- Evaluation of Helius MCT results
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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:

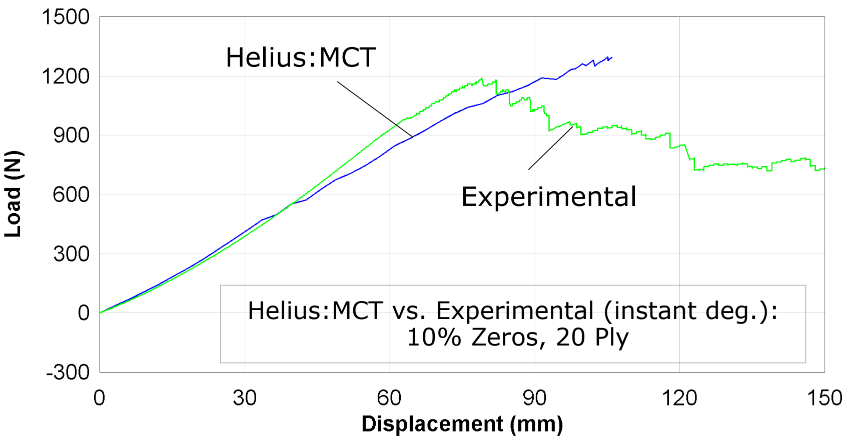
Volume fractions

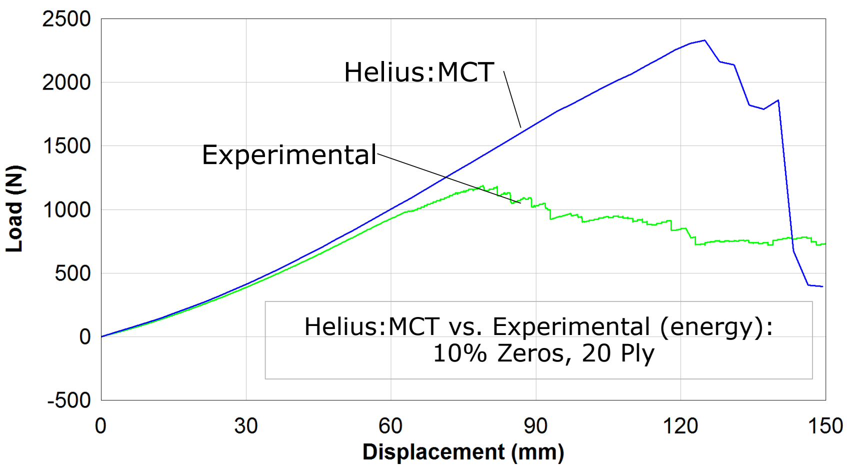
$$\sigma^c = \phi_f \sigma^f + \phi_m \sigma^m$$

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)

Abaqus/Standard with Helius:MCT





- 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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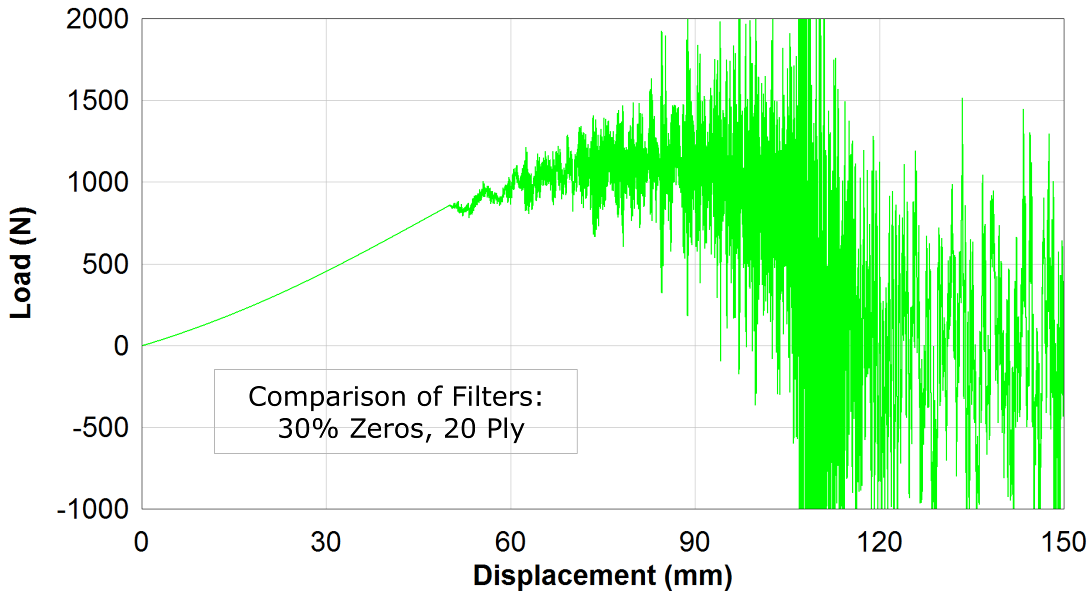
Abaqus/Explicit Analysis

- Why use explicit: implementation of element deletion and better convergence
- Solver basics:
  - Analysis used 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
- Determination of quasi static state
  - Varied total time until a majority of analysis was quasi static: kinetic energy < 10% internal energy
  - Total time considered (seconds): 0.25, 0.50, 1.00, 2.00, 4.00, 6.00, 8.00
  - 8 seconds chosen as total time increment

Abaqus/Explicit Analysis: One Layer Results

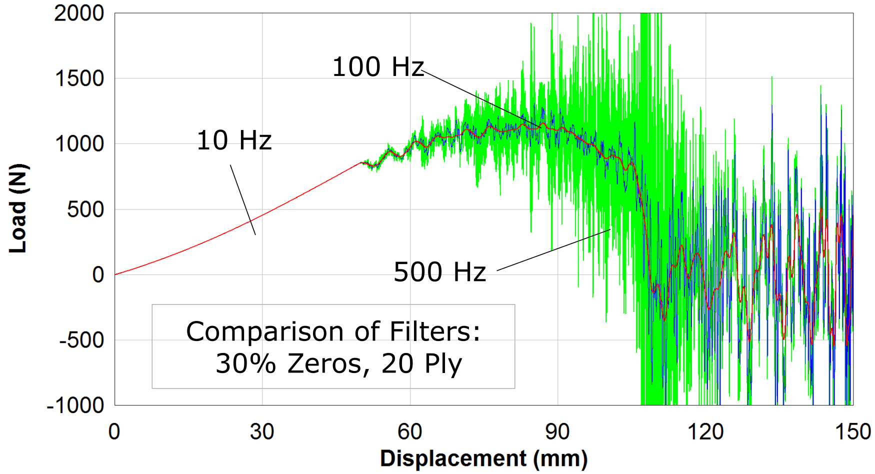


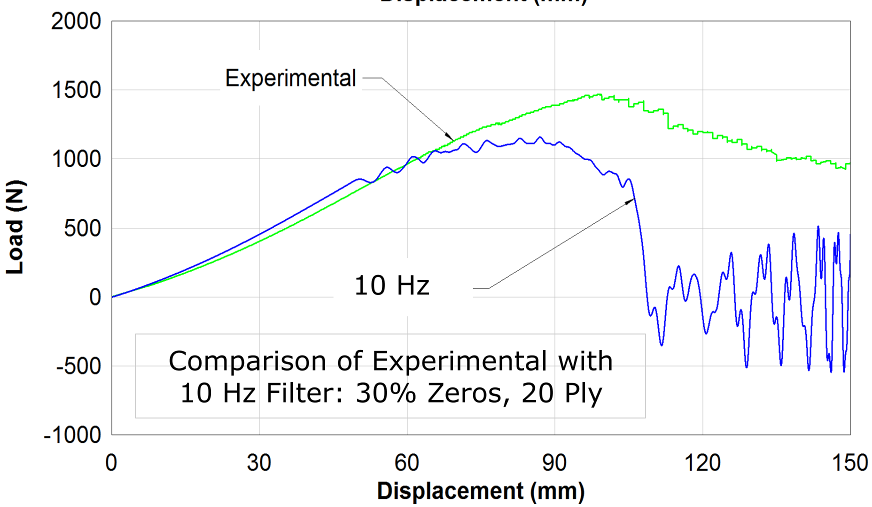
- Benefits: convergence in most cases
- Major challenges:
  - Extreme amounts of noise
  - Extremely long runtime
- Suggestions
  - Filtering the data
  - Implementing more layers

Abaqus/Explicit Analysis: Implementation of Filtering

- Dilemma: noise produced by the explicit solver possibly masks important information
- Solution: filter the load and displacement data
- Methods:
  - Determine natural frequency of model using Abaqus/ Standard
  - Filter selected configuration as results are produced (pre-processing)
  - Apply additional filters after runs are complete (post-process)
  - 2^{nd} order Butterworth filter

Abaqus/Explicit Analysis: Implementation of Filtering



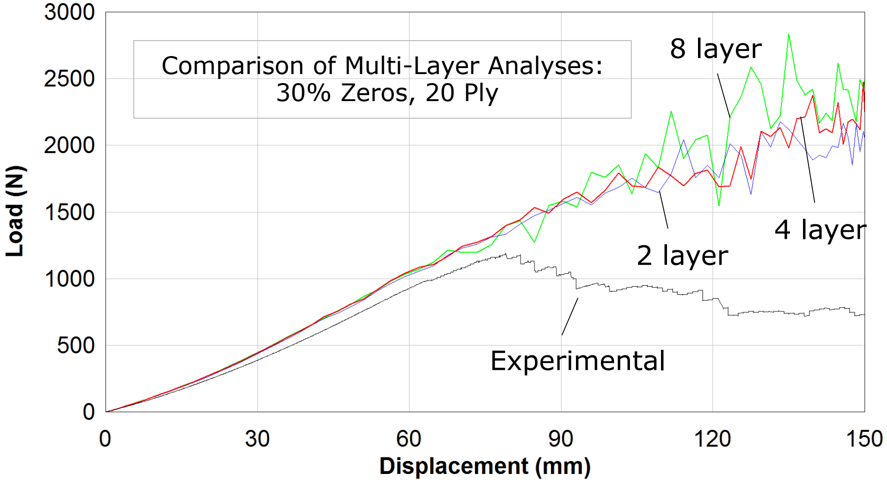


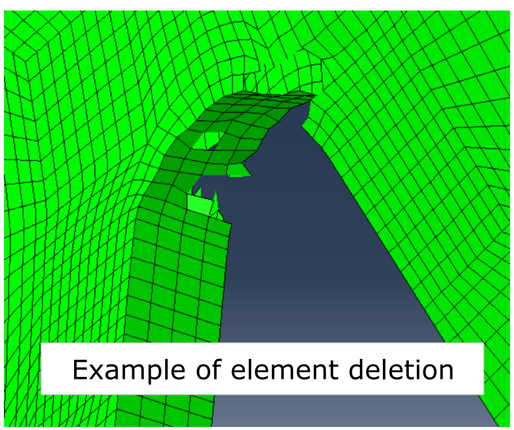
- Benefits: eliminates noise, presents a clearer picture of what is happening
- Major challenges:
  - Determining the cut-off frequency
  - Extremely large amounts of data, 10+ Gb per ODB file
- Suggestions
  - Method to determine the cut-off frequency
  - Determine what filter to apply
  - Would use method if confidence is higher

Abaqus/Explicit Analysis: Implementation of Multiple Layers and VCCT

- Dilemma: element deletion is not occurring
- Solution: create more layers so that the deletion criteria is met more readily
- Methods:
    - Create 2,4, and 8 layer models.
    - Varying degradation coefficient: 1.0,0.9,0.8,0.7
    - Implement VCCT

Abaqus/Explicit Analysis: Implementation of Multiple Layers




Example of element deletion

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

Conclusions for Explicit Analysis

- Analyses are extremely long
- Analyses are inherently prone to noise during extreme deformations or accelerations. How do we appropriately filter this noise?
- Convergence is not guaranteed and element deletion may not always be something we can take advantage of.

Conclusion

- 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

Questions

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 prop' per ply

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, $t/\eta_i \rightarrow \infty$
- 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 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

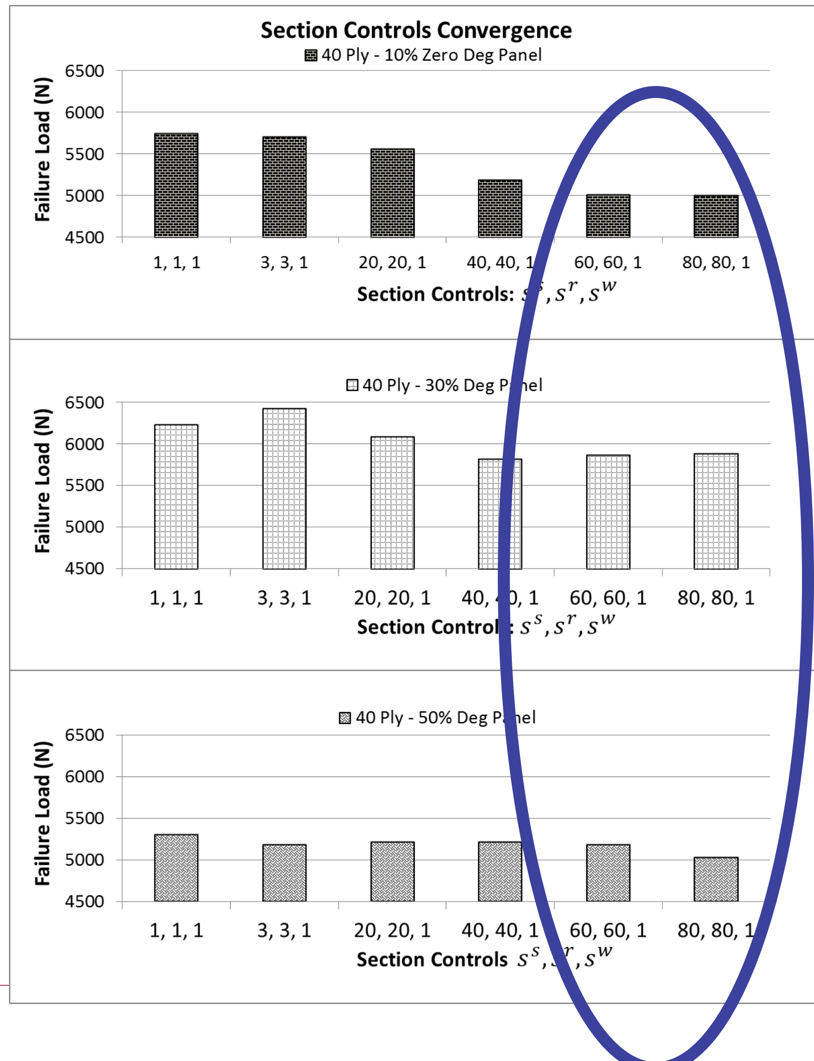
- Default hourglass stiffness was scaled to prevent severe element deformation
- Pure stiffness approach was recommended for quasi-static analysis
- Three user defined scaling factors

Factor	Description	Typical Range
$s{\uparrow}s$	Hour glass stiffness scaling factor for displacement degree of freedom	0.2 - 3.0
$s{\uparrow}r$	Hour glass stiffness scaling factor for rotational degree of freedom	0.2 - 3.0
$s{\uparrow}w$	Hour glass stiffness scaling factor for out-of-plane displacement degree of freedom	0.2 - 3.0

Scaling Hourglass Stiffness Cont

- 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

Scaling Hourglass Stiffness Cont



- 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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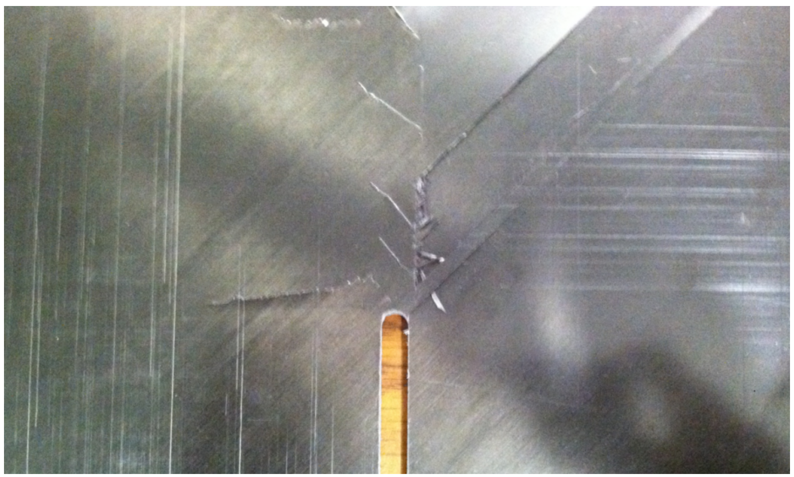
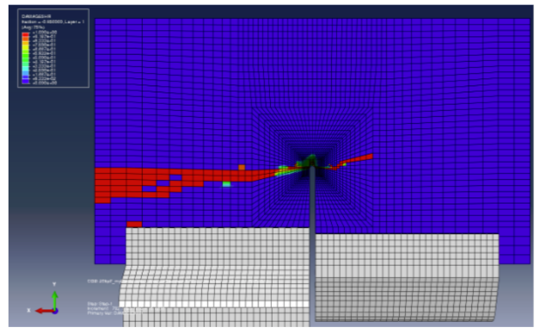
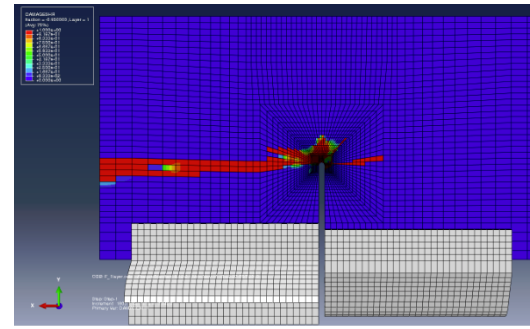
Damage Path Model



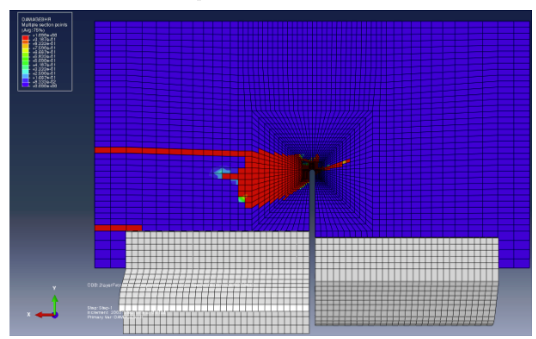
1 Layer – No SSF



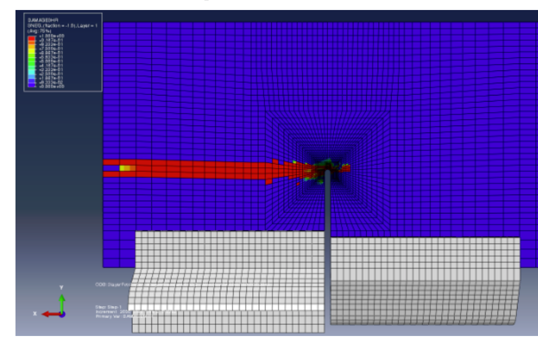
1 Layer – with SSF



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

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Helius:MCT Results – Boeing Parameters (Energy Degradation)

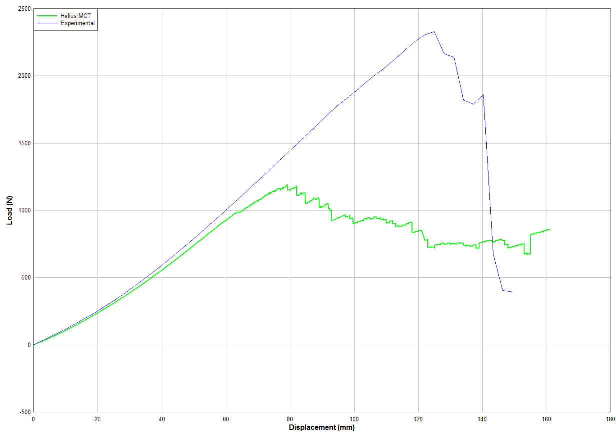


Fig 1. F Configuration

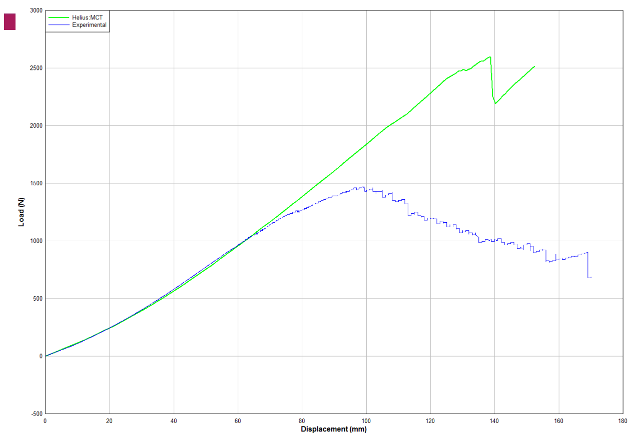


Fig 2. P Configuration

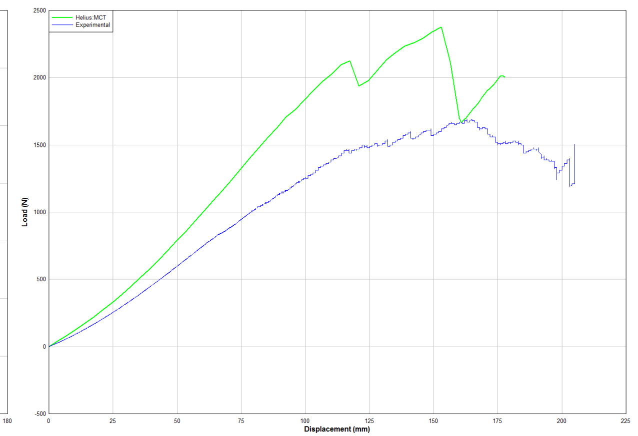


Fig 3. N Configuration

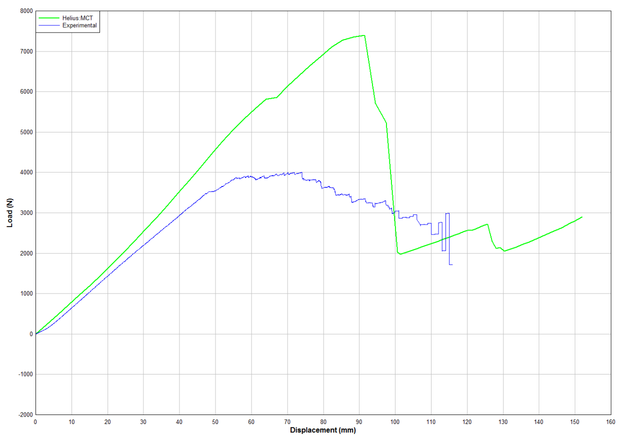


Fig 4. FP Configuration

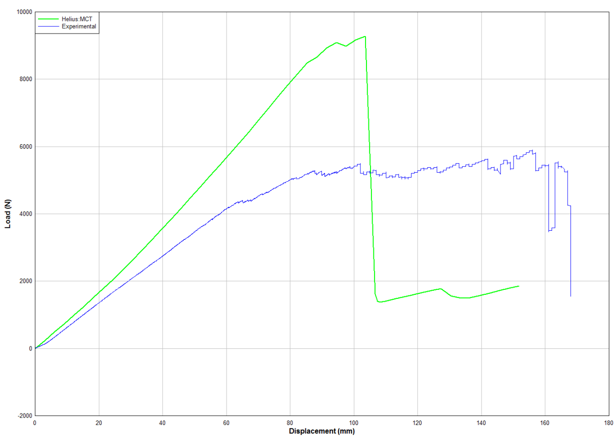


Fig 5. AR Configuration

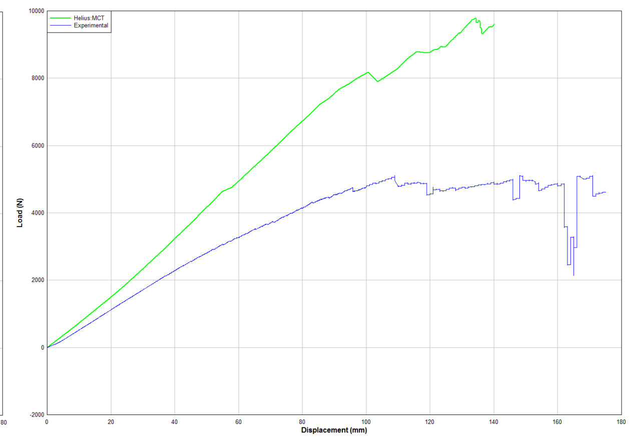


Fig 6. AN Configuration

Helius:MCT Results – Boeing Parameters (Instant Degradation)

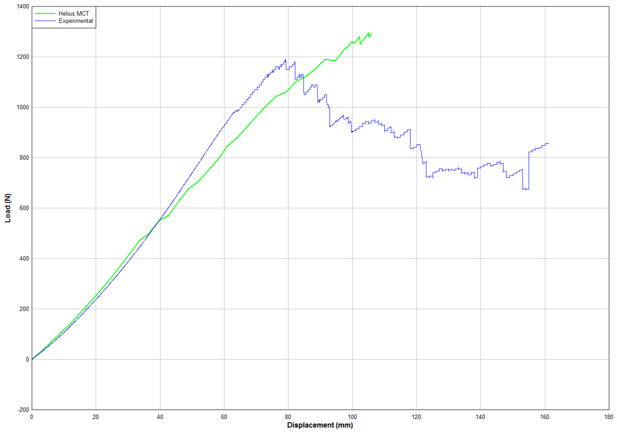


Fig 1. F Configuration

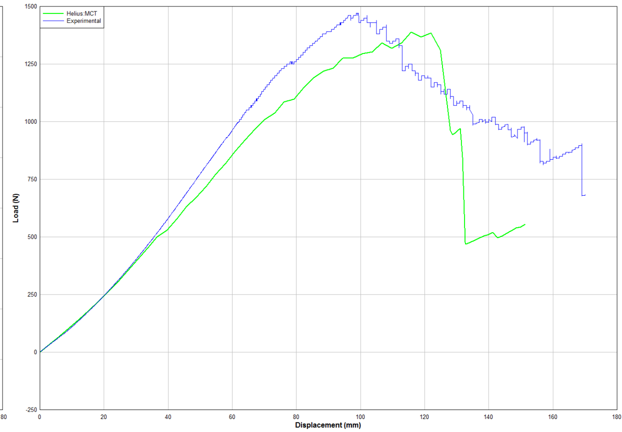


Fig 2. P Configuration

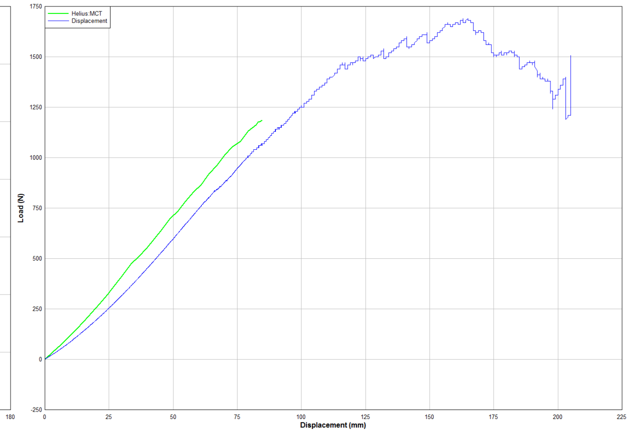


Fig 3. N Configuration

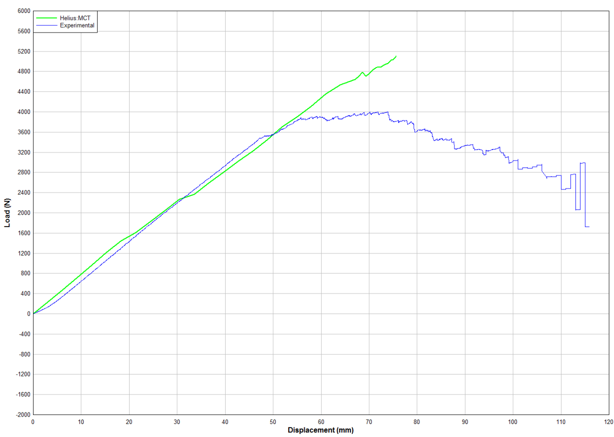


Fig 4. FP Configuration

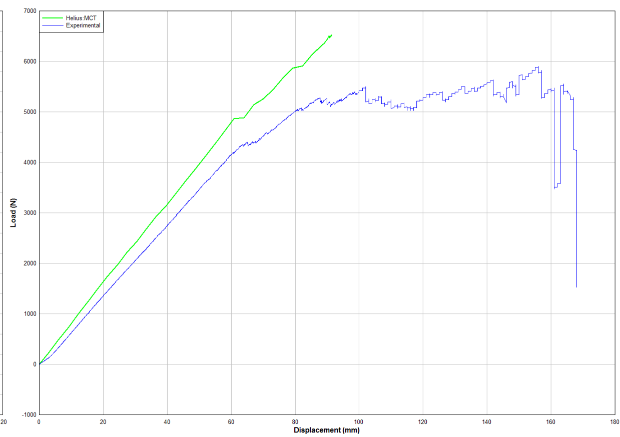


Fig 5. AR Configuration

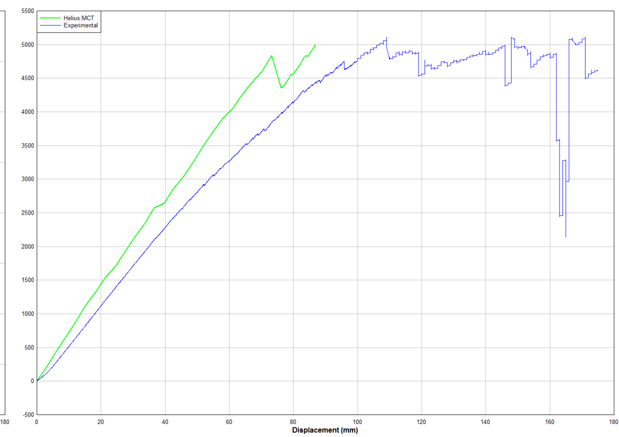


Fig 6. AN Configuration

Helius:MCT Results – Default Parameters

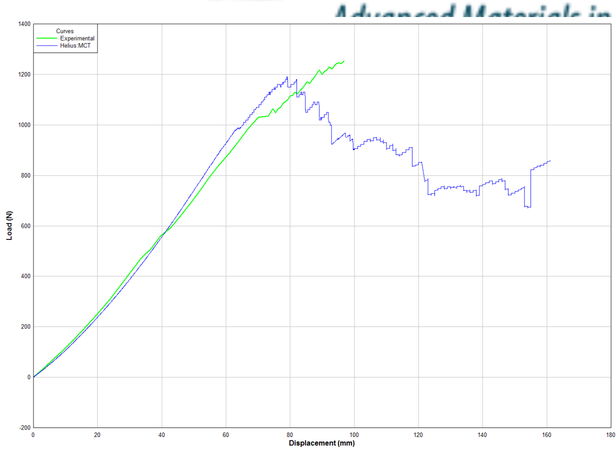


Fig 1. F Configuration

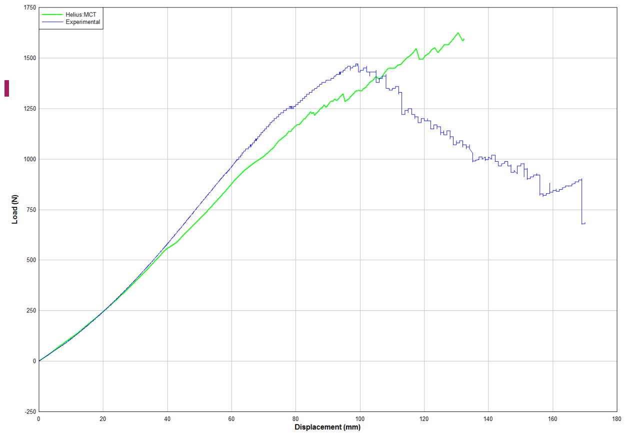


Fig 2. P Configuration

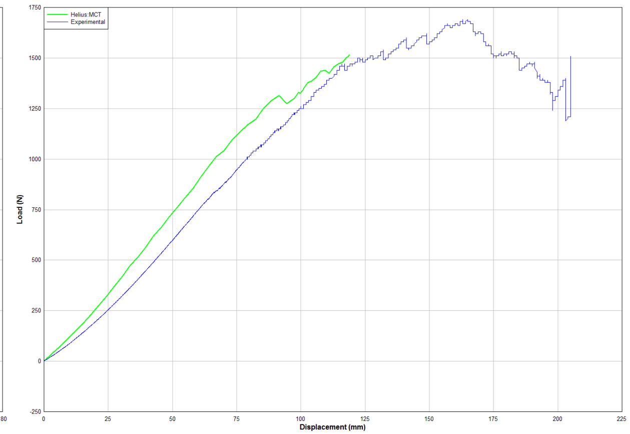


Fig 3. N Configuration

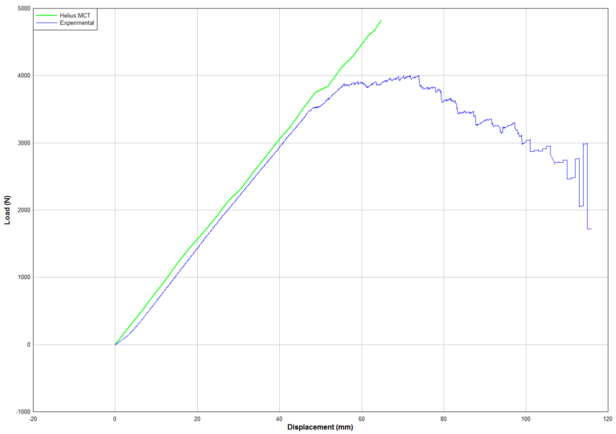


Fig 4. FP Configuration

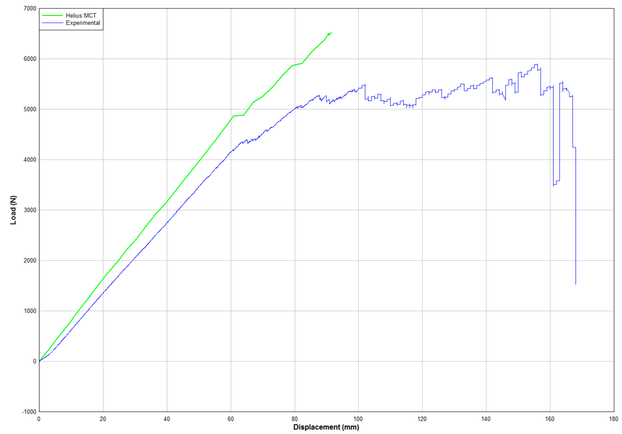


Fig 5. AR Configuration

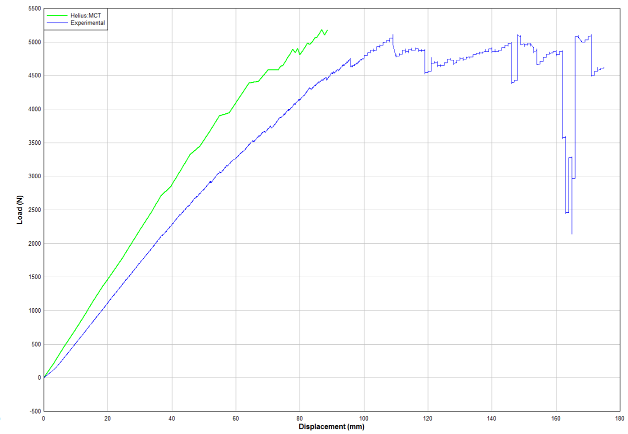
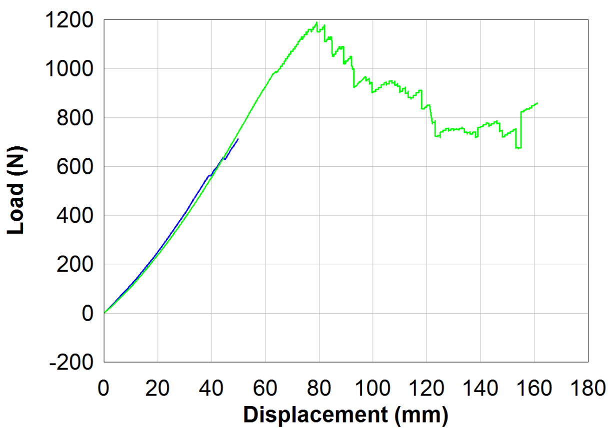
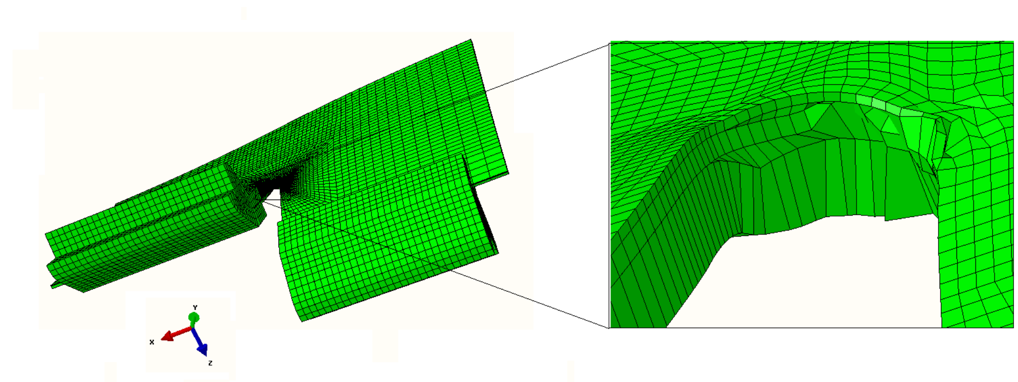
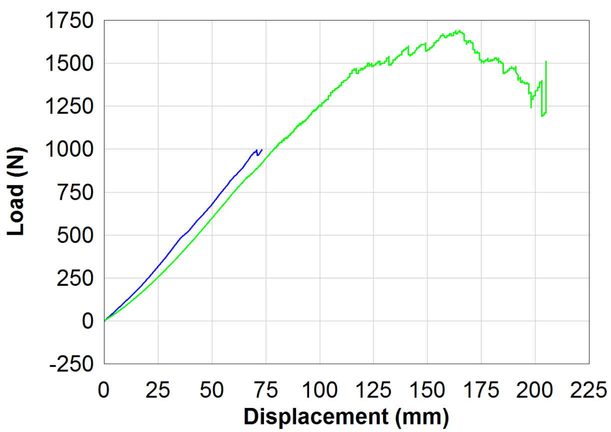


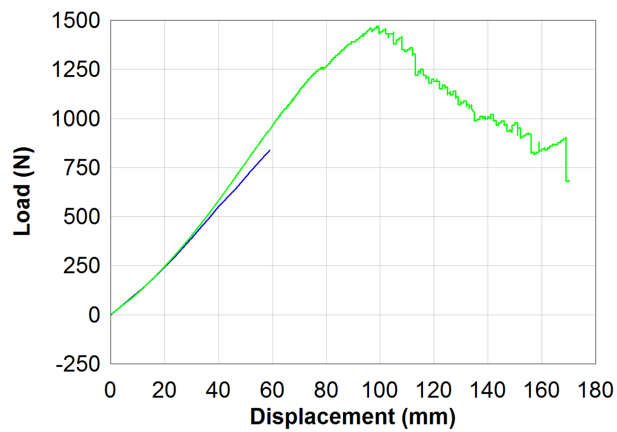
Fig 6. AN Configuration

Cohesive Zones in Helius:MCT



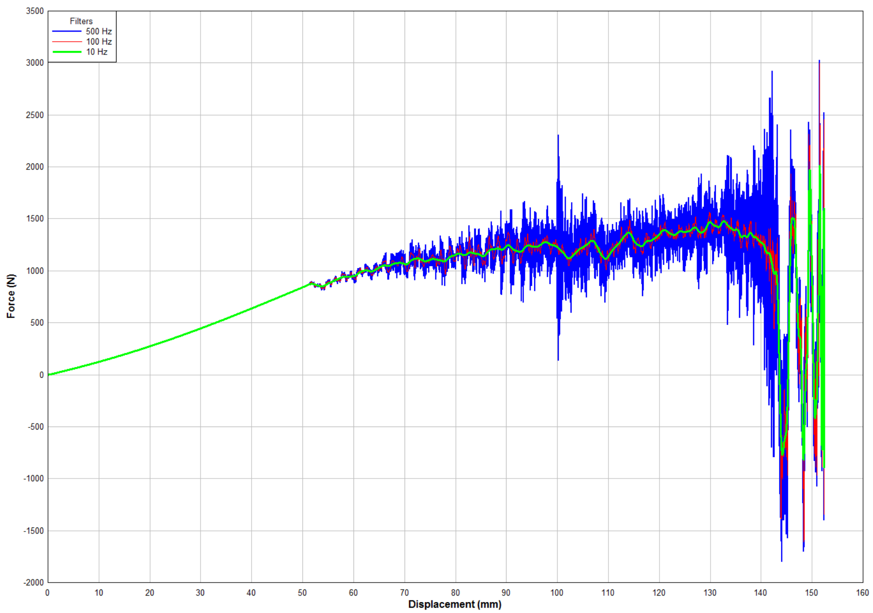






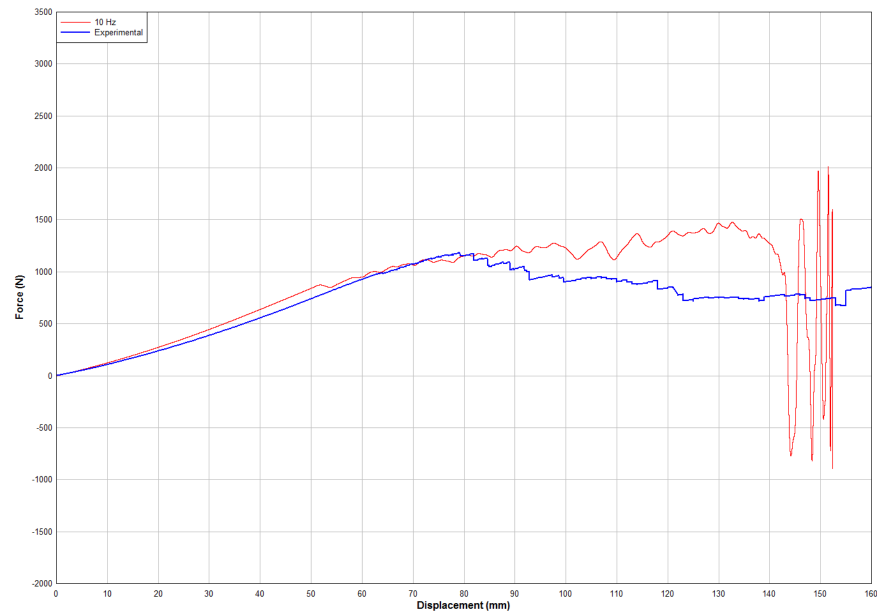
- Cohesive zone runs do not converge
- Deformation in cohesive zone areas can be observed but it is difficult to discern if this deformation is delamination

Filtering Results



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

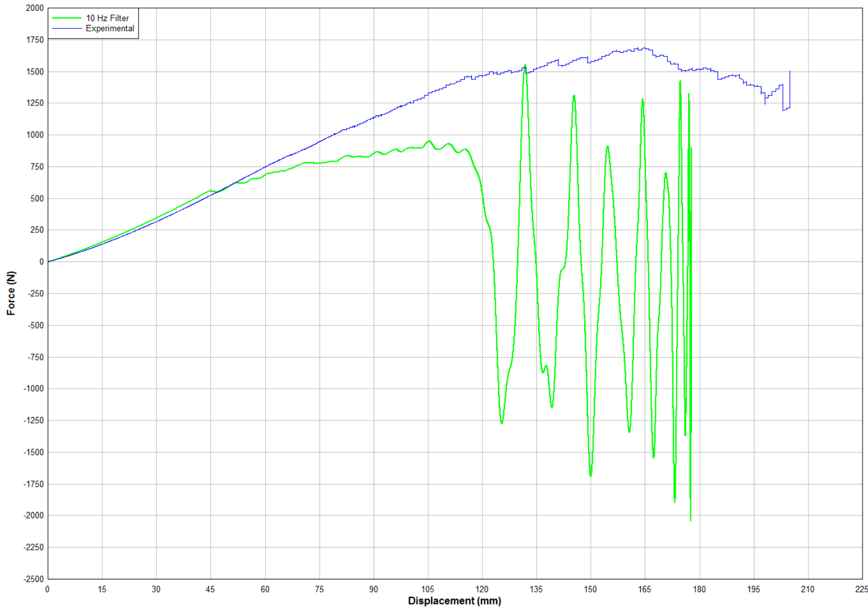
*10% zeros, 20 plies



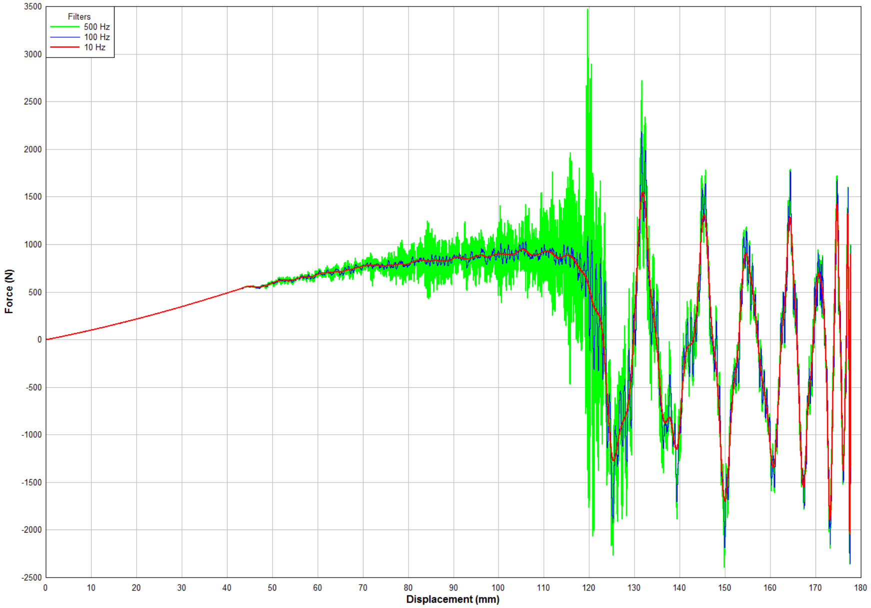
10 Hz cut-off filter compared to experimental results for F-configuration

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

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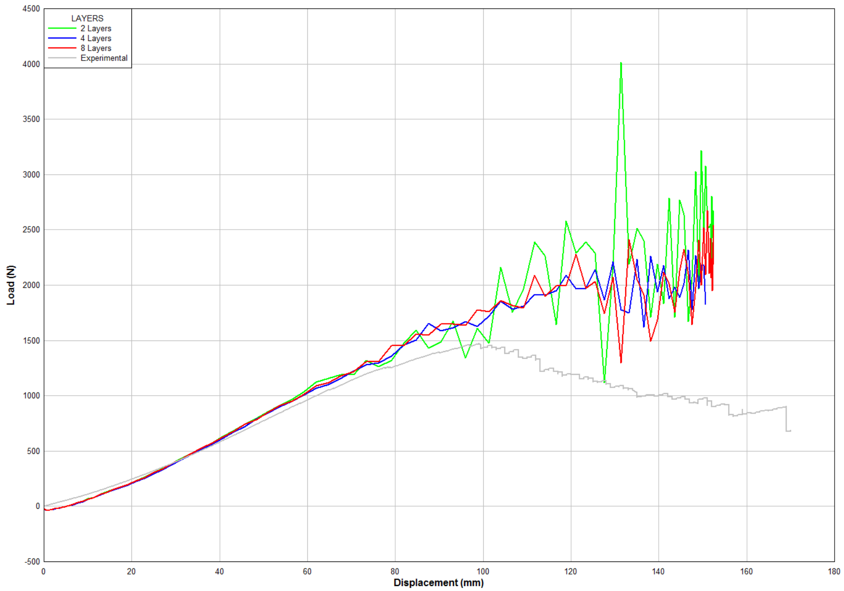
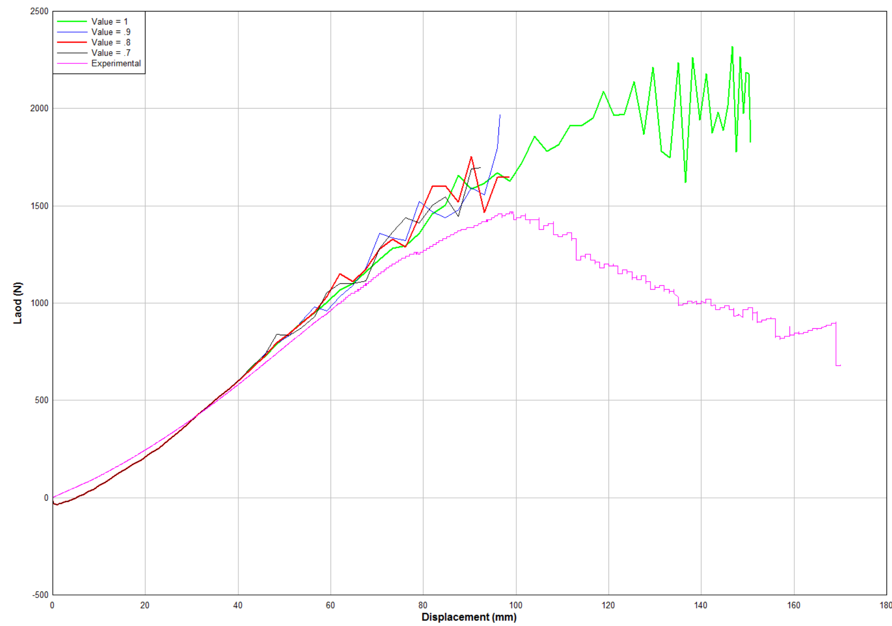
More Multi-Layer Results



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: $E\downarrow K \leq 0.1\ E\downarrow I$

Multi-Layer Run Time Table

Table 1. Run Times for Quasi-static models.

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