A Conceptual Framework for Practical Progressive Damage Analysis of Stiffened Composite Aircraft Structure with Large Notches Subjected to Combined Loading

Prepared by

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Outline

- Problem Description & Challenges
- Background
- Author's Perspective
- Proposed Framework
- Conclusions

Problem Statement (1 of 2)

Do not have the expertise to evaluate the details

- Provide reliable, accurate-to-conservative results
- Address the important physical responses observed
- Model complexity and solution times compatible with evaluating a broad range of configurations
- Usable for certification within 1-3 yrs

Includes non-acreage configurations, and growth/arrest phenomenon

Required for discrete source conditions (Cat 4) and often used to bound large impact damages (Cat 2/3). Less difficult than impact damage.

Including realistic scenarios, including flight and environmental (e.g., thermal-induced) loadings

A Conceptual Framework for

Practical Progressive Damage Analysis of

Stiffened Composite Aircraft Structure with

Large Notches Subjected to

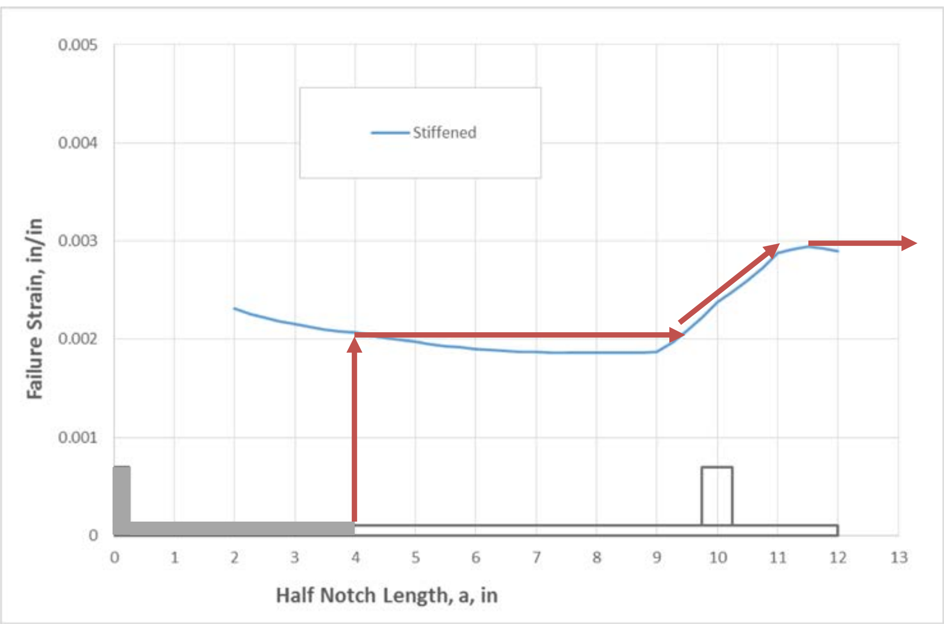
Combined Loading

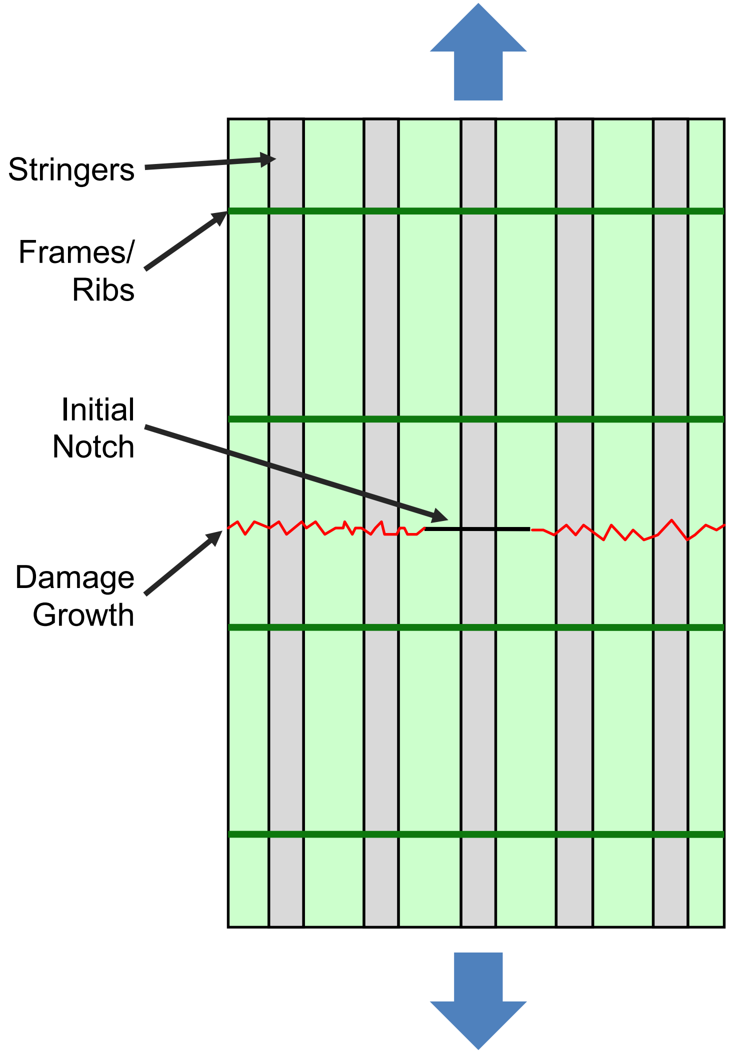
Problem Statement (2 of 2)

- Must be compatible with many individual analyses

Basic Structural Response

- General response for uniaxial loading of a notch severing a central stiffener
  - Damage growth in the skin
  - Arrest at intact stiffener
  - Failure of stiffener and/or skin/stiffener attachment
  - Unstable damage growth in the skin





Challenges (1 of 2)

- Capturing the complexities of structural failure
  - Load distributions near damage tip
    - *Vary significantly depending on layup, applied loading, trajectory of previous damage growth, location relative to stiffening elements, etc.*
  - Growth of damage within laminates (skins, stiffeners)
    - *Complex combination of fiber failure, matrix cracking and delamination*
    - *Load levels and macroscopic trajectories affected by numerous variables*
  - Attachment damage and growth

Challenges (2 of 2)

- Developing/validating a consistent methodology for nonlinear FE simulation
  - Structural idealization
    - *Element type, mesh refinement, boundary conditions, etc.*
  - Damage models for laminates and attachments
    - *Initiation criteria, evolution schemes*
    - *Compatible with arbitrary loading*
    - *Accurate timing of element and attachment damage is required to accurately capture failure loads and modes*
  - Analysis settings
    - *Stabilization/damping, time stepping, convergence criteria, etc.*
  - Validation with test results
    - *Multiple scales and multiple loading*
- Determining a methodology for obtaining inputs for the damage models
  - Initiation and evolution parameters for individual modes that are included in the methodology
    - *Testing methods and strategies, data reduction methods, generalization schemes, etc.*

Outline

Problem Description & Challenges

Background

- Unconfigured Responses
- Configured Responses
- Current Analysis Approaches

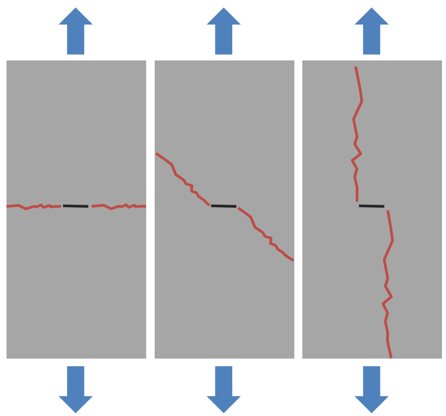
Author's Perspective

Proposed Framework

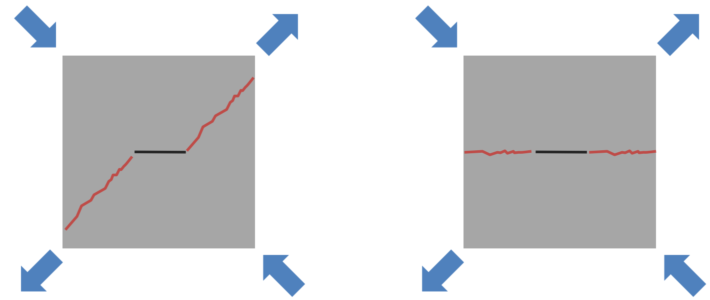
Conclusions

Damage Growth Trajectories (1 of 3)

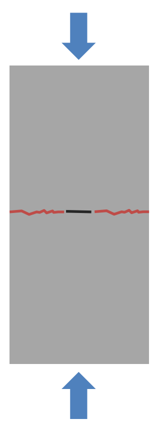
- Large-Notch Tension
  - Self-similar
  - Angled
  - Splitting
  - Combined



- Large Notch Shear
  - Angled
  - Self-similar

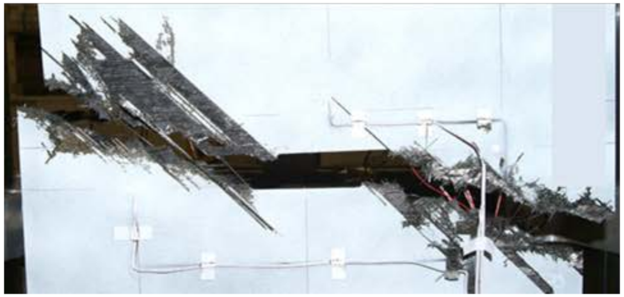


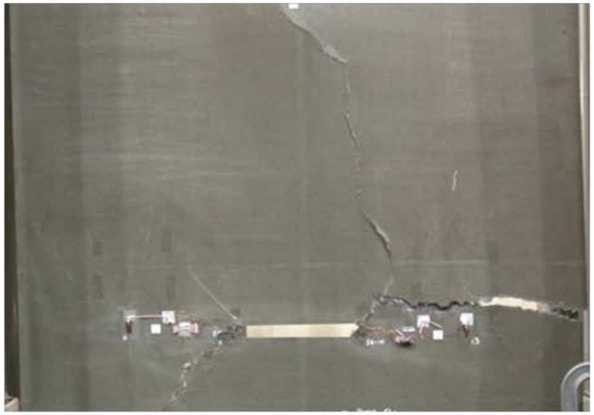
- Large Notch Compression
  - Self-Similar

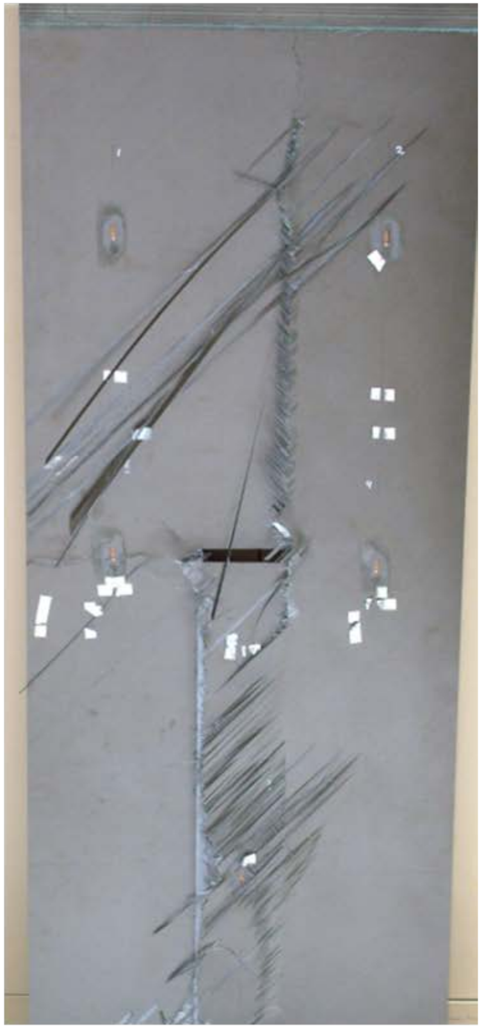


- General (Combined) Loading
  - Any combination of the above?

Damage Growth Trajectories (2 of 3)







Damage Growth Trajectories (3 of 3)

- Damage growth when multiple failure modes have similar criticality can be highly variable, and is not well understood
  - Likely dependent on multiple variables, including:
    - *Layup and stacking sequence*
    - *Location and orientation of damage*
    - *Precise damage state at "notch tip"*
    - *Environment*
    - *Inherent flaws*
  - Large strength variations have been observed between tested replicates

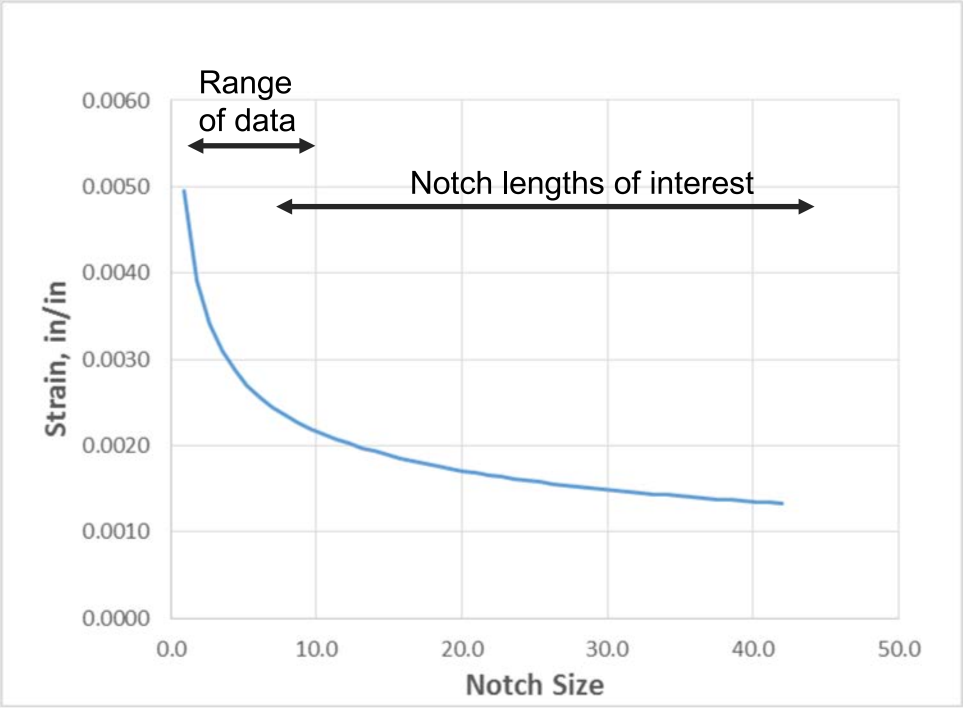
Important Unconfigured Effects (1 of 9)

- A wide range of variables affect the unconfigured response of large-notch panels
  - Loading
    - *Compression strengths are significantly lower than tension*
    - *Different influencing factors depending on the loading*
  - Material & Form
    - *Toughened resins produce a more brittle macroscopic response*
    - *Woven architectures tend to decrease notch-size sensitivity*
  - Processing
    - *Specific manufacturing details can introduce significant changes in strengths*
  - Layup (and probably stacking sequence)
    - *Dramatically affect failure loads and trajectories*
  - Thickness
    - *Significantly affects failure loads in compression (and probably shear)*
    - *Produces a smaller effect in tension*

Response is very complex, even for simple case of flat, unstiffened, uniaxial loading.

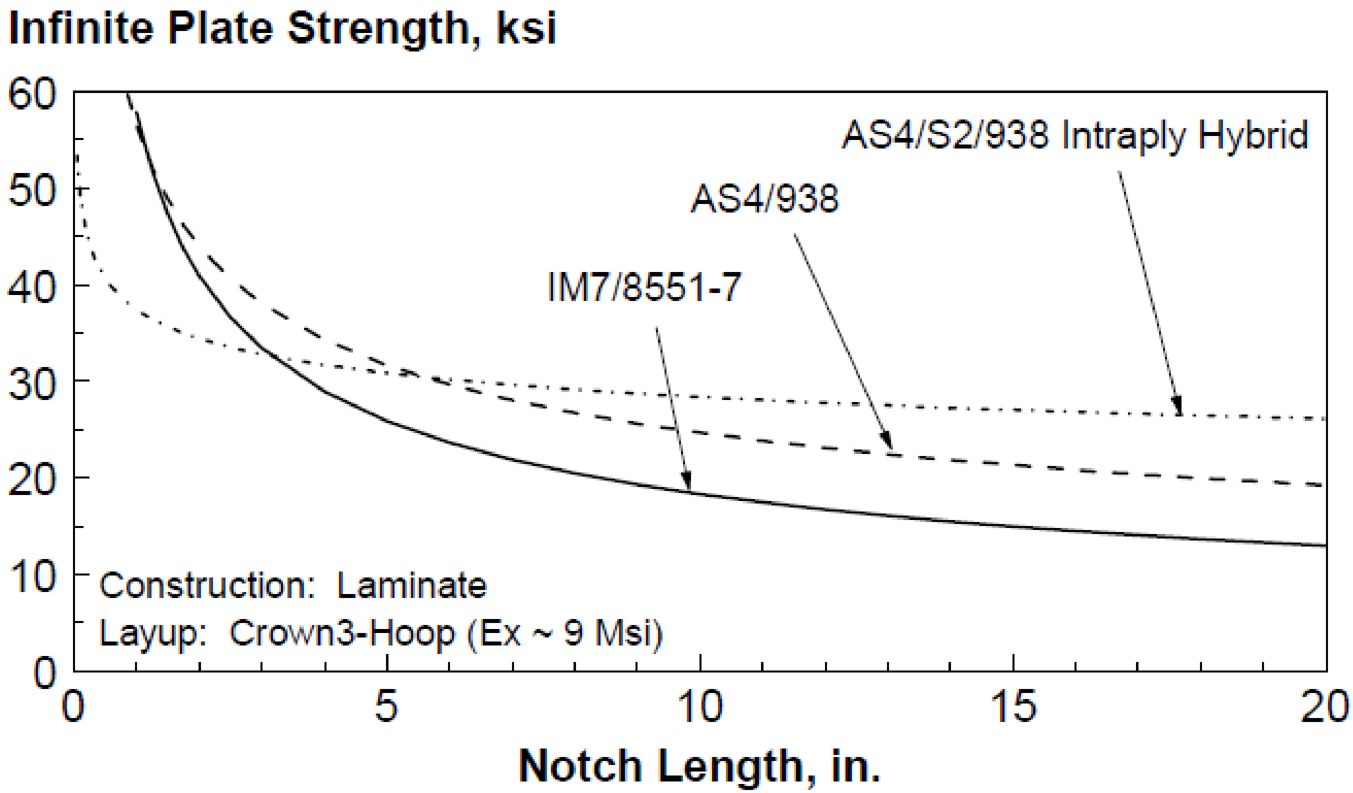
Important Unconfigured Effects (2 of 9)

- Notch-Size Effects
  - Decreasing strength with increased notch size
    - *Need to extrapolate significantly from the “coupon” test data*
  - Can influence damage trajectory



Important Unconfigured Effects (3 of 9)

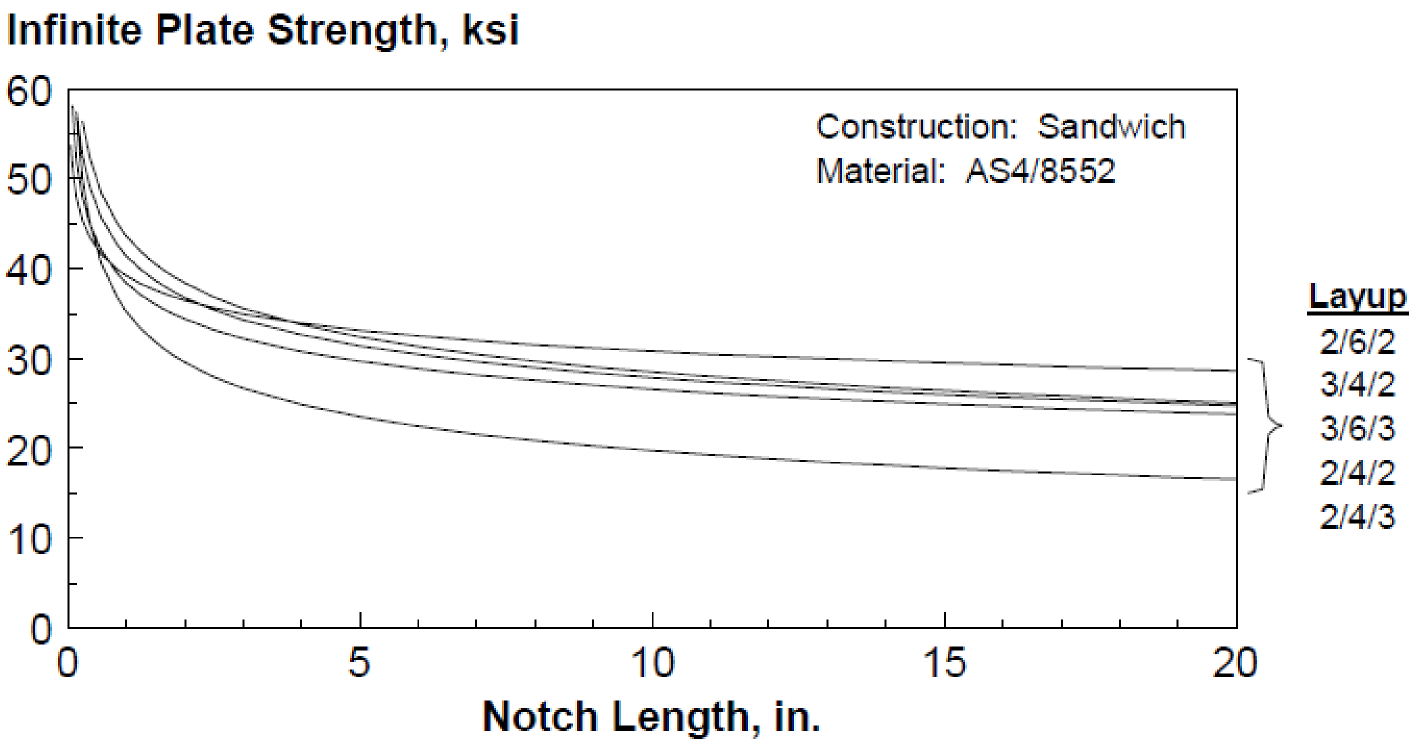
- Material Effects in Tension



Ref: T. H Walker, et al, “Damage Tolerance of Composite Fuselage Structure,” Sixth NASA/DOD/ARPA Advanced Composite Technology Conference, NASA CP-3326, 1996.

Important Unconfigured Effects (4 of 9)

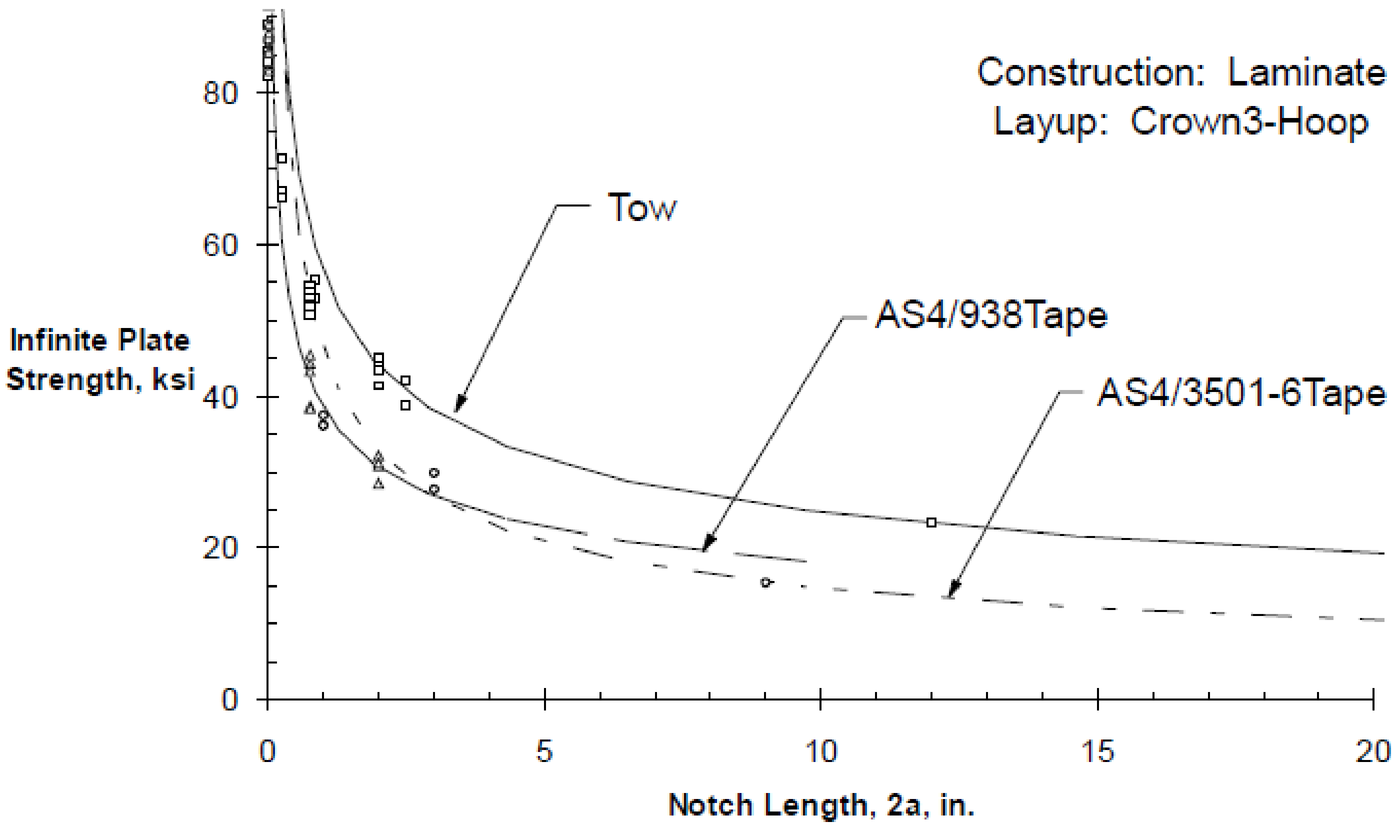
- Layup Effects in Tension



Ref: T. H Walker, et al, “Damage Tolerance of Composite Fuselage Structure,” Sixth NASA/DOD/ARPA Advanced Composite Technology Conference, NASA CP-3326, 1996.

Important Unconfigured Effects (5 of 9)

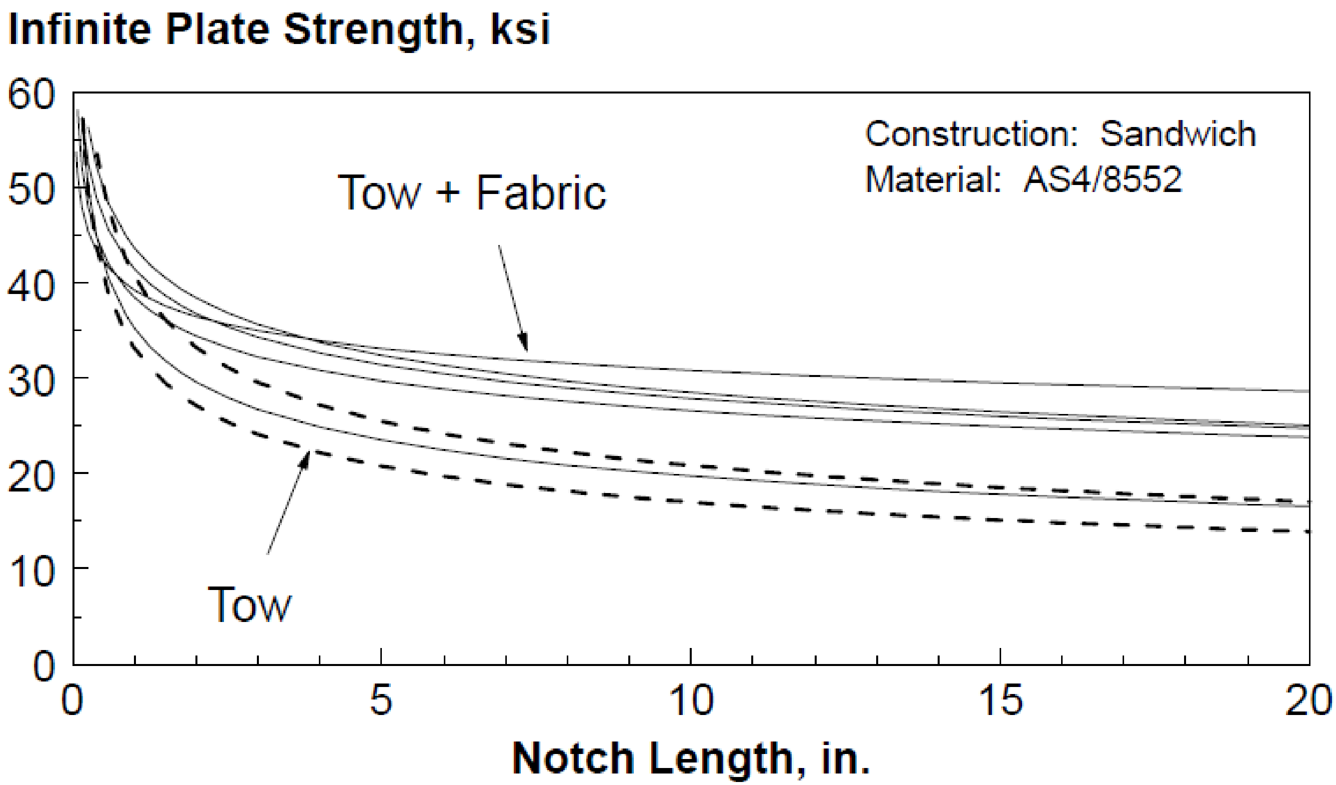
- Process-Induced Effects in Tension



Ref: T. H Walker, et al, "Damage Tolerance of Composite Fuselage Structure," Sixth NASA/DOD/ARPA Advanced Composite Technology Conference, NASA CP-3326, 1996.

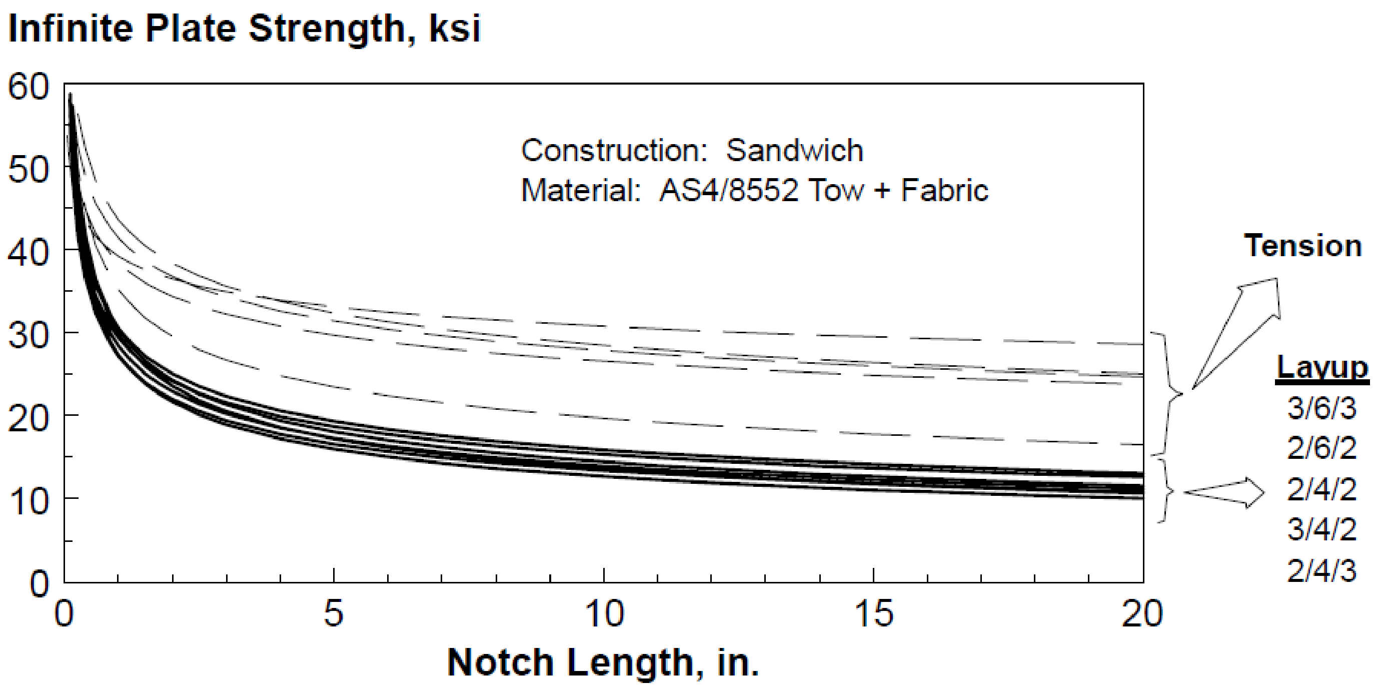
Important Unconfigured Effects (6 of 9)

- Fabric Surface-Ply Effects in Tension



Ref: T. H Walker, et al, “Damage Tolerance of Composite Fuselage Structure,” Sixth NASA/DOD/ARPA Advanced Composite Technology Conference, NASA CP-3326, 1996.

- Layup Effects in Compression



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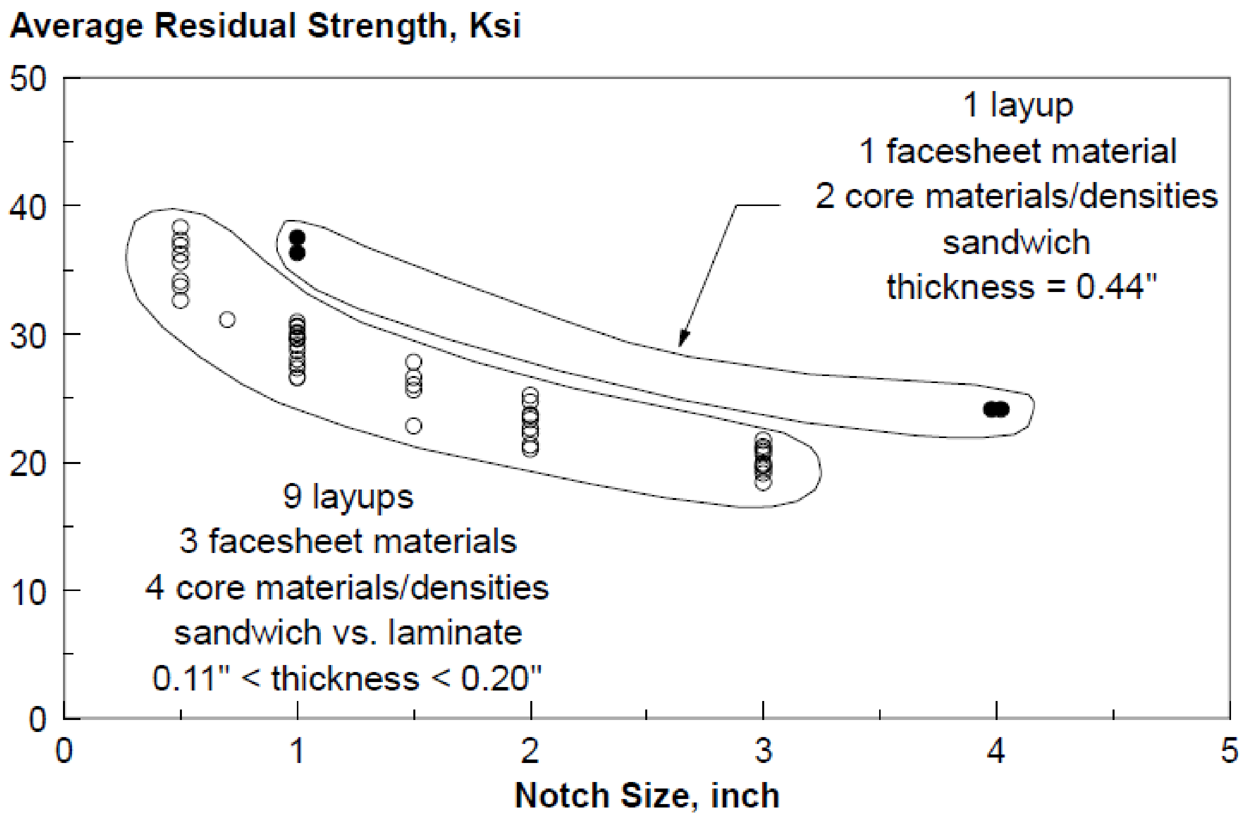
Important Unconfigured Effects (8 of 9)

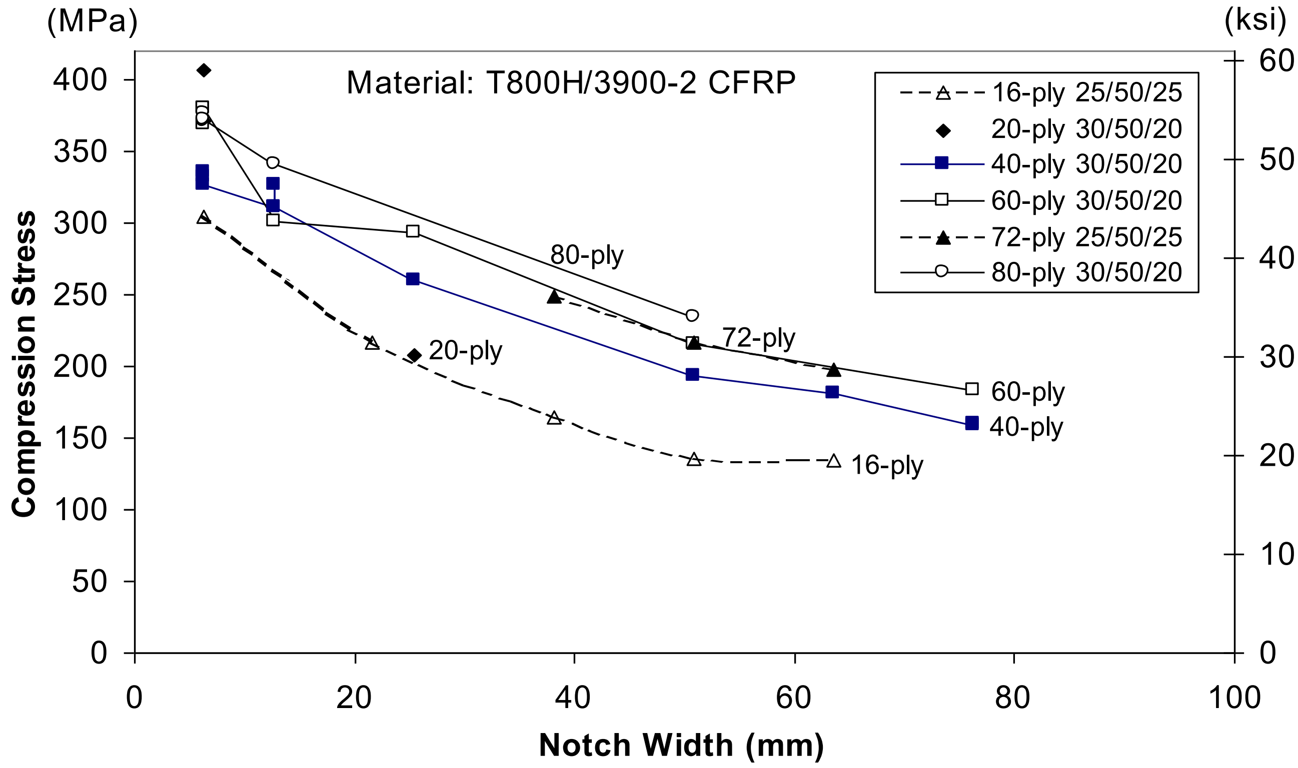
- Thickness Effects in Compression



Ref: T. H Walker, et al, “Damage Tolerance of Composite Fuselage Structure,” Sixth NASA/DOD/ARPA Advanced Composite Technology Conference, NASA CP-3326, 1996.

Important Unconfigured Effects (9 of 9)

- Thickness Effects in Compression (cont.)



Ref: S. H. Ward and H. Razi, "Effect of Thickness on Compression Residual Strength of Notched Carbon Fiber/Epoxy Composites", 28th International SAMPE Technical Conference, Seattle, WA. November 4-7, 1996.

Outline

Problem Description & Challenges

Background

- Unconfigured Responses
- Configured Responses
- Current Analysis Approaches

Author's Perspective

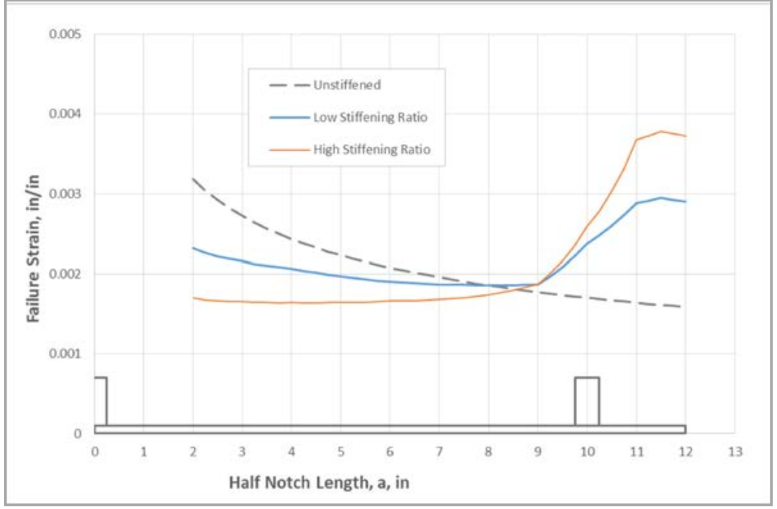
Proposed Framework

Conclusions

Factors Affecting Damage Growth – Configured

- The addition of realistic structural details (e.g., stiffeners, curvature) adds complexity to the unconfigured response
  - Load distributions are more complex
    - *Additional load from severed central stiffener*
    - *Arrest capability of intact stiffeners*
    - *Combined loading (in-plane, bending, pressure, non-uniform)*
  - Additional failure modes participate, and interact, in panel failure
    - *Stiffener failure*
    - *Skin/stiffener disbonding*
- Numerous configuration variables affect failure
  - Skin layup (thickness, stiffness, orthotropy)
  - Stiffener geometry, layup, spacing, attachment
  - Panel curvature
- Key relationships between these variables and residual strength are not well established
  - e.g., stiffening ratio

Effect of Stiffening Ratio on Residual Strength



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Current Analysis Capability

- Several types of progressive-damage approaches have recently been used for failure predictions of configured composite structure with large notches
  - Discrete-Mechanism Approaches (micro-, meso-, or multi-scale)
  - Cohesive Zone Models (CZM)
  - Point-Strain (or Stress)

Discrete-Mechanism Method (1 of 2)

- Description
  - Material failure determined at ply or constituent level using strengths from coupon tests
  - Damage growth in arbitrary directions via stiffness degradation of individual elements
  - Element disbonding (and any delamination) is addressed via cohesive or VCCT approaches
  - Two scales of modeling
    - *At least one element per ply, often with delamination planes at each ply interface*
    - *One to several elements through the thickness of the laminate, stacking sequence addressed via CLPT, possibly with delamination planes at critical sublaminate interfaces*
- Benefits
  - Can potentially capture the interactions between the detailed damage modes
  - Can address general damage trajectories (and branching)
- Shortcomings and Challenges
  - Determining appropriate input strength properties, and test methods to obtain them
    - *Fiber and matrix strengths and associated energies*
    - *Applicability to in-situ scenarios uncertain*

Discrete-Mechanism Method (2 of 2)

- Shortcomings and Challenges (cont.)
  - Difficult to capture some laminate scale effects
    - *Thickness effects*
    - *Hybridization effects*
    - *Processing effects*
    - *Changes in apparent toughness due to damage complexity associated with competing modes*
  - Very long solution times for structural-scale models
    - *Numerically challenging due to local failures combined with global collapse*
    - *Large models*

Cohesive Zone Method

- Description
  - Skin and stiffener damage idealized as a cohesive crack at the laminate scale
    - *Growth allowed along a prescribed self-similar path*
    - *Cohesive response calibrated using large-notch test results from unconfigured laminates*
    - *Interpenetration (for tension) or opening (for compression) are restricted by contact included in commercial implementations of cohesive response*
  - Disbonding of skin and stiffeners addressed via interface methods (cohesive or VCCT) using coupon-based fracture properties
- Benefits
  - Relatively simple damage model, keeping computing requirements modest
  - Inherently captures laminate-scale effects via unconfigured large-notch testing
- Shortcomings and Challenges
  - CZM accuracy becomes less reliable when trajectories vary significantly from self-similar
  - Significant amount of unconfigured large-notch testing required to address range of laminates, thicknesses, and notch sizes
  - Can be used for tension- or compression-dominant loading in a single analysis, but not both
    - *Cohesive-element contact precludes allowing both to occur*

Point Strain Method

- Description
  - Predict onset of growth from a prescribed damage using notch-tip strains
  - Not progressive, but can simulate growth via manual extension of damage
- Benefits
  - Computational requirements are low, due to lack of progressive damage
- Shortcomings and Challenges
  - Characteristic dimensions are not a material property
    - *Vary with notch size and laminate*
    - *Must be calibrated for each analysis based on expected response*
  - Accuracy of criterion is questionable
  - Difficult to address sequencing of multiple interacting failure modes
    - *e.g., disbonding or failure of the stringer as skin damage progresses beneath it*

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Physics of Failure (1 of 2)

- Failure within a notched laminate consists of multiple competing failure modes.
  - At a structural scale, these modes can be thought of as growth of the through-thickness damage in different directions
- Damage growth trajectory and failure load are determined by a combination of driving forces (stresses) and resistance to growth (toughness) in each of the directions

Driving Forces in Each Direction

Initially affected by:
- layup
- notch size and orientation
- loading
- severed stringer load
- proximity of intact stiffeners

Later affected by:
- skin damage growth, including path
- stringer damage growth
- attachment damage growth

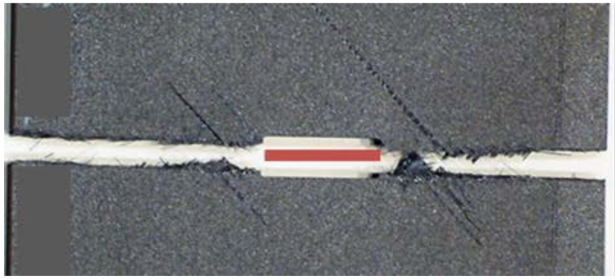
Apparent Toughnesses in Each Direction

Affected by:
- layup
- possibly thickness
- relative criticality of the different modes

Damage Growth Load & Trajectory

Physics of Failure (2 of 2)

- Damage growth affects the driving forces
  - e.g., splitting growth reduces self-similar driving forces
  - e.g., damage trajectory changes
- Relative criticality of the different failure modes affects apparent toughnesses
  - Dominance by a single mode results in “cleaner” damage-growth paths and lower apparent toughnesses
  - When multiple modes are competing (i.e., have similar criticality), the damage-growth path in a given direction is more complex and results in a higher apparent toughness



- The proximity of stiffeners reduces the driving forces associated with skin damage growth beneath the stiffener
  - This tends to increases the criticality of non-self-similar modes
  - This effect is dependent on damage state (extent and path of previous growth)

Key Analysis Considerations

- Desired uses of analysis
  - Determine the levels of apparent toughnesses which can be reliably achieved for a given laminate (or range of laminates)
    - *Using unreliable high apparent toughnesses during structural design could result in unconservative predictions for untested configurations*
  - Study the effect of structural variables and damage growth path on load redistribution, damage path tendencies, and panel strength
- Desired attributes of analysis
  - High-level control of laminate toughness
  - Simulation of arbitrary damage growth and associated load redistribution

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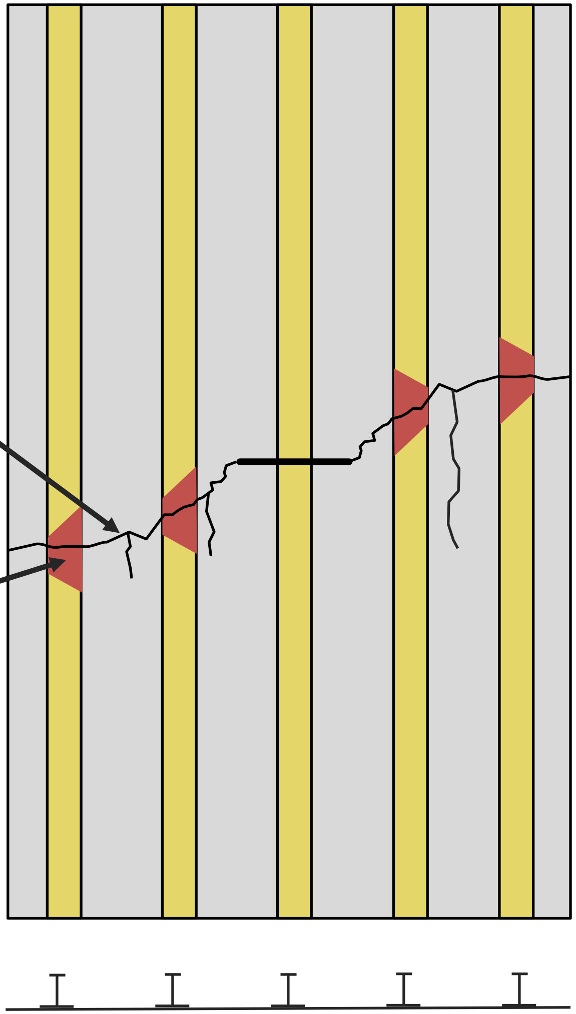
Proposed Analytical Framework

- Non-linear FEA with progressive damage
- In-plane skin and stiffener damage growth
  - Mesh-independent method
    - *Ideally includes crack branching*
  - Laminate-level generalized cohesive response
- Skin/stiffener disbonding
  - Existing interface methods (cohesive or VCCT)



Application of Framework

- Apply damage criteria and allow growth in a discrete number of growth directions
  - e.g., 0°, ±45°, ±90° directions

- For design sizing
  - Use toughnesses in each direction that are the lower values associated with “clean” growth, not the higher values associated with complex growth
  - Optionally, modestly suppress modes that tend to increase strength but cannot be relied upon (e.g., splitting) by increasing the associated growth resistance

Key Technology Requirements

- Development and/or implementation of several key technologies are required
  - Mesh-independent damage growth
  - Generalized laminate-level cohesive response
  - Methodologies for determining cohesive laws in analysis directions
  - (see following slides for more details)

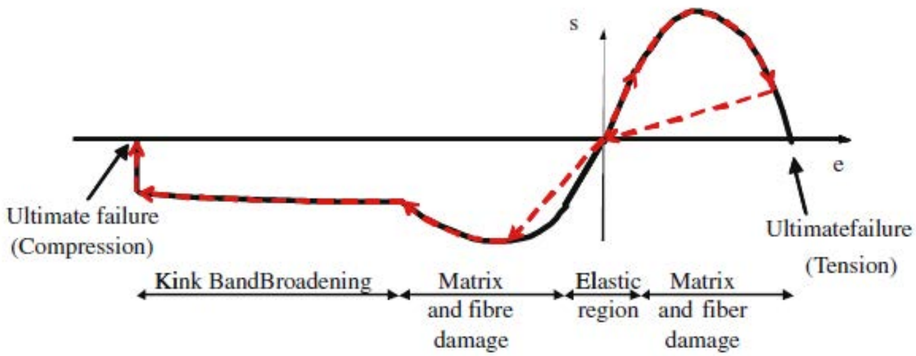
Mesh-Independent Damage Growth

- Addresses the need for arbitrary damage growth trajectories
- Ideally contains crack-branching capability
- XFEM technology in ABAQUS
  - Seems feasible, but has limitations
    - *No crack branching*
    - *No generalized cohesive response*
- Floating node method (Ref. 1)
  - Appears capable of branching
  - Need to implement with appropriate element types needed for 3D analyses
    - *e.g., shells, continuum shells, solids*

1. Chen, B. Y., S. T. Pinho, N. V. De Carvalho, P. M. Baiz, and T. E. Tay. "A Floating Node Method for the Modelling of Discontinuities in Composites." *Engineering Fracture Mechanics* 127 (September 2014): 104–34.

Generalized Laminate-Level Cohesive Response

- Cohesive response without contact
  - Addresses tension and compression continuously
- Addresses need for arbitrary loading
  - Tension or compression failure can occur at any point
- Similar concepts in literature
  - Univ. of British Columbia (Ref. 2)
  - Univ. of Toulouse (Ref. 3)
  - Others?

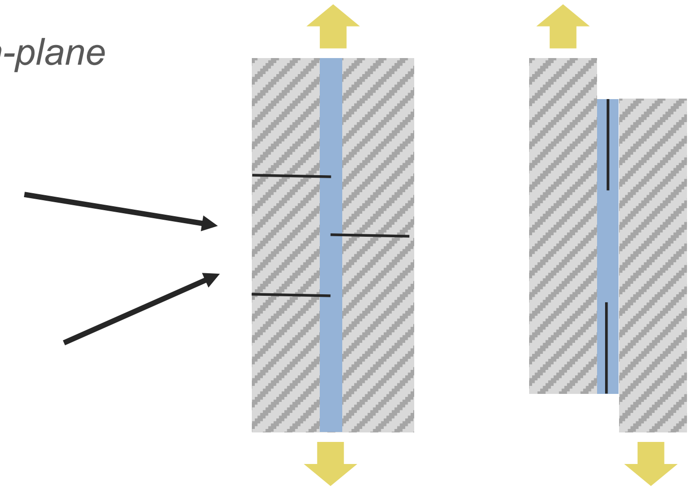


- Need to implement within selected mesh-independent damage growth scheme

2. Zobeiry, N., A. Forghani, C. McGregor, R. Vaziri, and A. Poursartip. “Progressive Damage Modeling of Composite Materials under Both Tensile and Compressive Loading Regimes.” In *Mechanical Reponse of Composites*, 10:179–95. Computation Methods in Applied Sciences, 2008.
3. Rivallant, S., C. Bouvet, and N. Hongkarnjanakul. “Failure Analysis of CFRP Laminates Subjected to Compression after Impact: FE Simulation Using Discrete Interface Elements.” *Composites Part A: Applied Science and Manufacturing* 55 (December 2013): 83–93.

Methodologies for Determining Cohesive Laws (1 of 2)

- Testing methods for determining Mode 1 and 2 response along specific paths
  - Mode I
    - *e.g., compact tension, compact compression, MSU in-plane loader (Ref. 3)*
  - Mode II
    - *Methods not well developed (MSU in-plane loader?)*
  - Need to constrain fracture to be along specific paths to provide apparent toughness in that direction
    - *Can doublers accomplish this? Zpins? Stitching?*

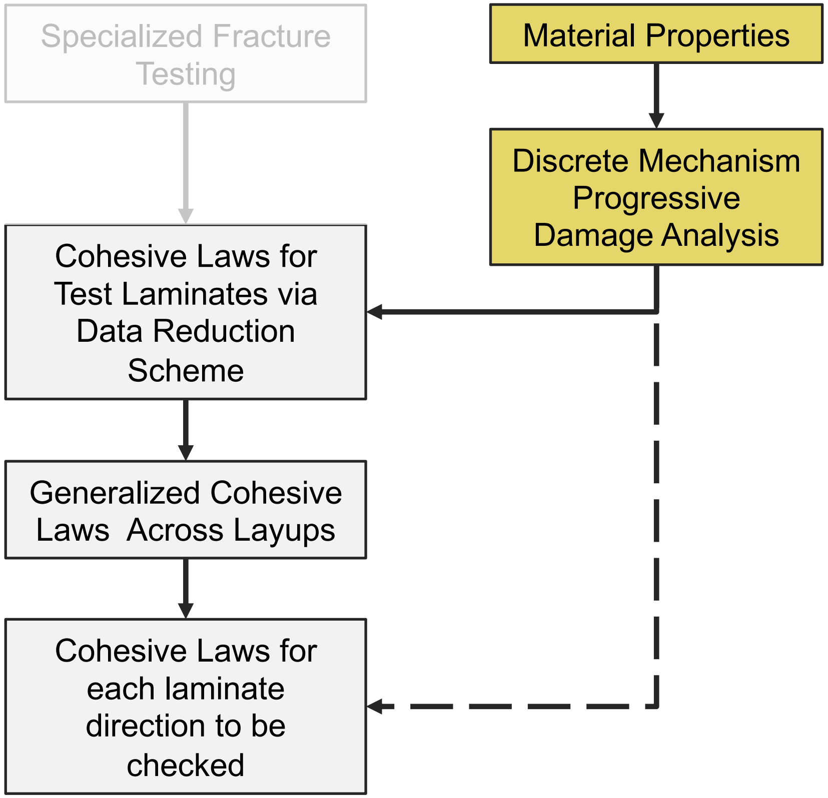


- Data reduction methods to convert test results into cohesive laws
    - *Techniques may already exist (Ref. 4)*

3. Cairns, D., and Will Ritter. "Application of Energy Methods to Modeling Failures in Composite Materials and Structures." Montana State University, 2009.
4. A. C. Bergan, C. G. Dávila, F. A. Leone, J. Awerbuch, and T.-M. Tan. "Mode I Cohesive Law Characterization of Through- Crack Propagation in a Multidirectional Laminate." ASC Conference, La Jolla, CA, 2014.

Methodologies for Determining Cohesive Laws (2 of 2)

- Longer-term, results from discrete-mechanism progressive failure analysis (and coupon-level testing) can be substituted for specialized test data
  - i.e., when discrete-mechanism PFA becomes sufficiently mature



Advantages of Proposed Framework (1 of 3)

Attribute	Prescribed-Path Cohesive Zone Model	Discrete Mechanism Models	Proposed Framework
Arbitrary damage path	✘	✓	✓
Arbitrary loading	✘	✓	✓
Direct control of laminate toughness	✓	✘	✓
Model complexity & analysis runtime	+	–	+ (?)

- It can address various damage trajectories (and changes in trajectory) observed in testing, and the associated effects on load redistribution
- Generalized cohesive response allows damage growth under any in-plane loading
  - Failure under bending loads can likely be captured by through-thickness discretization
- Laminate-level definition of strengths and toughnesses results in more direct and intuitive control of the growth resistance than Discrete Mechanism strategies
  - Design sizing can be accomplished using only as much of the apparent laminate toughness as can be justified

Advantages of Proposed Framework (2 of 3)

Attribute	Prescribed-Path Cohesive Zone Model	Discrete Mechanism Models	Proposed Framework
Arbitrary damage path	✗	✓	✓
Arbitrary loading	✗	✓	✓
Direct control of laminate toughness	✓	✗	✓
Model complexity & analysis runtime	+	–	+ (?)

- Laminate-level characterization of strengths and toughnesses also increases confidence that all key effects on strength are addressed
  - e.g., process-related, hybridization, material-form, thickness
- Analysis run times are expected to be significantly lower than Discrete Mechanism strategies
  - Therefore more compatible with structural-scale analyses

Advantages of Proposed Framework (3 of 3)

- It provides an intermediate step in complexity (relative to Discrete Mechanism strategies) that helps develop an understanding of the various factors effecting panel response
  - e.g., presence of stringers, crack-path history
- Allows Discrete Mechanism strategies to be developed at a scale compatible with reasonable solution times
  - e.g., compact tension and compact compression specimens

Outline

Conclusions

- Progressive damage methodologies for large-notch response are urgently needed
  - Reduce test costs
  - Develop an understanding of the key trends
  - Support design development and substantiation
- Ply- or constituent-based progressive damage models are not currently up to the task
  - Cannot <u>reliably</u> predict the complex failure and the effect of all variables
  - Computational requirements are too high
- Laminate-scale cohesive approaches provide a near-term solution