

# A Composite Damage Tolerance Simulation Technique to Augment the Building Block Approach

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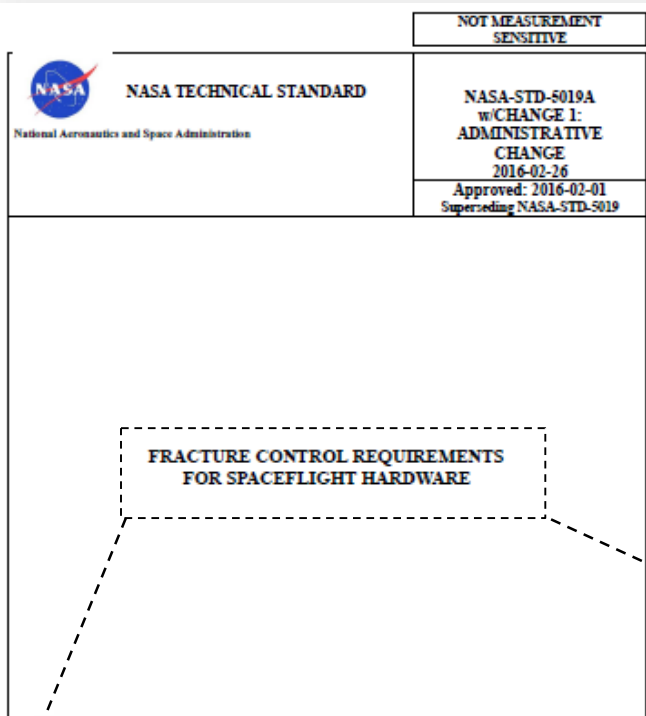
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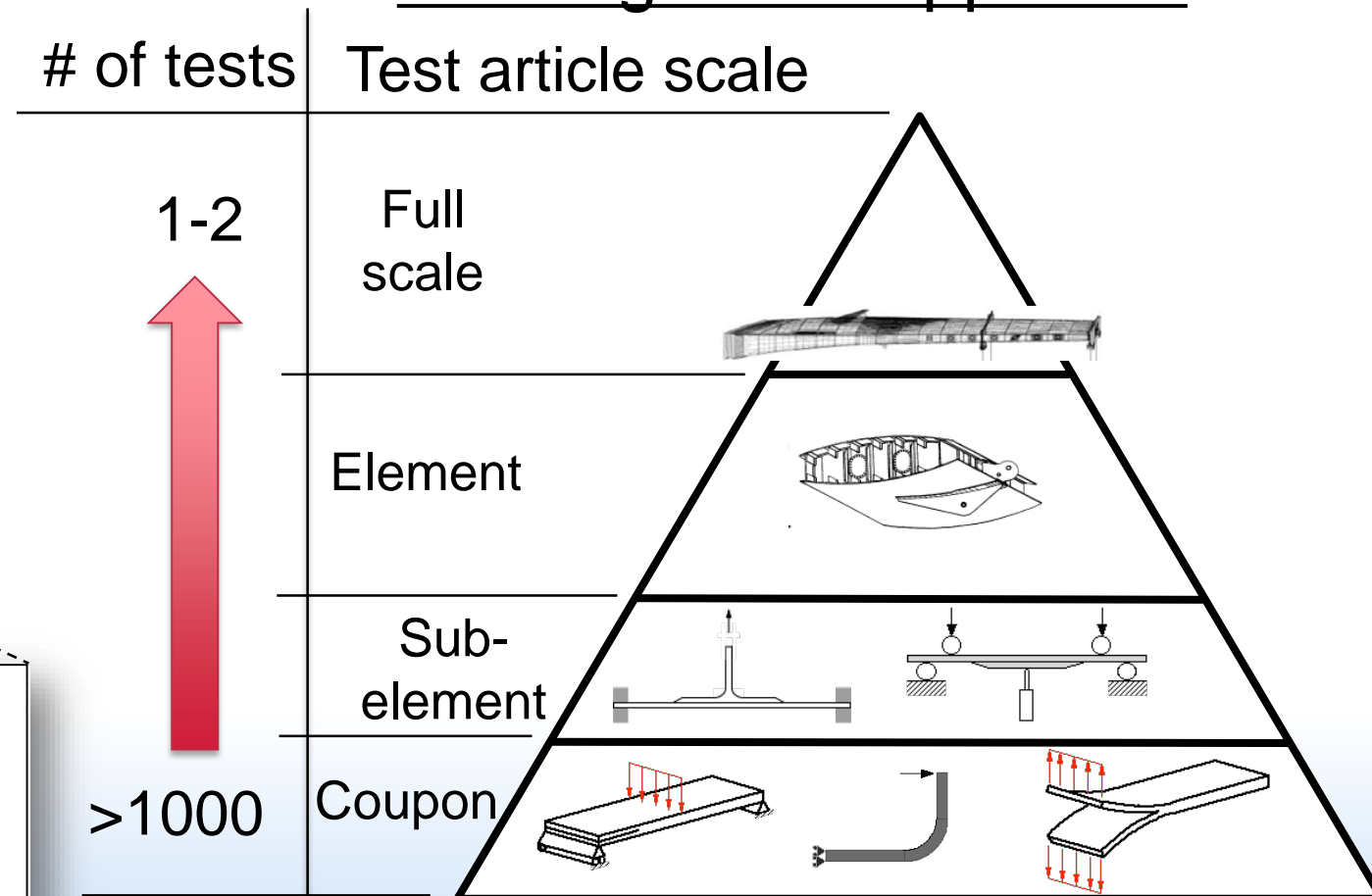
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**FRACTURE CONTROL REQUIREMENTS FOR SPACEFLIGHT HARDWARE**  
 (damage tolerance is required for human spacecraft structures)

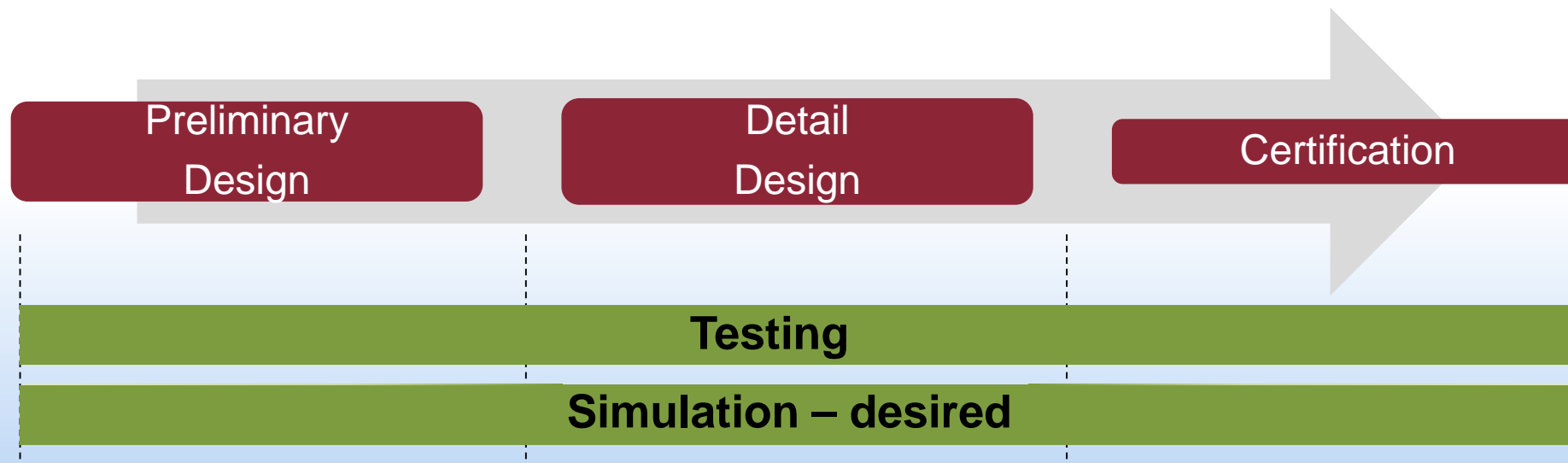
## Building Block Approach



Goal: Determine reduced strength when damage is present

## Design and certification process for composite aerospace structures

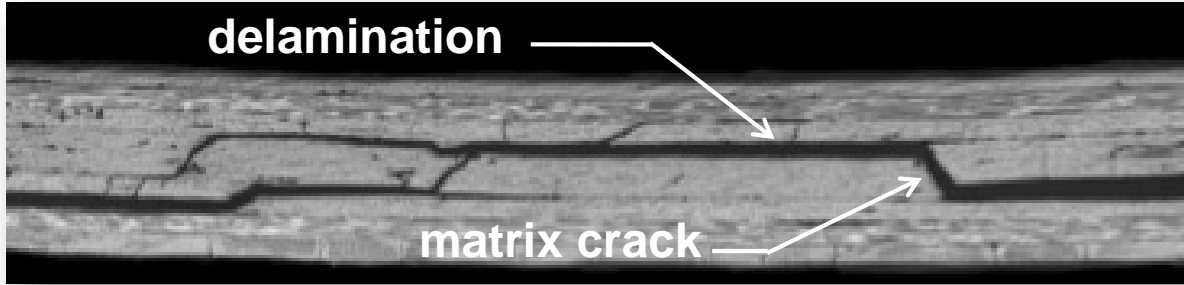
- Heavily reliant on tests
- Expensive
- Damage simulation tools may reduce the need for some testing
  - manufacturing flaw
  - compression after impact
  - worst case credible damage



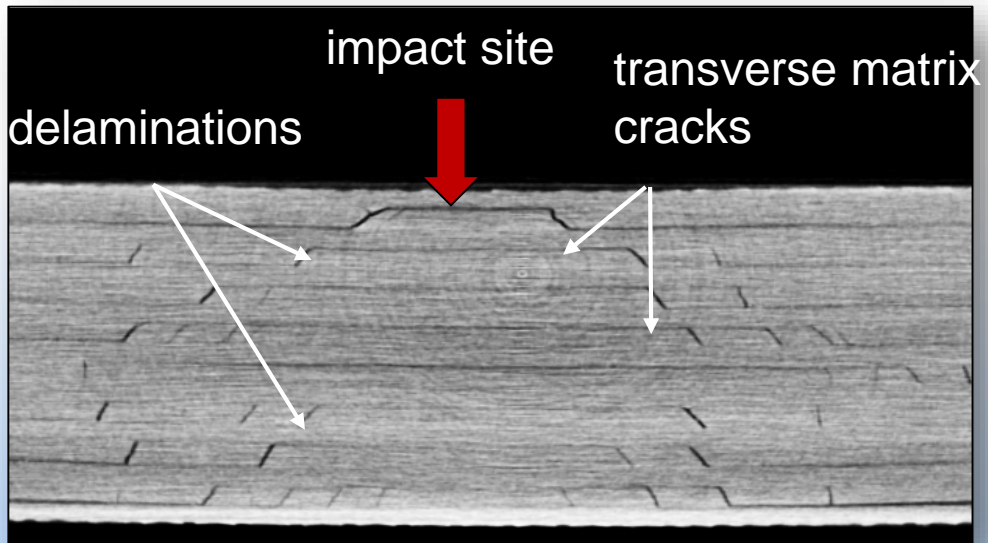
# IMPACT DAMAGE



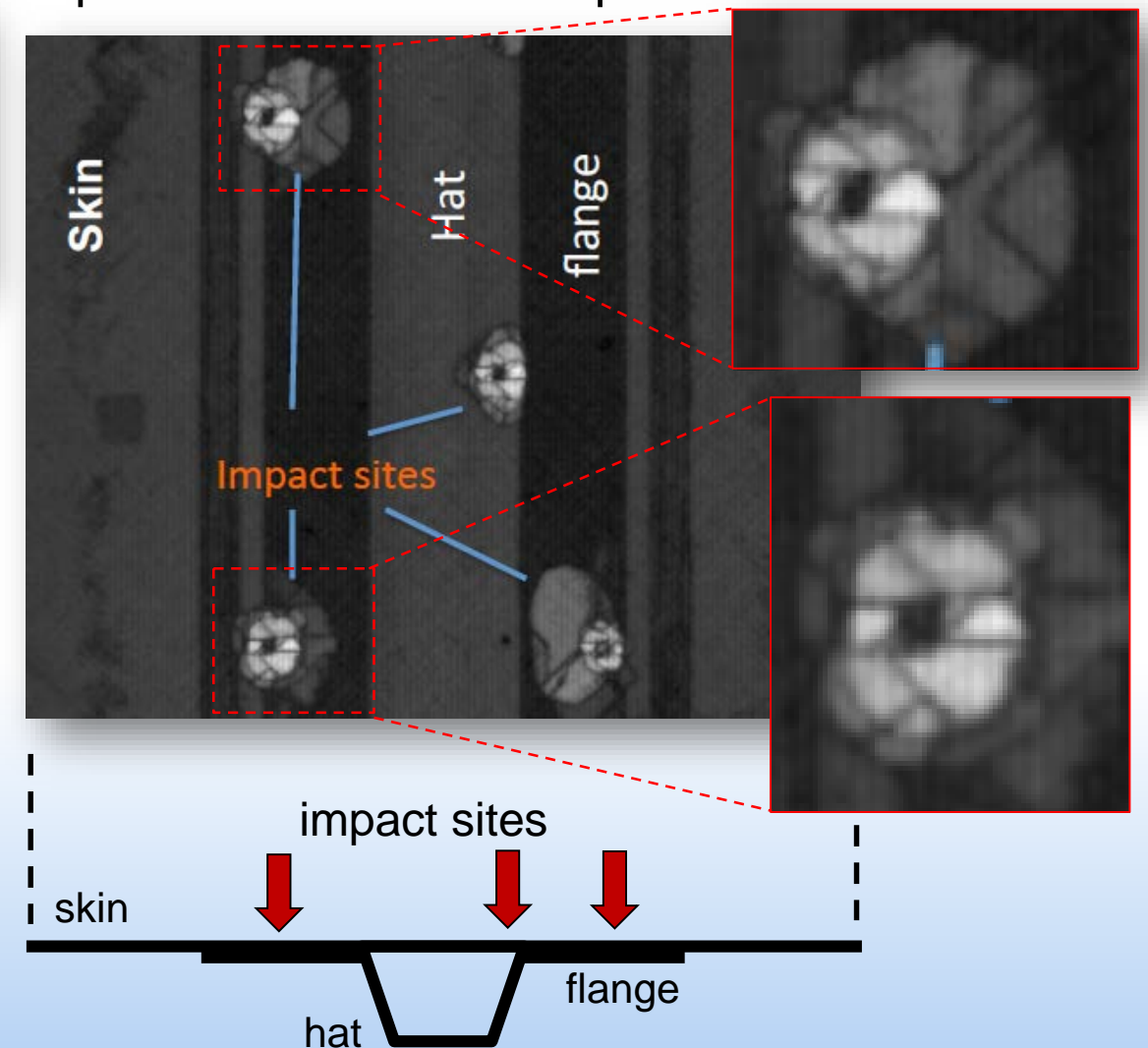
Example 1: X ray CT scan of impact damage in a CFRP plate

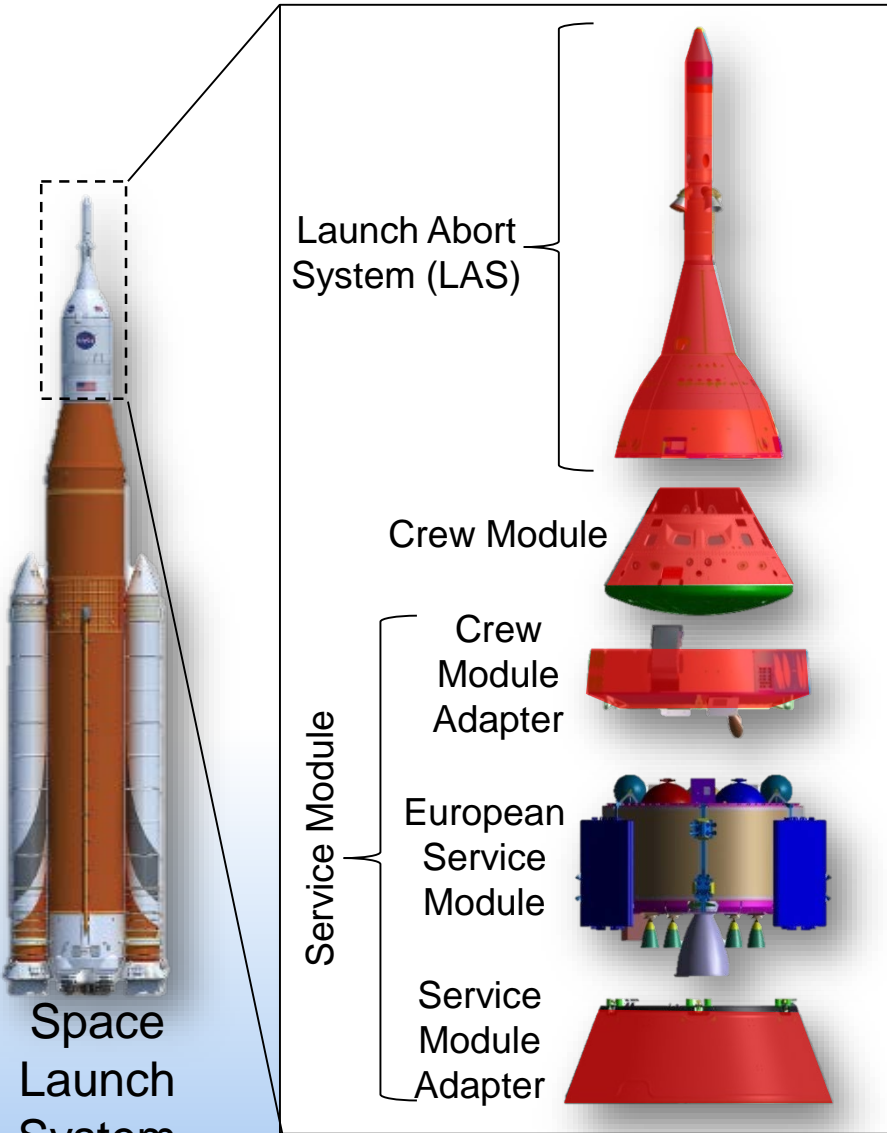


Example 3: X ray CT scan of impact damage in a CFRP plate



Example 2: Ultrasonic scan of multiple impact sites on stiffened panel



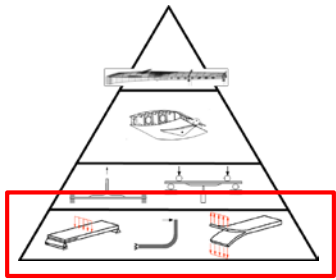


- NASA crew module
- Deep space human exploration
- First test flight: 2014
- First crewed flight: 2023

## Composite considered in this study

- Solid laminate
- IM7/977-3 Woven Carbon Fiber Reinforced Polymer
- Layup
  - $[+45^\circ/0^\circ/-45^\circ/90^\circ]_{2s}$
  - Adhesive at mid-plane

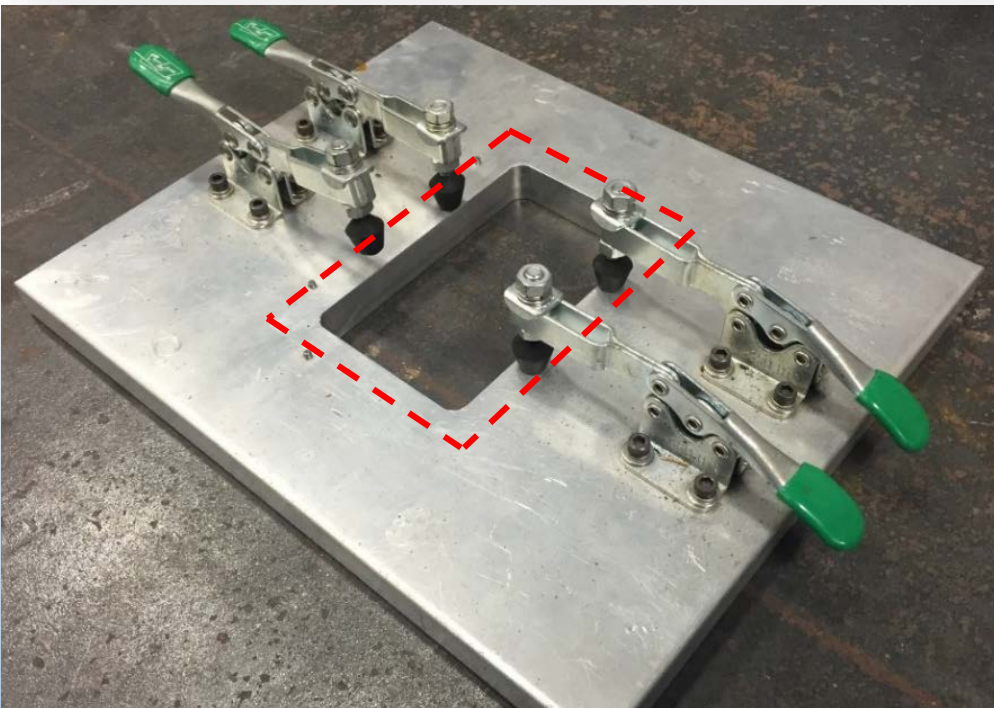
# COMPRESSION AFTER IMPACT



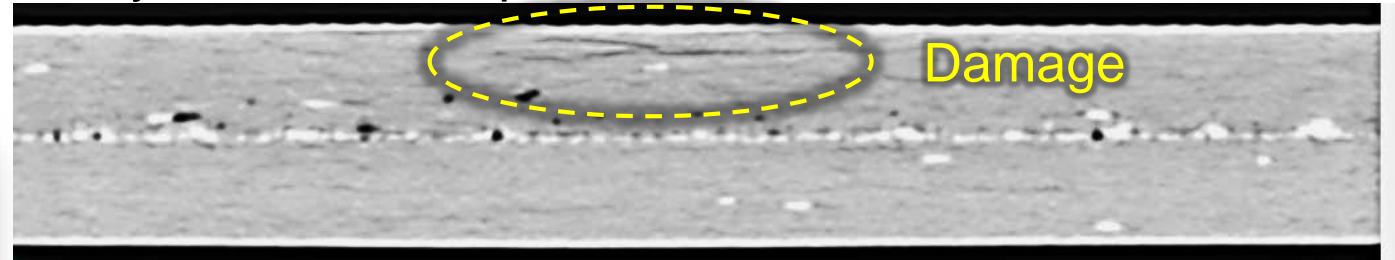
Compression after impact test are at "coupon scale"

Impact energy = 15 ft-lbs

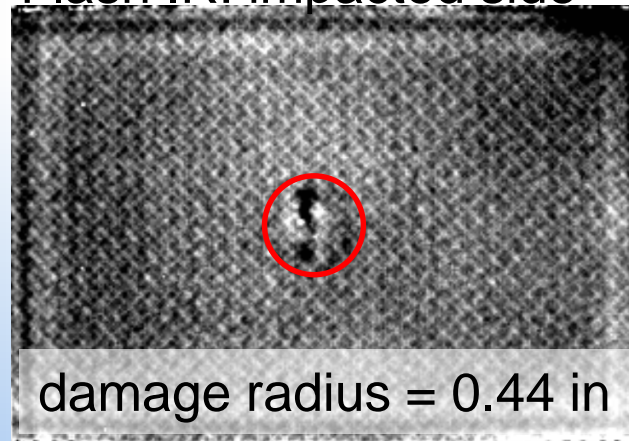
ASTM Impact Test Fixture



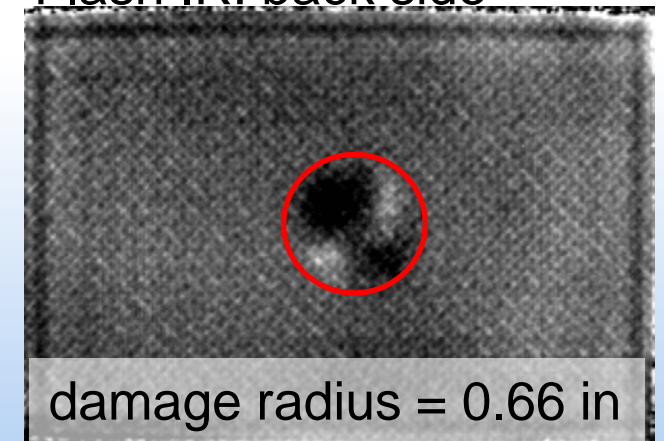
X-ray CT scan at impact site



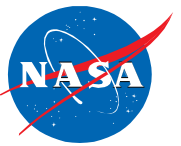
Flash IR: impacted side



Flash IR: back side

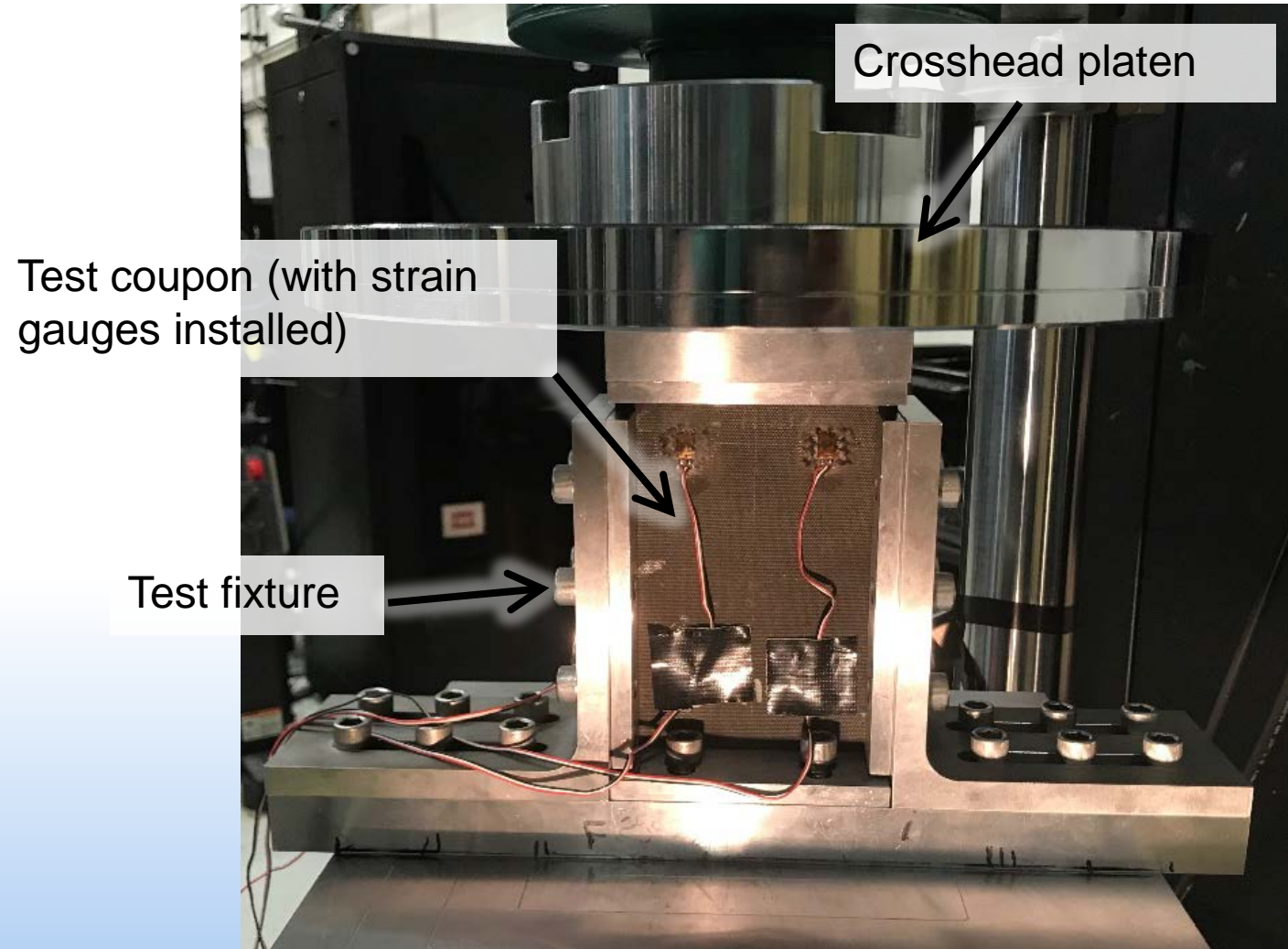


# COMPRESSION AFTER IMPACT



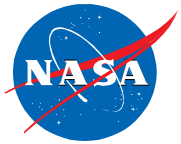
Test set-up

Test specimen (failed)



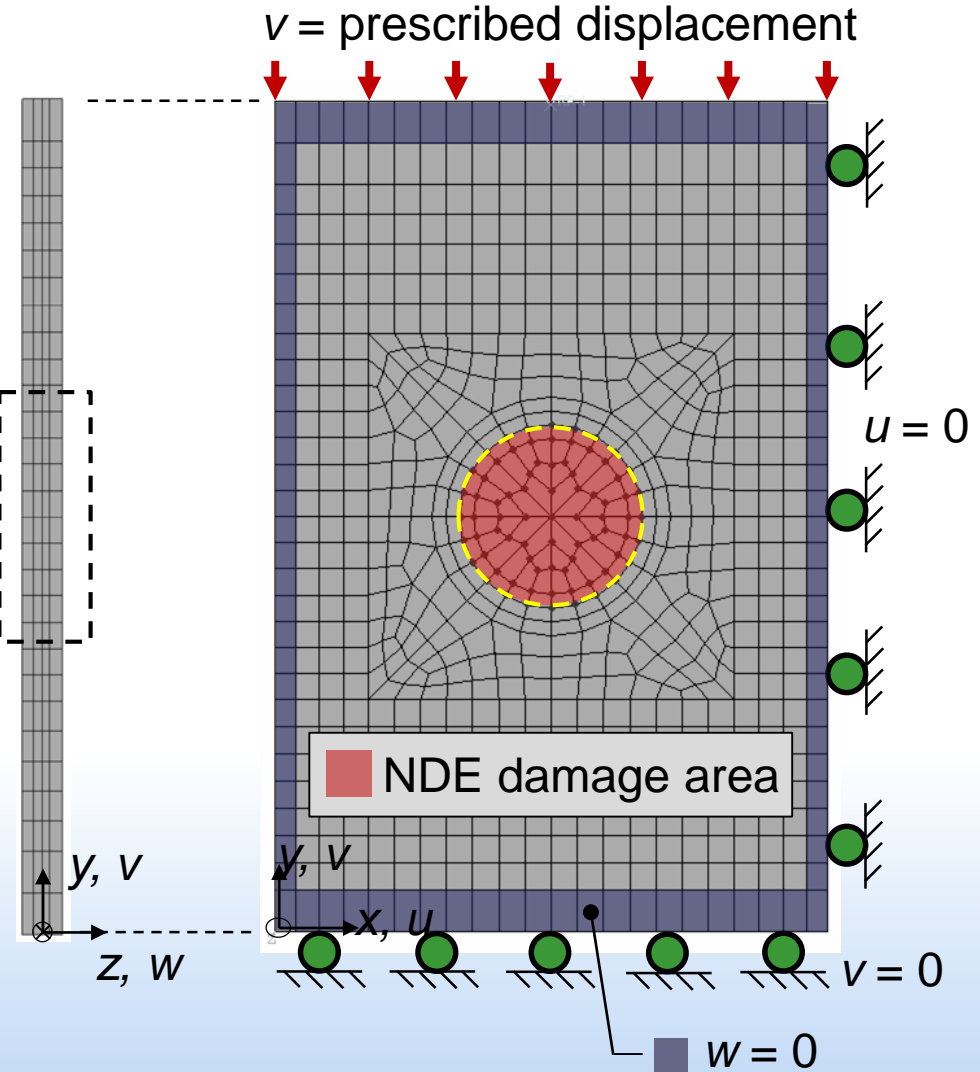
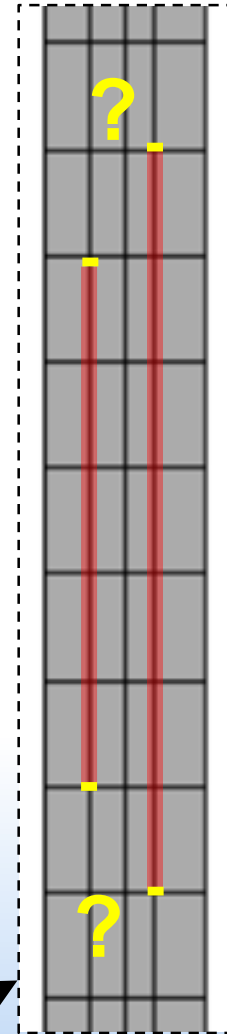
**INSERT TEST  
COUPON PIC**

# FINITE ELEMENT MODEL



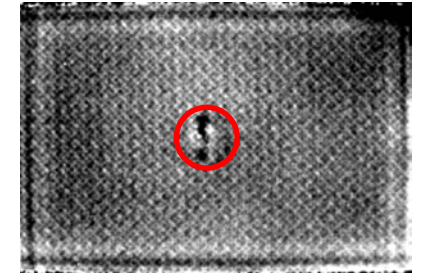
- Abaqus 2017
- Continuum shell elements
- Preexisting impact damage defined as discrete delaminations in mesh
- Virtual Crack Closure Technique (VCCT) to predict delamination onset
- First ply failure (FPF) to predict lamina failure onset
- Critical force assumed to correspond with damage initiation (VCCT or FPF)

How should preexisting impact damage be represented?





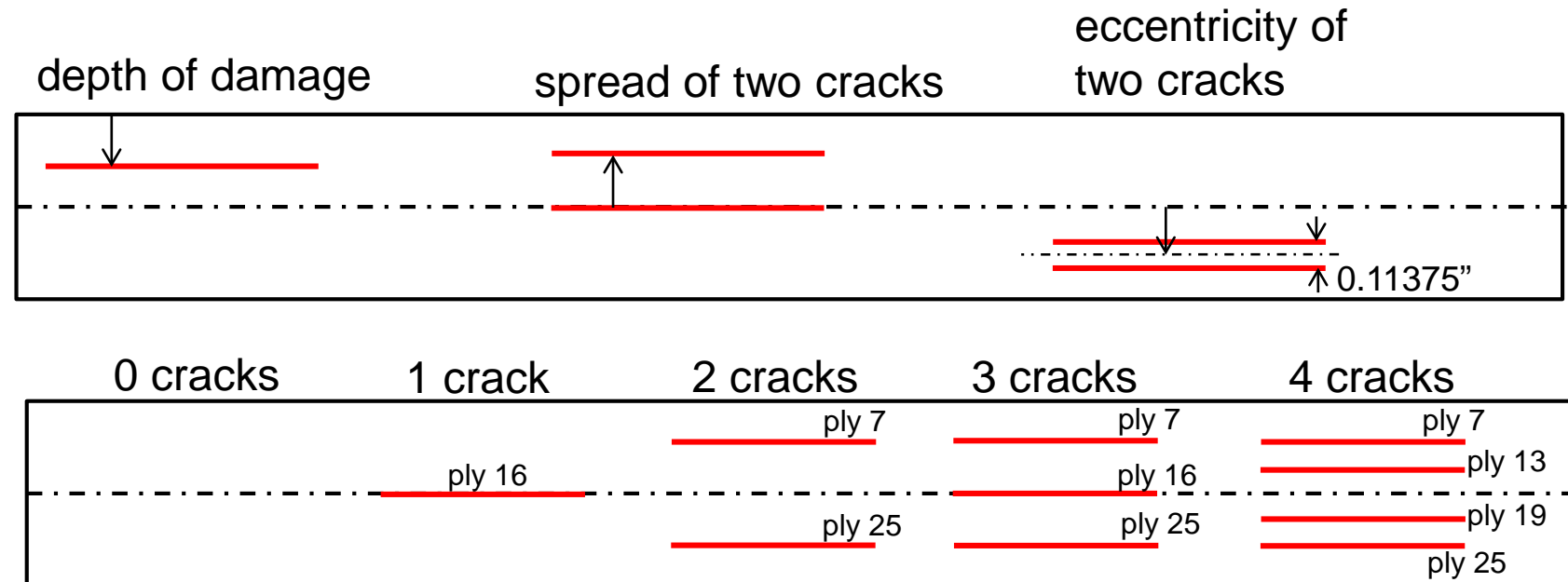
- Is Flash IR NDE fidelity sufficient for CAI model definition?
- Goal: Determine model configuration that...
  - ✓ Predicts critical force accurately
  - ✓ Is insensitive to slight variations in model definition
  - ✓ Can be defined and solved in a “timely manner”



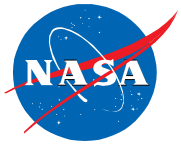
Projected damage area only in Flash IR

## Parametric study

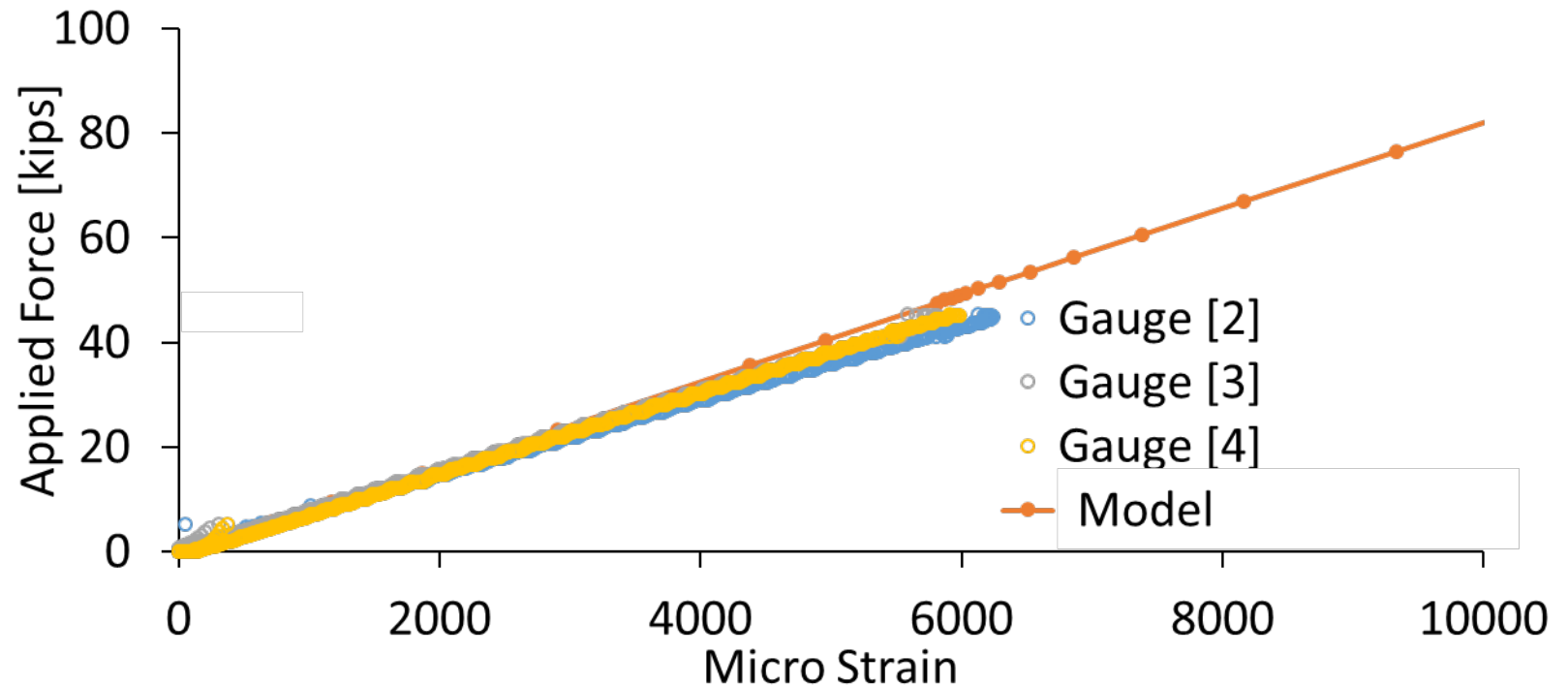
- Depth of damage
- Spread of two cracks
- Eccentricity of cracks
- Number of cracks



# LINEAR ELASTIC RESPONSE



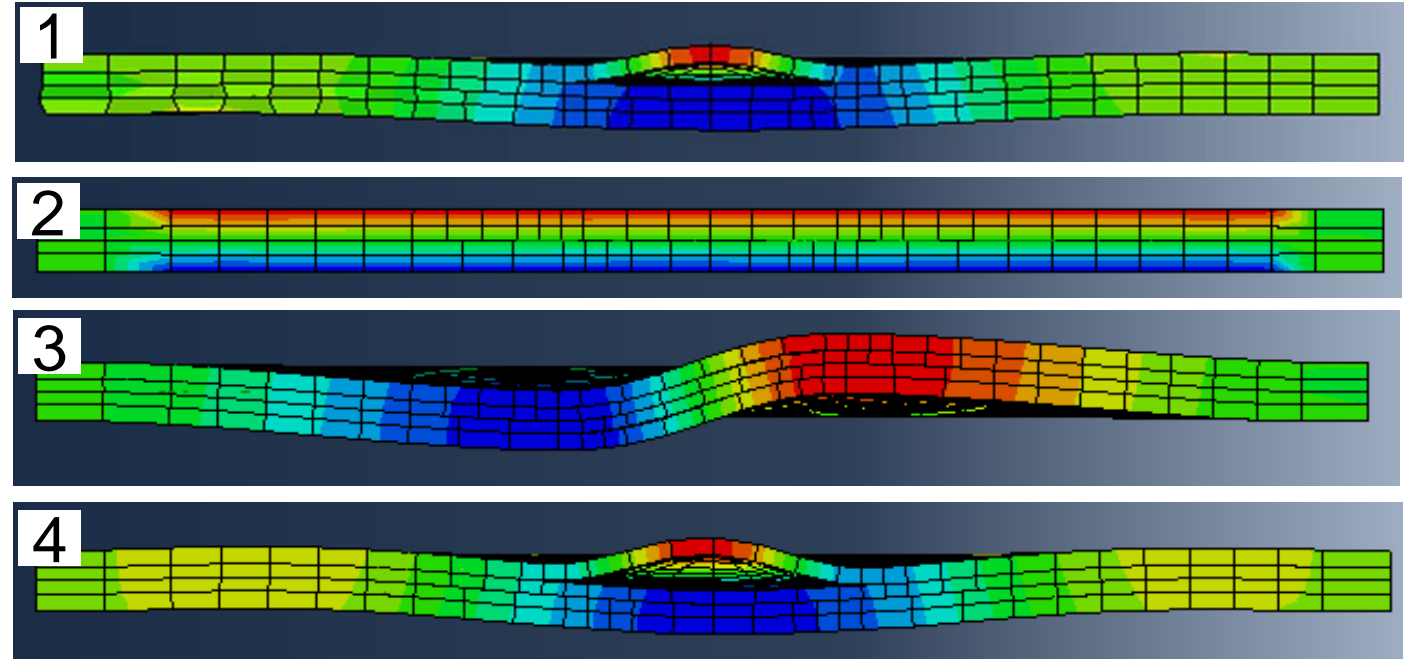
1. Elastic response is well captured by model
2. Test specimen is positioned in fixture to ensure uniform strain



# CONTACT ALGORITHM



1. Global response is highly sensitive to contact algorithm
2. Global response constrained if VCCT activated
3. Case 1 and 4 to be used henceforth

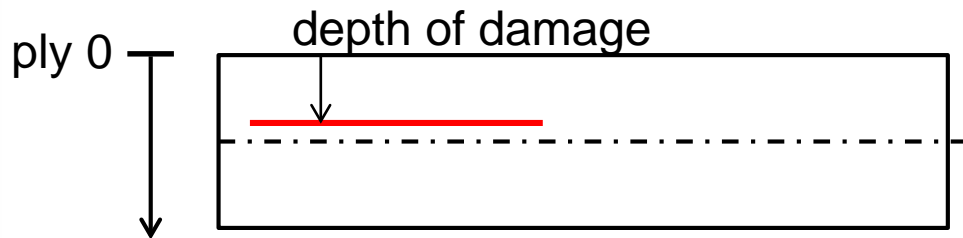
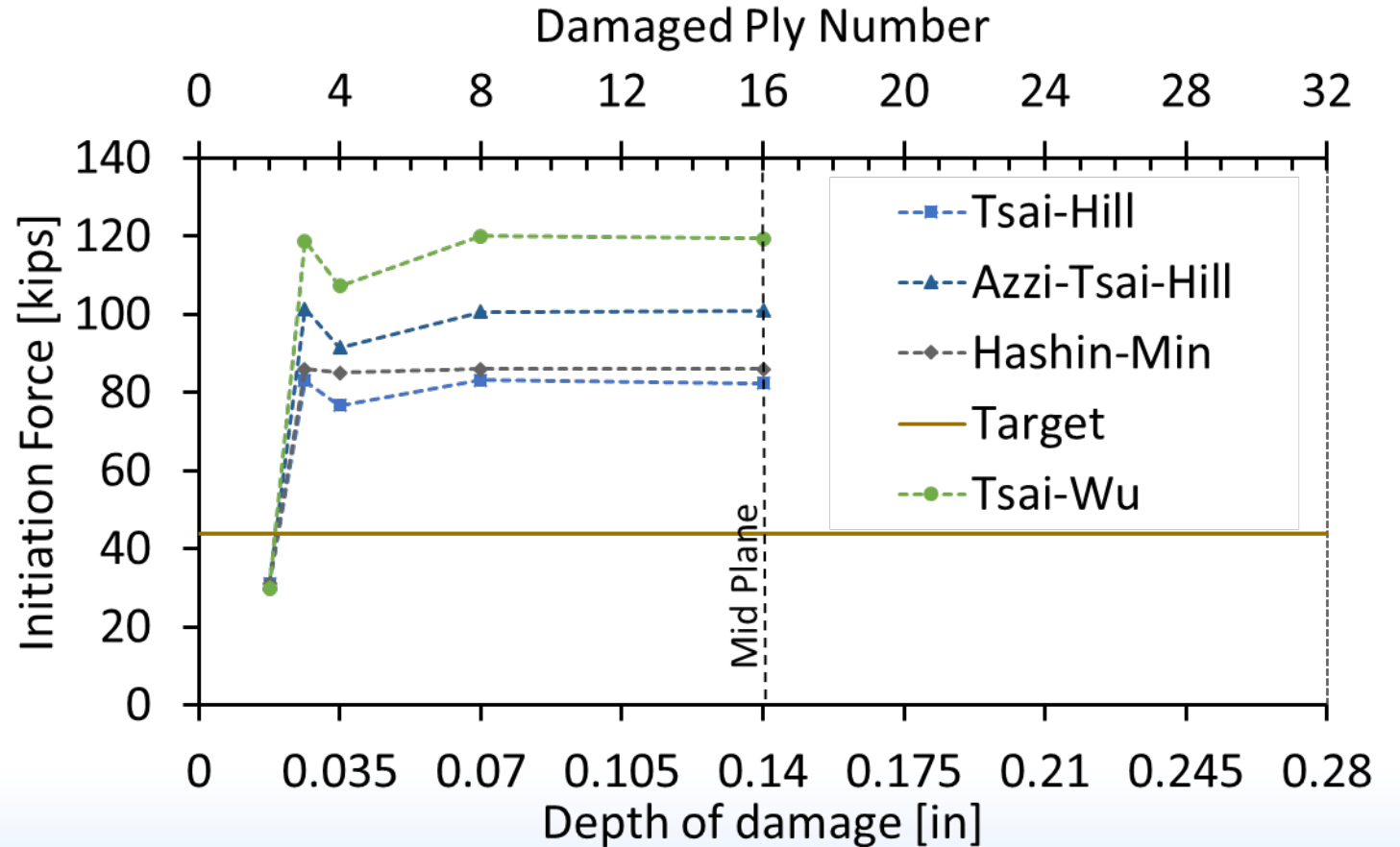


<u>Case</u>	<u>VCCT Status</u>	<u>Contact Property option</u>	<u>Pressure Overclosure</u>	<u>Constraint reinforcement method</u>
1	On	VCCT Fracture Criterion	N/A	N/A
2	Off	Normal Behavior	"Hard Contact"	Penalty
3	Off	Normal Behavior	"Hard Contact"	Direct
4	Off	Normal Behavior	"Hard Contact"	Default

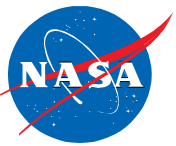
# STARTING DEPTH OF DAMAGE



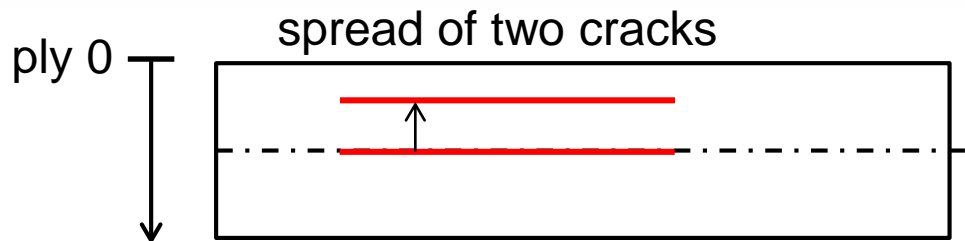
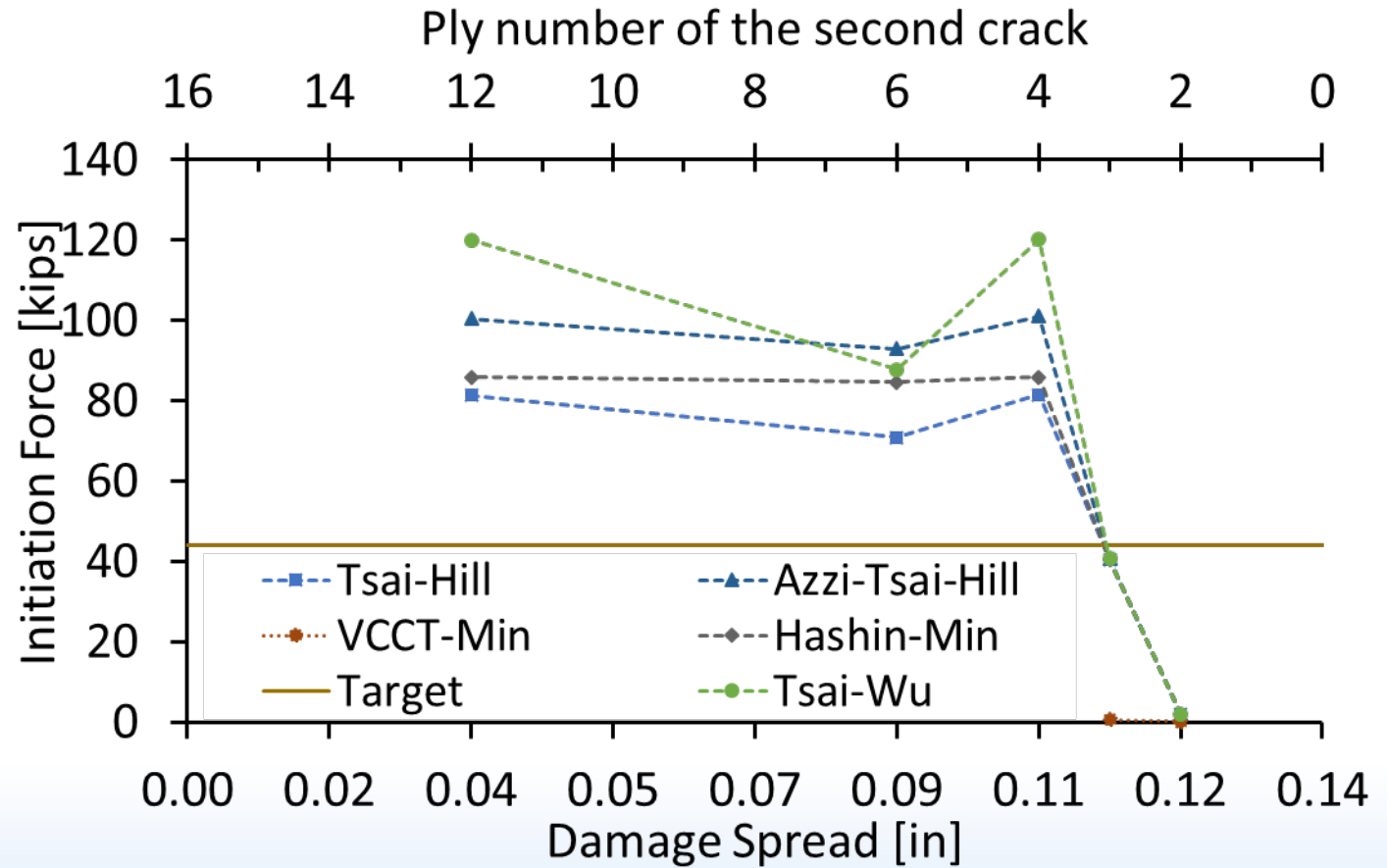
1. Generally, model over predicts test data
2. Predictions are insensitive if crack is placed at least 3 plies away from the impacted laminate surface



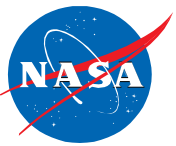
# SPREAD OF TWO DELAMINATIONS



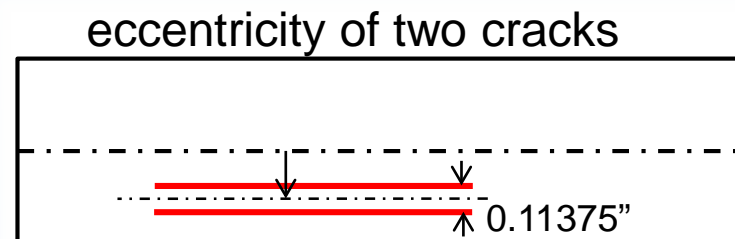
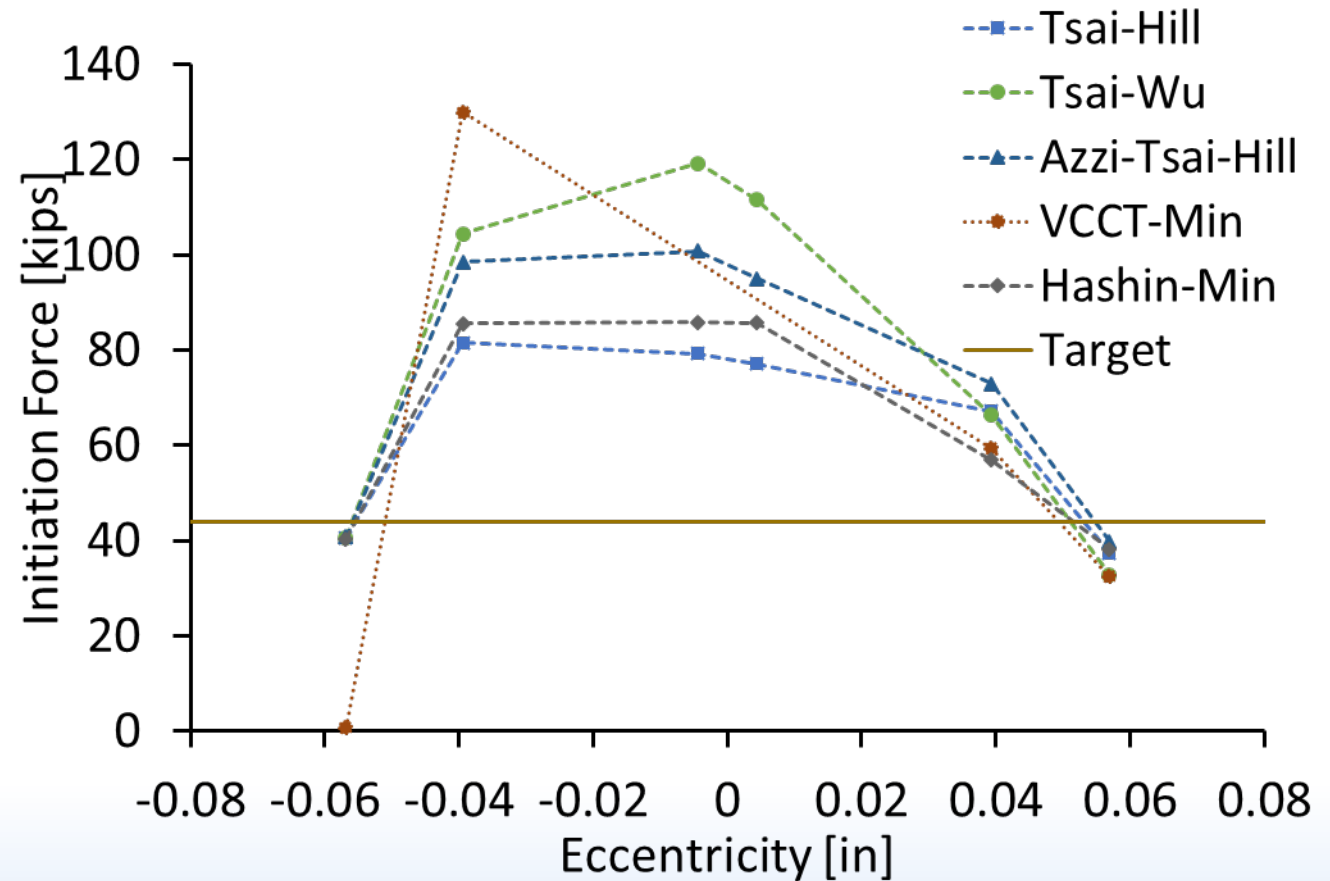
1. Generally, model over predicts test data
2. Predictions are insensitive if cracks are spread at less than 0.11375"
3. VCCT causes non-convergence or near zero critical force prediction



# ECCENTRICITY OF TWO DELAMINATIONS



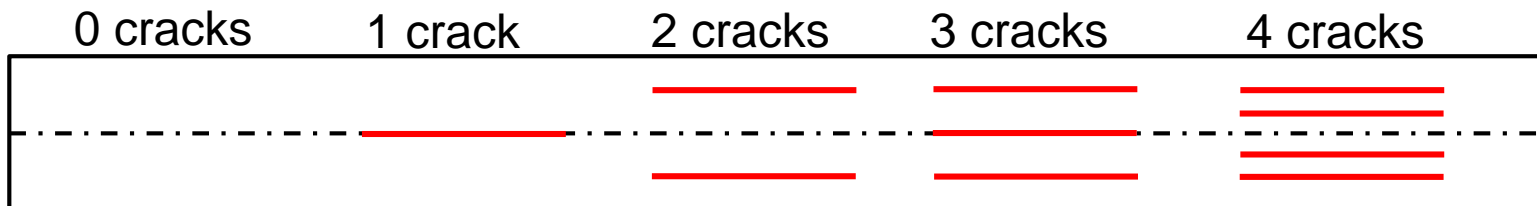
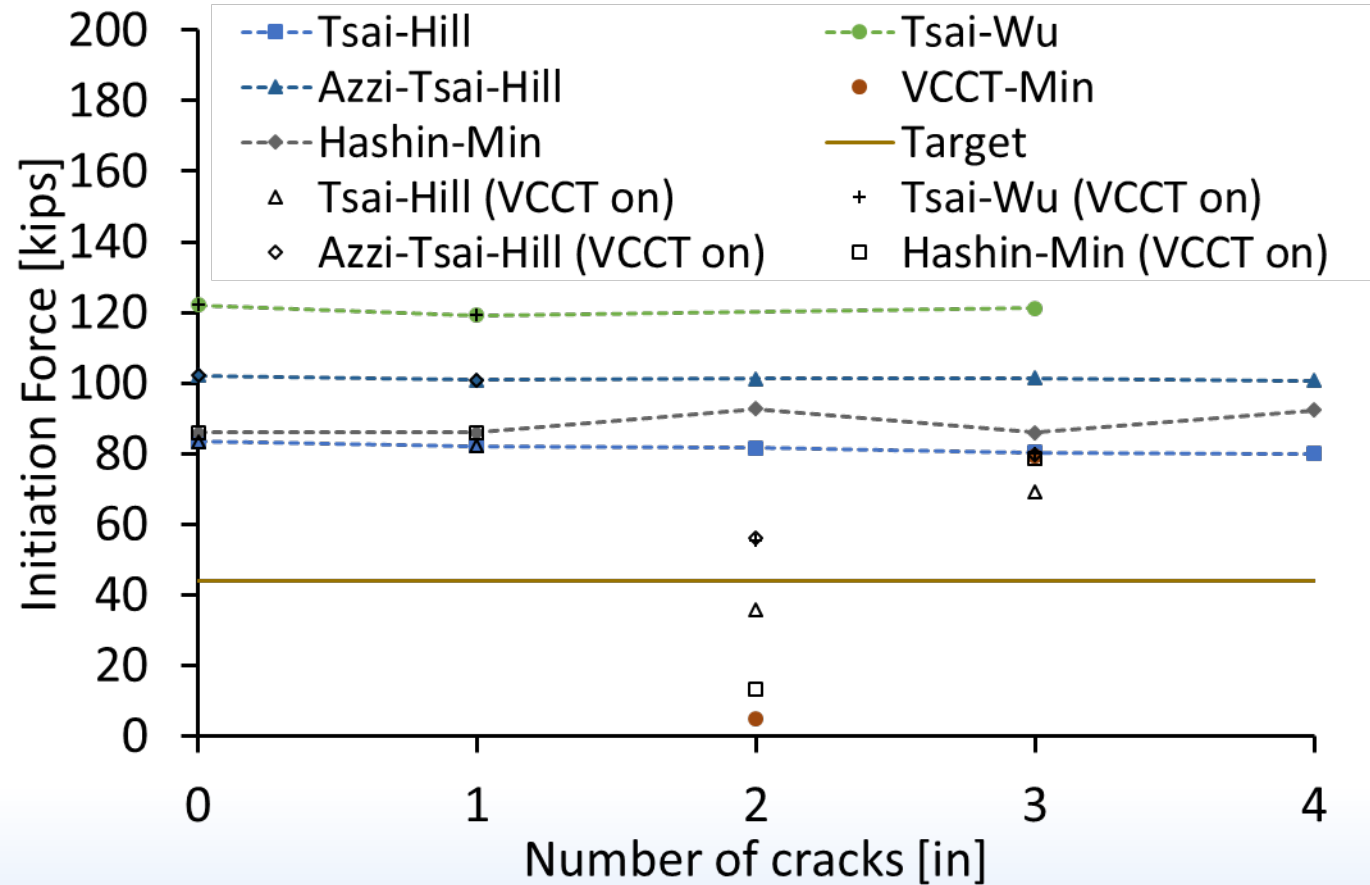
1. Prediction accuracy is a function of proximity to the laminate surface
2. Good correlation is seen when the delaminations are defined near the laminate surface
3. VCCT predictions are more sensitive than first ply failure
4. VCCT often causes non-convergence



# NUMBER OF DELAMINATIONS



1. Predictions are not sensitive to the number of cracks
2. If VCCT is activated, predictions change significantly
3. VCCT under-predicts strength
4. VCCT causes convergence problems

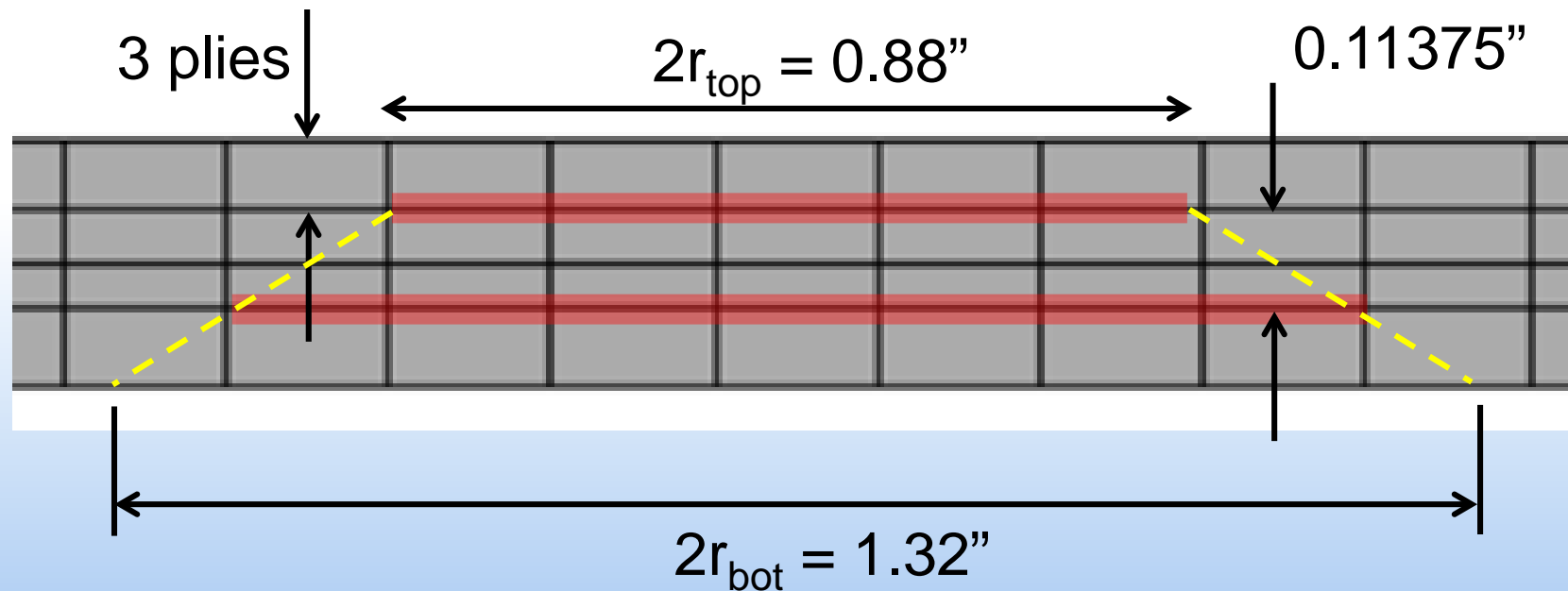


# SENSITIVITY STUDY: CONCLUSION



How should preexisting impact damage be represented?

- Two preexisting delaminations
- Spaced less than or equal to 0.11375" apart
- Located near the impacted surface of the coupon (3 plies)
- Sizes of the two preexisting delaminations correspond to projected damage area from Flash IR NDE of each side of the coupon

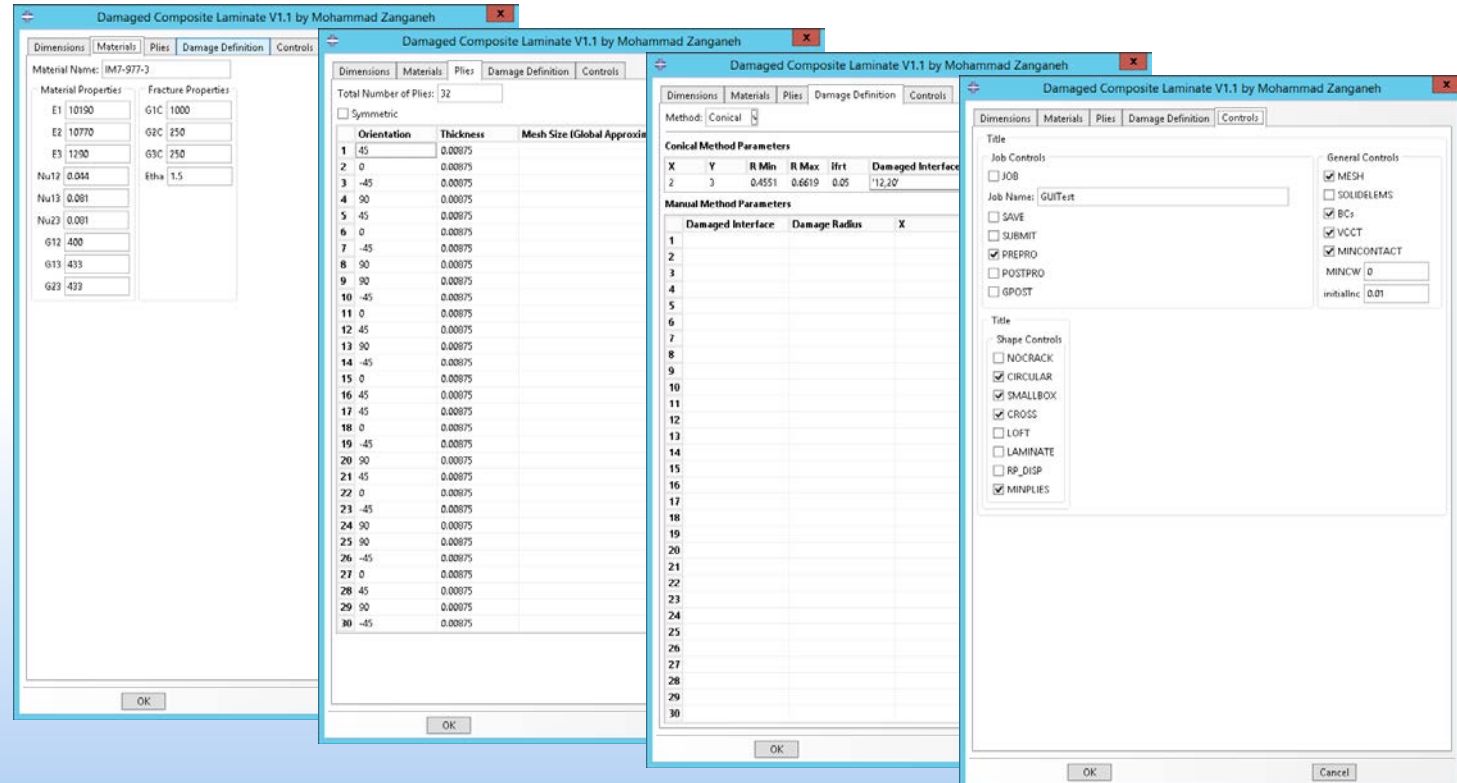
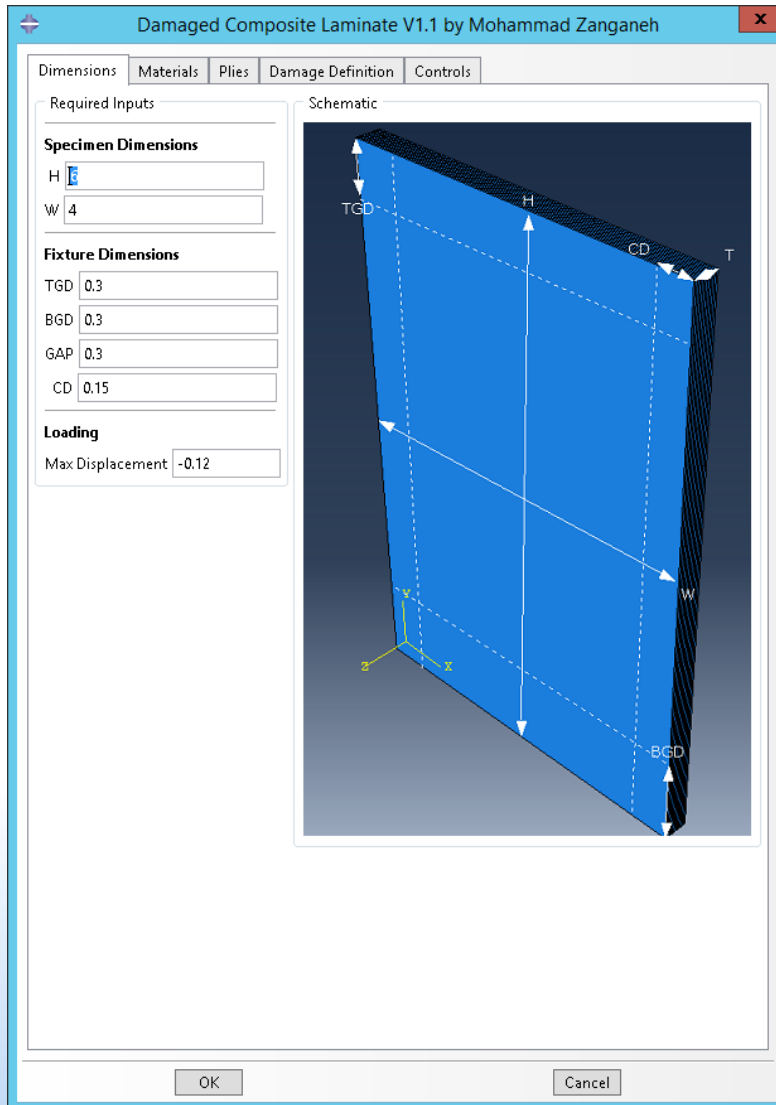




# GRAPHICAL USER INTERFACE



- Abaqus plug-in
- CAI simulation of solid laminate
- User enters model definition parameters
- Automatic model definition and execution



- Current status
  - Completed sensitivity study on model definition parameters
  - Validated model prediction accuracy
    - One impact energy
    - One layup
    - One material system
- Future work
  - Attempt model test correlation of additional impact energies
  - Attempt test correlation of additional layups
  - Generate recommendation for use in future BBA
- Application: if used to replace otherwise planned CAI test...
  - Same material system
  - Similar layup
  - Similar environment
  - No expected differences in failure mode



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# QUESTIONS

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