Failure of Notched Laminates under Out-of-Plane Bending. Phase IV

Fall 2011 Meeting

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

- 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)

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

- Principal Investigators & Researchers
  - John Parmigiani (PI) & Brian Bay, OSU faculty
  - Will Beattie & Thomas Wright, 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)

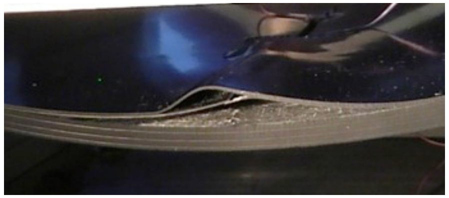
- Out-of-plane bending experiments w/composite plates
- ABAQUS modeling with progressive damage

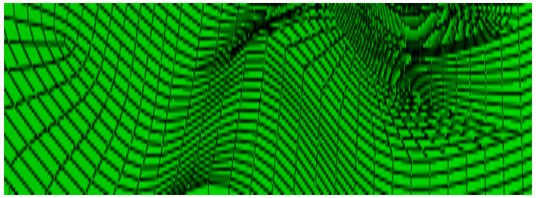
Phase II (2008-09)

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

Phase III (2009-10)

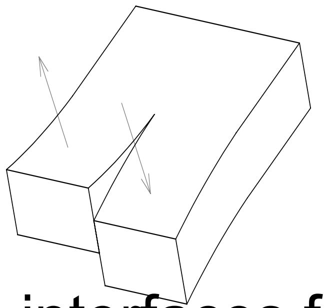
- ABAQUS modeling w/ more delamination interfaces





Project Overview

- Phase IV (2010-11)
  - Out-of-plane shear experiments & ABAQUS modeling
  - 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
  - Special cases: all-ninety and all-zero degree plies for out-of-plane bending



Today's Topics

- Sensitivity study w/ Boeing material property values
- Effects of additional delamination interfaces
- Feasibility of XFEM for future work
- Feasibility and accuracy of Abaqus/Explicit for future work

Out-of-plane Shear work was covered during 2011 JAMS meeting, and will be continued in Phase V.

Initiating vs. propagating toughness values were covered during 2011 JAMS meeting.

All-ninety and all-zero degree plies will be continued in Phase V.

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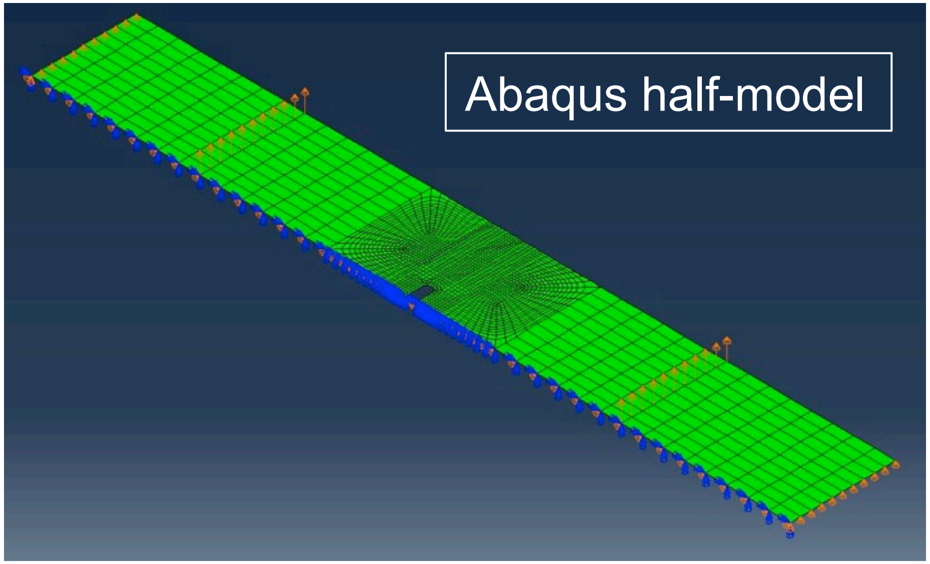
Sensitivity Study

- Using design-of-experiments techniques, analytically* investigate the effect of variations in strength parameters on the failure load of two notched-panel layups
  - #1: 40% zero-degree plies
  - #2: 20% zero-degree plies
  - Loading: Out-of-plane bending
  - Panel dimensions
    - 18-in long
    - 5-in wide
    - 20 plies
    - 0.25-in wide, 1-in long center notch



* Study consists exclusively of Abaqus simulations

Sensitivity Study

- Strength parameters included in study:
  - XT: Tensile strength, parallel-to-fiber direction
  - XC: Compressive strength, parallel-to-fiber direction
  - YT: Tensile strength, perpendicular-to-fiber direction
  - YC: Compressive strength, perpendicular-to-fiber direction
  - SL: Shear strength, in-plane
  - SC: Shear strength, transverse
  - Gft: Energy to fully damage ply, fiber tension only
  - Gfc: Energy to fully damage ply, fiber compression only
  - Gmt: Energy to fully damage ply, matrix tension only
  - Gmc: Energy to fully damage ply, matrix compression only

10 parameters to be considered

Sensitivity Study

- Design-of-Experiments Plan
  - Vary each parameter +/- 20% from nominal value
  - Use a 2-level fractional factorial
- Prior Work: Study conducted in earlier project phase
  - Generic material properties
  - 2^10-6 fractional-factorial design (16 runs)
  - Results showed key parameters for both layups to be
    - Gft: Energy to fully damage ply, fiber tension
    - XT: Tensile strength, parallel-to-fiber
    - Gfc: Energy to fully damage ply, fiber compression
    - XC: Compressive strength, parallel-to-fiber
  - **Limited number of runs precluded information on interactions!**

Sensitivity Study

Lay-up 1: 40% zero-degree
Lay-up 2: 20% zero-degree

- Current Work
  - Boeing material properties
  - 2^10-4 fractional-factorial design (64 runs for 10 parameters)
  - Results show key parameters to be
    - XT: Tensile strength, parallel-to-fiber (lay-up 1 and 2)
    - XC: Comp. strength, parallel-to-fiber (lay-up 1)
    - Gft: Energy to fully damage via fiber tension (lay-up 1 and 2)
    - Gfc: Energy to fully damage via fiber comp. (lay-up 1 and 2)
    - YC: Comp. strength, perp. to fiber (lay-up 2)
    - Interaction, XT / Gft (lay-up 1)
    - Interaction, XT / Gfc (lay-up 1)
    - Interaction, XC / Gft (lay-up 1)
    - Interaction, XC / Gfc (lay-up 1)

Sensitivity Study

- Current Work, Summary & Conclusions:
  Factors influencing failure moment
  - Both higher and lower percent-zero-degree-ply lay-ups showed fiber fracture-energy and fiber tensile-strength to be key…
    … fibers are primary load-carrying components
  - The lower percent-zero-degree-ply (more compliant) lay-up also showed matrix compressive strength to be key…
    … less stiff, so matrix properties more relevant
  - The higher percent-zero-degree-ply lay-up (more stiff) also showed fiber compressive-strength and fiber strength & fracture energy interactions to be key…
    … strength & energy interaction likely indicating displacement-to-fracture is important as lay-up becomes stiffer

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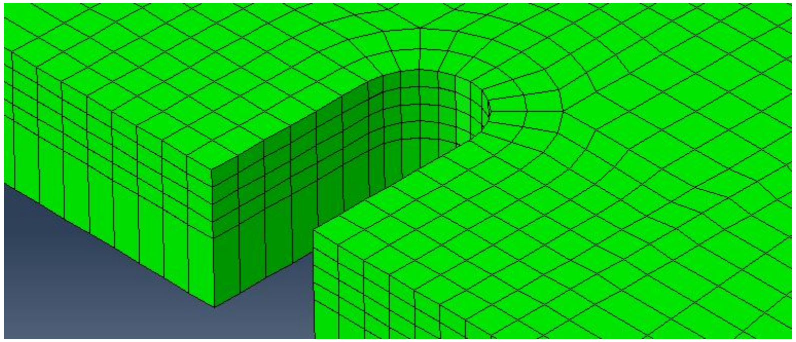
Additional Interfaces

- Current simulations with Out-of-Plane Bending have been done with 4 delamination interfaces at critical plies, as determined through experimentation
- The focus is to examine the effects of additional interfaces, at various locations

This figure depicts a 4-interface layup, with element divisions at delamination interfaces



Additional Interfaces

- One 40 ply lay-up w/ interfaces at different locations
- "Simulation Plan": interfaces near zero-degree plies

Number of Interfaces	**Configurations** **# of Configurations (#plies-interface-#plies-interface, etc.)**
2	2 (32-7-1, 32-3-5)
4	1 (32-3-2-2-1)
5	4 (30-2-3-2-2-1, 24-3-4-3-3-3, 27-4-3-3-2-1, 31-1-2-1-2-3)
6	5 (25-5-2-3-2-2-1, 31-1-1-2-1-2-2, 22-2-3-4-3-3-3, 24-3-4-3-3-2-1, 27-3-2-3-2-2-1)

- Evaluate using:
  - Maximum applied moment
  - Run Time
  - Convergence

Additional Interfaces

Number of Interfaces	2	2	4	5	5	5
Max Moment [in-lb]	N/A	1030.3	1019.4	998.4	1042.4	N/A
Run Time [hr]	43.3	7.7	136.4	116.3	59.9	184.5

Number of Interfaces	5	6	6	6	6	6
Max Moment [in-lb]	N/A	1075.5	N/A	1007.1	1062.0	N/A
Run Time [hr]	184.5	238.0	191.3	375.8	491.1	342.4

- Due to convergence issues, some configurations of delamination interfaces did not produce a maximum moment
- Computing time was greatly increased

Additional Interfaces

Conclusions:

- Additional interfaces do not greatly affect (< 6%) recorded maximum moments
- However, as interfaces are increased, convergence becomes more difficult
- Additional interfaces significantly increase run times
- When deciding where to put interfaces, extra interfaces will not hurt accuracy, but will increase run time, if convergence can even be reached

Today's Topics

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- Feasibility and accuracy of Abaqus/Explicit for future work

eXtended Finite Element Method

- Purpose of this portion of the project is to conduct a preliminary investigation of the feasibility of XFEM
- Conventional FEM only permits crack propagation along element boundaries
- XFEM allows for cracks to propagate through the interior of elements
- Designed for use of fiber and matrix cracking in laminated composites

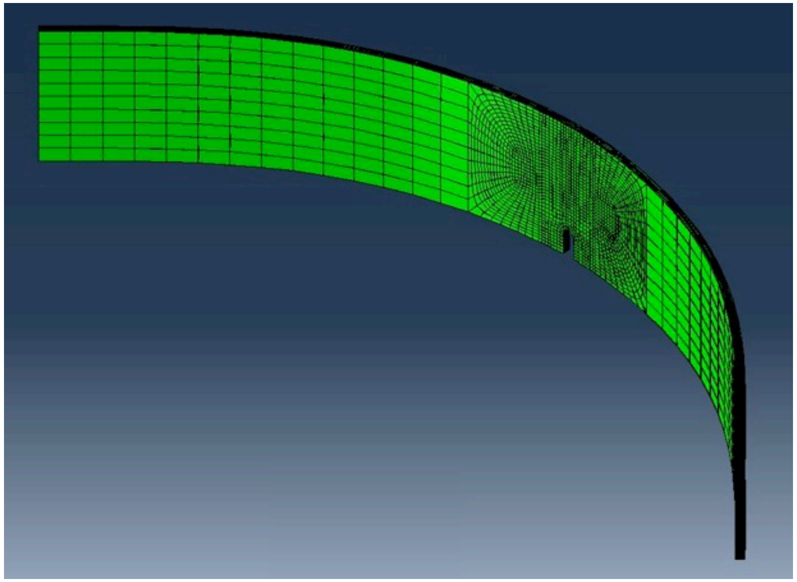
eXtended Finite Element Method

Difficulties in modeling and implementing:

- XFEM does not support use of Hashin Damage criterion (used Max Stress)
- Cannot use shell or solid **composite** elements (used individual layers)
- Model must have one ply per element due to non-support of shells and solid composites
- With current mesh, and necessity for minimum of 20 layers, temporary storage space must be very large

eXtended Finite Element Method

- Convergence issues occurred before max applied moment was found



- Approximations of damage criteria do not allow for accurate results
- XFEM in Abaqus in its current form is not useful for the purpose of this project

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Abaqus/Explicit

- Explicit methods are used for analyses like:
  - High-Speed dynamics
  - Large, nonlinear, quasi-static analyses
  - Highly discontinuous postbuckling
  - Extreme deformations
- Utilizes a constant, very small time increment
- No iteration or convergence checking required
  - Previous work in Abaqus/Standard has produced major issues with convergence
  - Since Abaqus/Explicit is stable, it is of interest

Abaqus/Explicit

- Stable time increment is determined by Abaqus, and cannot be changed by the user
- Total time can be defined by user which changes run time of simulation
- Longer total time decreases dynamic effects but increases run time
- Δt is referred to as stable time increment:

$$\Delta t = L^e / \sqrt{E/\rho}$$

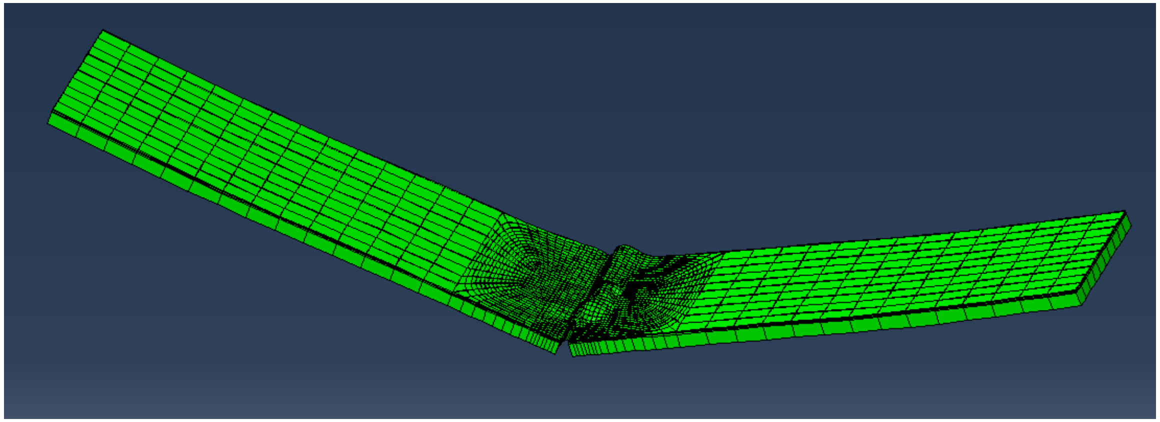
- L^e is the characteristic element length
- E is the Young's modulus
- ρ is the current material density

Abaqus/Explicit

- Goal: Compare implicit and explicit approaches to modeling the fracture of specimens of this study
- Study consisted of making several runs at a range of total times and comparing:
  - Failure moment (Experimental vs. Standard vs. Explicit)
  - Run time (Standard vs. Explicit)
  - Energy (Verify Quasi-static)

Abaqus/Explicit

- For Abaqus/Explicit analysis to be considered quasi-static, the kinetic energy (ke) must be less than 10% of the internal energy (ie)
- Several runs of varying total times were completed with one of the lay-ups



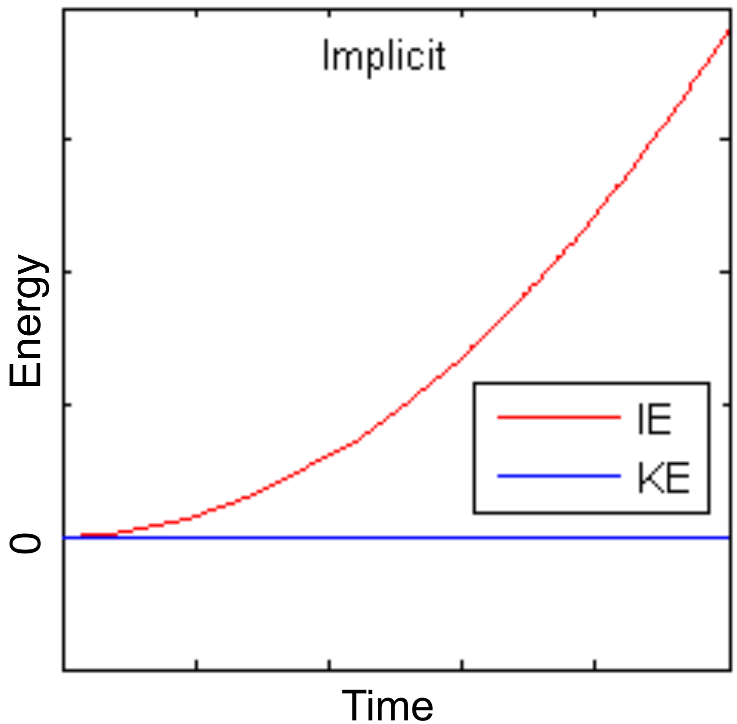
Abaqus/Explicit

Maximum applied moments and run times of several explicit runs. Large variation in moment was likely due to dynamic issues at smaller total times

Total Time [s]	Max Moment [in-lb]	Run time [hr]
2.0	904.6	124.7
1.5	962.5	165.7
1.0	906.1	104.3
0.5	1050.8	45.7
0.25	931.6	18.1
0.10	1390.5	9.3
0.05	1219.7	3.7

Experimental Max Moment = 906 in-lb

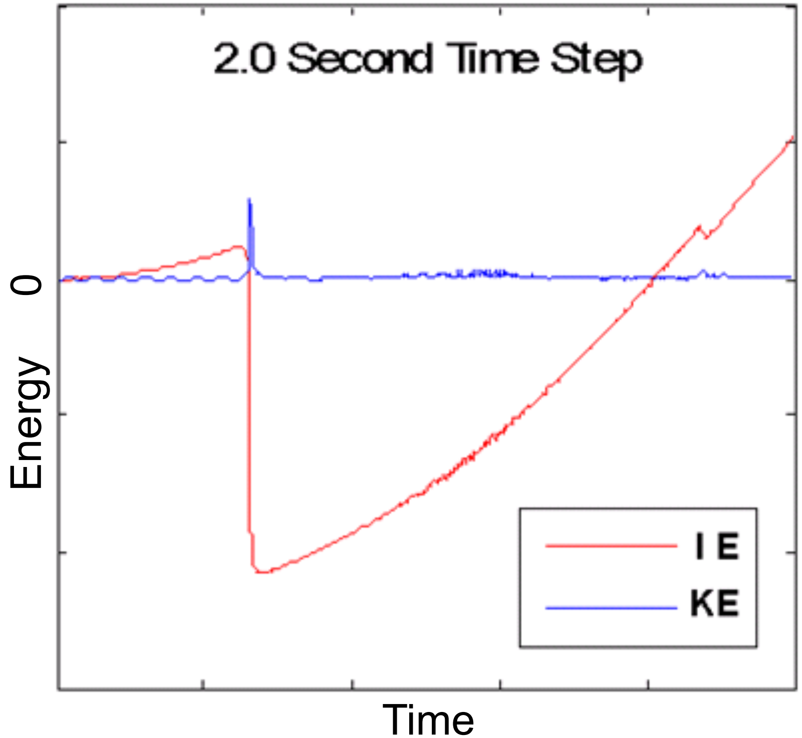
Abaqus/Standard



Plot comparing Internal and Kinetic Energy during an Standard Run

- Kinetic energy is zero because it is a static, implicit analysis
- Internal energy gradually slopes upward throughout the run
- All Abaqus/Standard runs completed for this project have the same general form

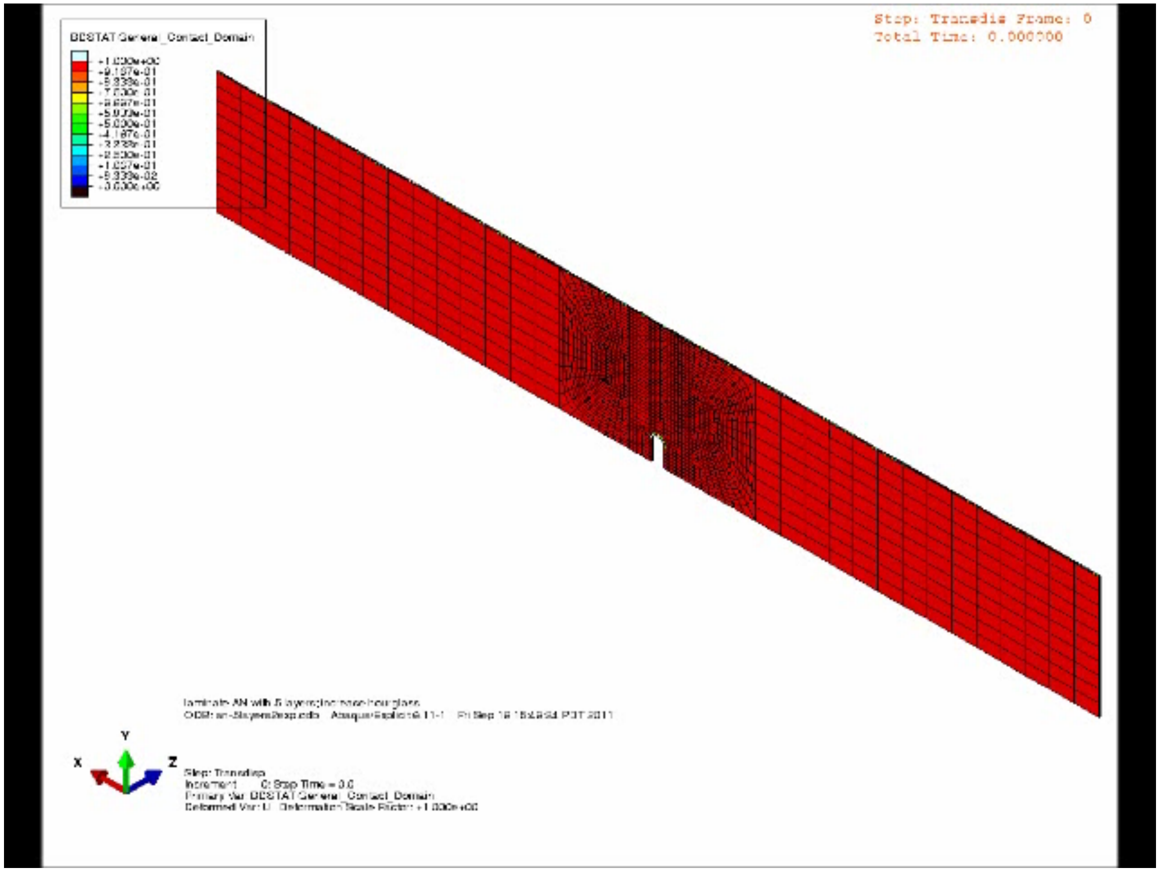
Abaqus/Explicit



Plot comparing Internal and Kinetic Energy during an Explicit Run

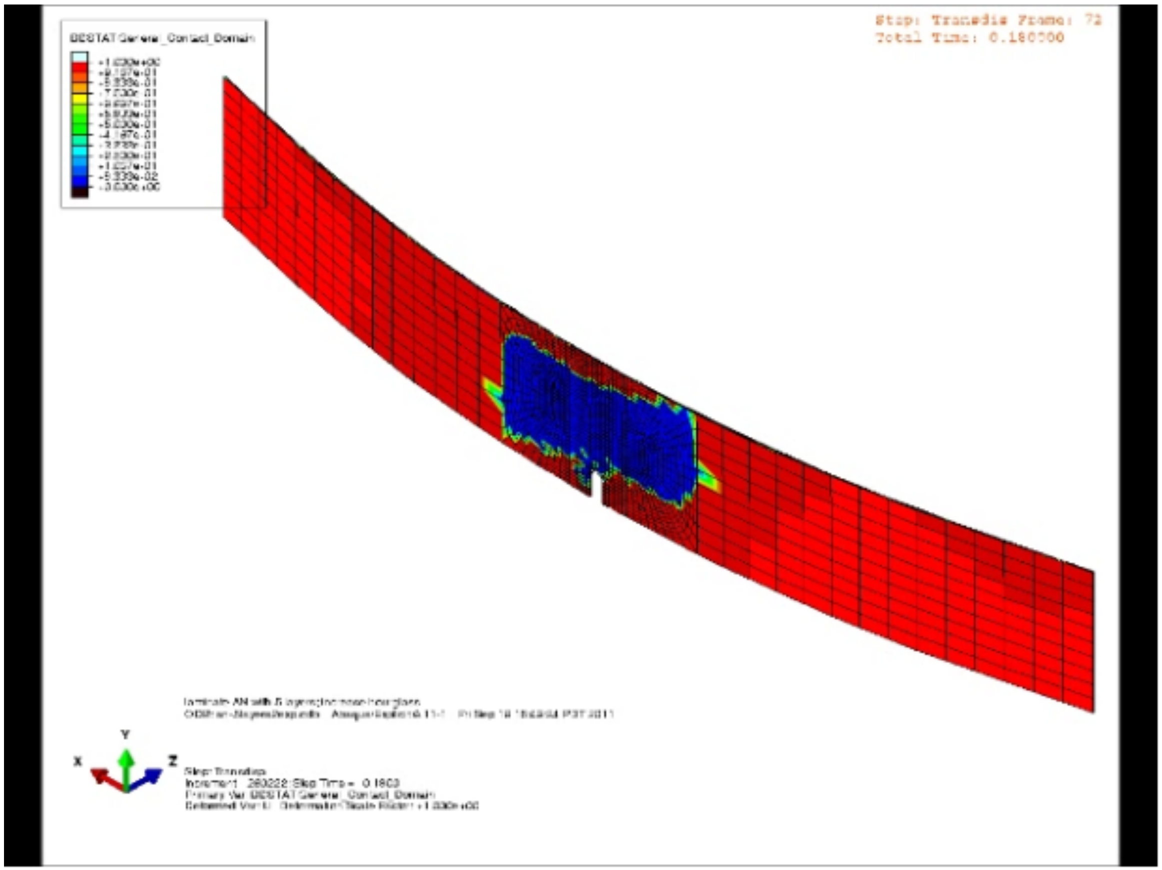
- Kinetic energy stays fairly low, with the exception of a spike
- Internal energy has large drop at location of the spike in kinetic energy
- This does not correspond to normal implicit analysis

Abaqus/Explicit



- Red corresponds to bonded material
- Blue corresponds to debonded material
- Watch for sudden delamination occurring in middle of part

Abaqus/Explicit



- Red corresponds to bonded material
- Blue corresponds to debonded material
- Watch for sudden delamination occurring in middle of part

Abaqus/Explicit

- Sudden massive delamination is the cause of the big drop in internal energy and spike in kinetic energy
- This is a dynamic event which is inconsistent with Standard analysis and with the experiments performed
- Considerably longer total time would be necessary to remove dynamic event

Abaqus/Explicit

- Completed one run of each layup using Abaqus/Explicit with total time of 2 seconds
- The run times range from approximately 5 days to over 22 days
- A significant increase in total time is impractical

Layup: # of plies (% 0°)	Run Time [hrs]
20 (10%)	149.7
20 (30%)	334.5
20 (50%)	241.4
40 (10%)	541.9
40 (30%)	222.3
40 (50%)	124.7

Abaqus/Explicit

Conclusions:

- 2.0 seconds is not a long enough total time to provide accurate results using Abaqus/Explicit
- Increasing total time is not feasible, given current run times of over three weeks
- While there were no convergence issues, the amount of time necessary to achieve an accurate solution using Abaqus/Explicit proves it is not a feasible solution for future work
- Failure to model a quasi-static simulation means Abaqus/Explicit is not a useful tool for this project

Questions

Abaqus/Explicit

- Why not try mass scaling?

$$\Delta t = L_e / \sqrt{E/\rho}$$

  - Multiplying density by x^2 causes Δt to increase by x
  - To bring run time for Explicit at 2 second total time down to a comparable level with Standard, density must be increased by an order of magnitude
  - Even that order of magnitude increase only makes a 2 second total time comparable, but a much longer total time is necessary, so two orders of magnitude increase of ρ is likely necessary