Engineering, Test & Technology

Rapid Analysis Tools for Aircraft Battle Damage Repair

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- Introduction
  - ABDR Requirements & Options
  - Bonded vs Bolted Repair
- Where to get loads?
- Rapid Damage Disposition
- Rapid Repair Analysis
- Fail-Safety Analysis
- Summary

(U.S. Air Force photo by Lauren Kelly @ Tinker AFB https://www.tinker.af.mil/News/Photos/igphoto/2003554415/)

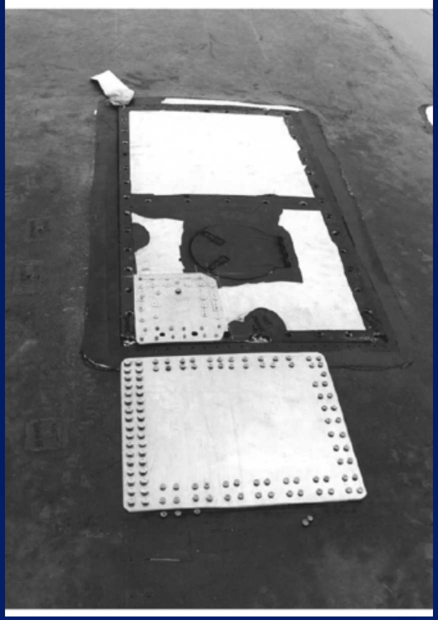
Damage types sustained during combat operations

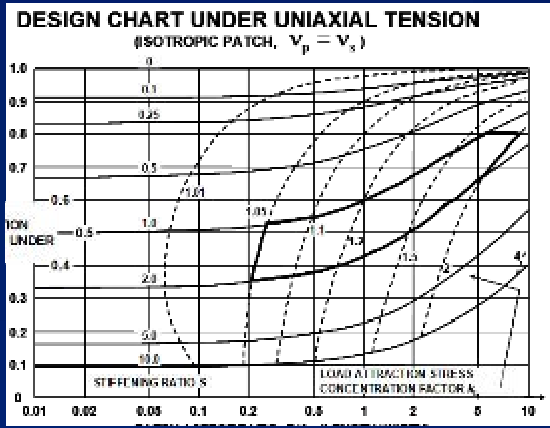
- Combat Damage – Caused by munitions/projectiles
  - Holes, section loss, spalls, gouges, cracks, tears
  - Buckles, cripples, disjoints and excessive deformation due to blast/overpressure
- Mishap Damage – Ground/Air Operations and or malfunctions
  - Contact With Ground Based Objects
  - Mid-air Collisions
  - Maintenance Accidents
- Other damages
  - Fire damage
  - Lightning Stike
  - High-g maneuvers

Picture Source: Lt Sarah Yankech, USAF Hill ABDRE Site Lead "Aircraft Battle Damage Repair Engineering (ABDRE) Program", 2024 JCAMS

ABDR General Structural Requirements

1. Ultimate load capability for an operating life of around 100 hours.
2. Rapid & simple repair technique, possible to implement at a forward operational base or in the field with the minimum of equipment and personnel.
3. The repair must be able to be designed using very simple analytical tools or charts
4. Materials used in the repair must have long storage lives at room temperature.
5. All repair equipment and materials must be easily transportable to the repair site





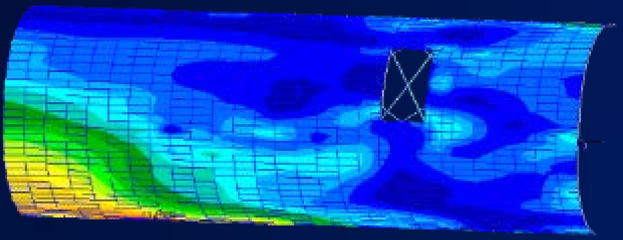
ABDR Repair Options

1. Bolted doublers: Metallic or Composite
2. Bonded doublers
   - Metallic + 250F Cure Film adhesive
   - Composite (e. g., Boron/Epoxy) + 250F film adhesive
   - Dry-fabric wet-layup
     - Precured + 2-part paste adhesive 150F cure
     - Bond-in-place under vacuum and room temperature cure
   - Bolted vs Bonded

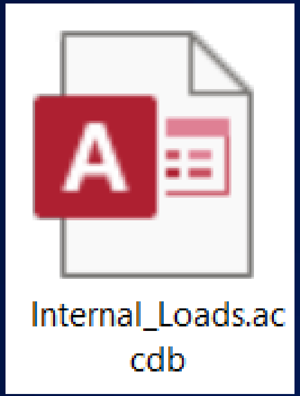
Bolted	Bonded
Less effective load transfer, lots of fasteners	More effective load transfer, single bondline
Require less skill	Require more skill, surface prep
Usually for low contour surface	More versatile especially when use composite patch

Where to Get Loads

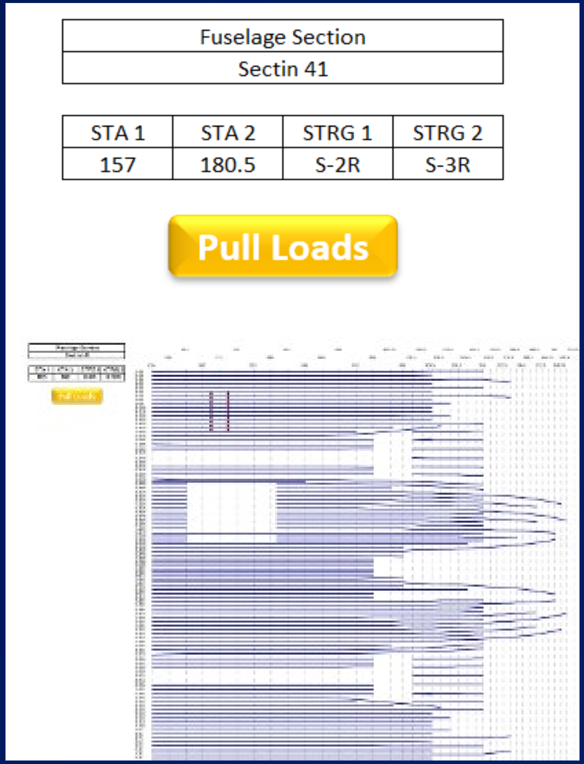
Method 1 – Query Loads Model / Database



Convert to Access Database



Pulled by Location

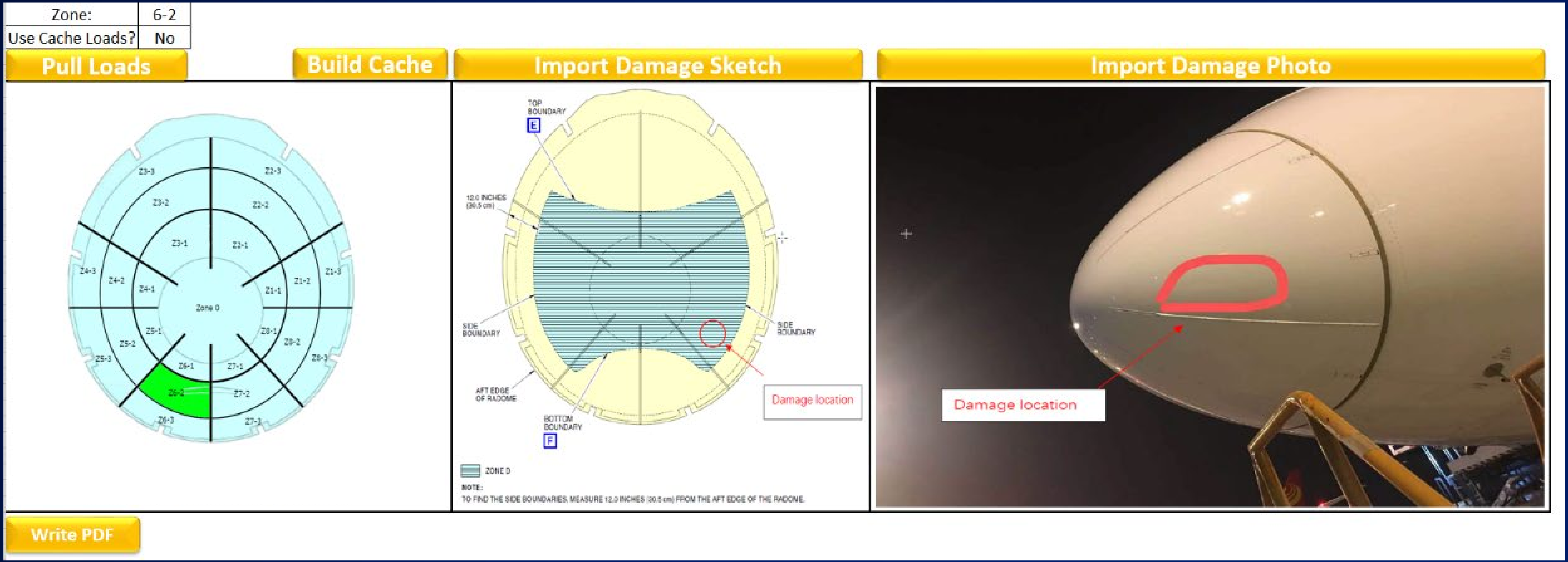


Loads_COUAD4:										
EID	LC	nx	ny	qxy	qxz	qyz	mx	my	mxy	
41002492	D726	1.506	-0.25	1.433	0	0	0	0	0	
41002492	I010	-0.794	0.185	-0.076	0	0	0	0	0	
41002492	P806	1.086	-0.021	1.84	0	0	0	0	0	
41002492	I007	-0.886	0.159	-0.076	0	0	0	0	0	
41002492	FR9C	-0.15	0.048	-0.433	0	0	0	0	0	
41002493	D726	1.482	-0.282	1.427	0	0	0	0	0	
41002493	I010	-0.765	0.213	-0.069	0	0	0	0	0	
41002493	P806	1.083	-0.023	1.842	0	0	0	0	0	MAX qxy
41002493	I007	-0.863	0.182	-0.073	0	0	0	0	0	
41002493	FR9C	-0.177	0.052	-0.477	0	0	0	0	0	MIN qxy
41002494	D726	1.45	-0.314	1.416	0	0	0	0	0	

Method 2 – Reverse Engineering

- <u>For Primary Structure:</u>
- Repair Design Ultimate Running Load = Notched Strain Allowable x Young's Modulus x Local Thickness
- <u>For Secondary Structure</u>
- Repair Design Ultimate Running Load = Unnotched Strain Allowable x Young's Modulus x Local Thickness
- DLL = DUL / 1.5

Where to Get Loads



Graphic Damage Location Input

Automated Loads

→

Rapid Analysis Template
ADL Impact Analysis

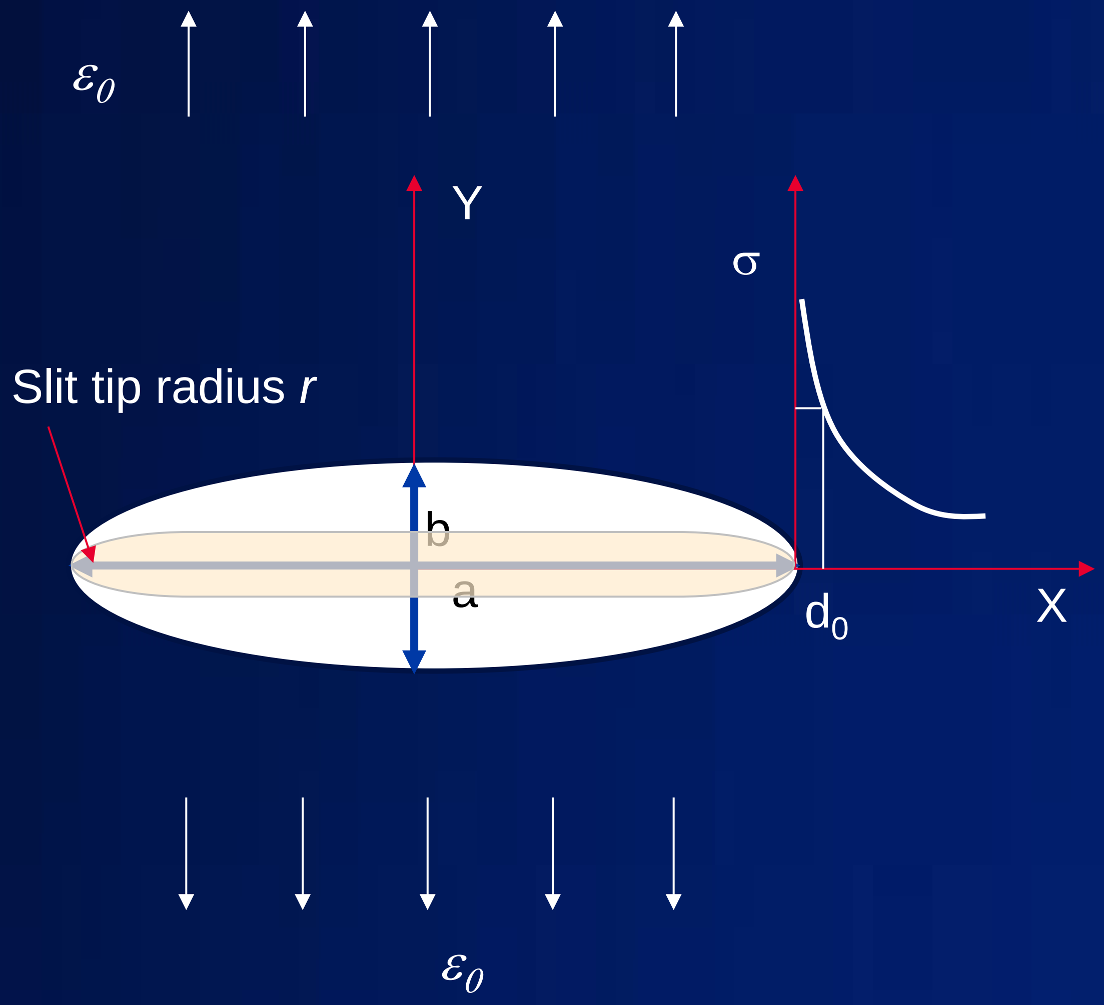
→

- ADL Impact Analysis Min Nx.csz
- ADL Impact Analysis Min Nx.pdf
- ADL Impact Analysis Min Ny.csz
- ADL Impact Analysis Min Ny.pdf
- ADL Impact Analysis.csz
- Rapid Radome Dent Analysis Tool v2_0.xlsm

Damage Assessment Tool

Holes and Slits

a



$$K_{d0} = \frac{1}{2} C_w \left\{ 2 + \left(\frac{a}{a+d_0}\right)^2 + 3\left(\frac{a}{a+d_0}\right)^4 - (K_T^\infty - 3)\left[5\left(\frac{a}{a+d_0}\right)^6 - 7\left(\frac{a}{a+d_0}\right)^8\right]\right\}$$

$$C_w = \left\{ \frac{3(1-2\,a/W)}{2+(1-2\,a/W)^3} + \frac{1}{2}\left(\frac{2a}{W}M\right)^6 (K_T^\infty - 3)\left[1 - \left(\frac{2a}{W}M\right)^2\right]\right\}^{-1}$$

$$M^2 = \frac{\sqrt{1 - 8\left[\frac{3(1-2a/W)}{2+(1-2a/W)^3} - 1\right]} - 1}{2(2a/W)^2}$$

$$K_T^\infty = 1 + \sqrt{2\left(\sqrt{\frac{E_x}{E_y}} - \nu_{xy}\right) + \frac{E_x}{G_{xy}}}\ \left(\frac{b}{a}\right)$$

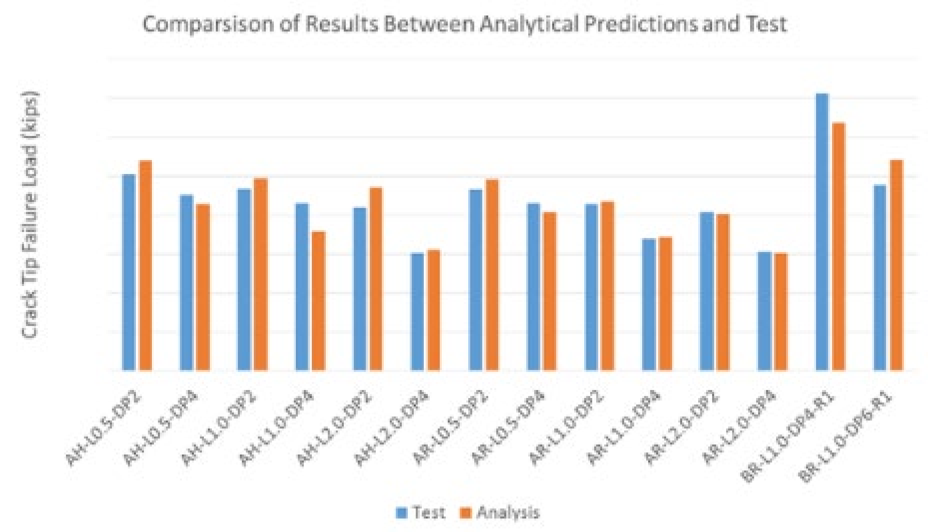
W = Part width

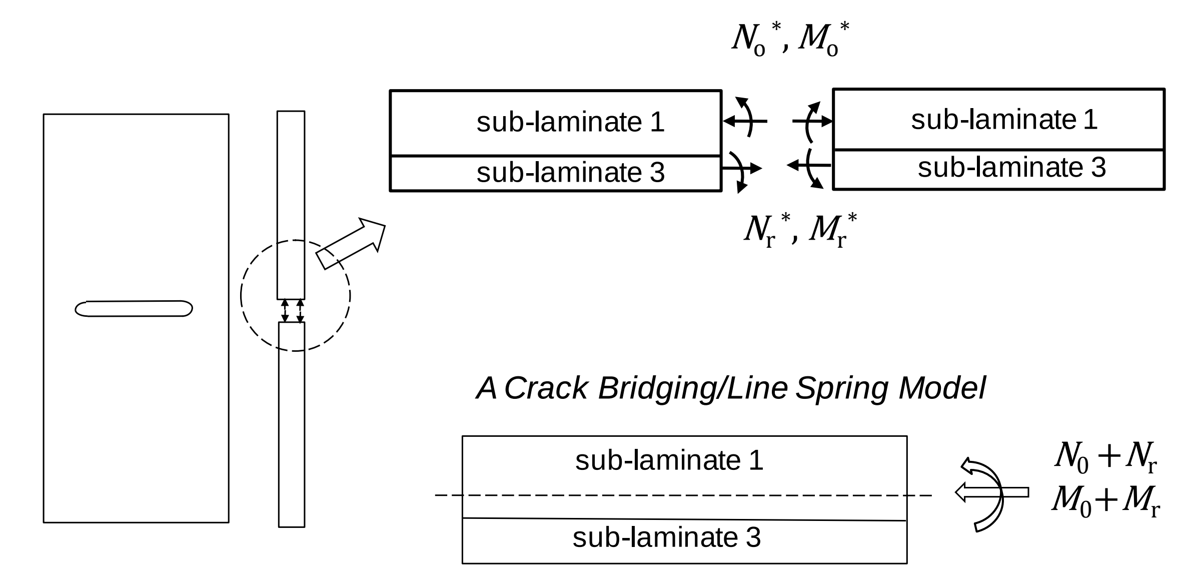
$a = 2r$ *when it is a slit*

$$MS = \left(\frac{\varepsilon_{allow}}{K_{d0}\varepsilon_0}\right) - 1$$

Damage Assessment Tool

Deep Surface Scratch & Gouge





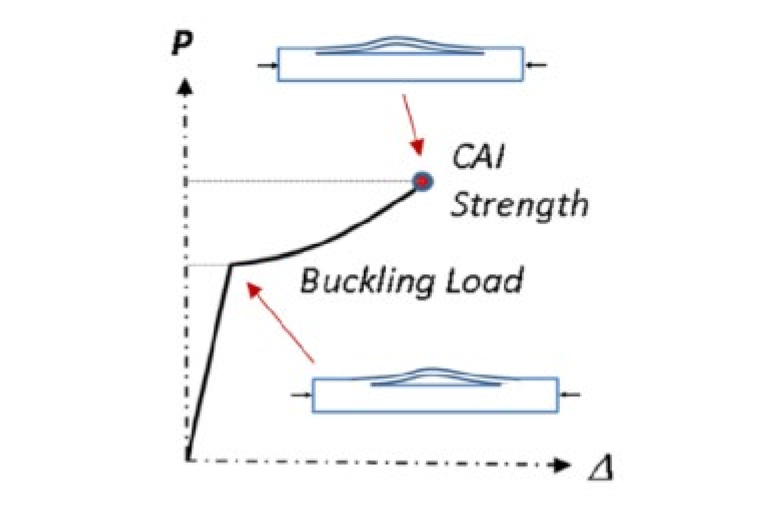
- Calculate energy release rates
- Calculate stress intensity factor at the crack tip using linear elastic fracture mechanics

$$K_I = K_{Ic}$$

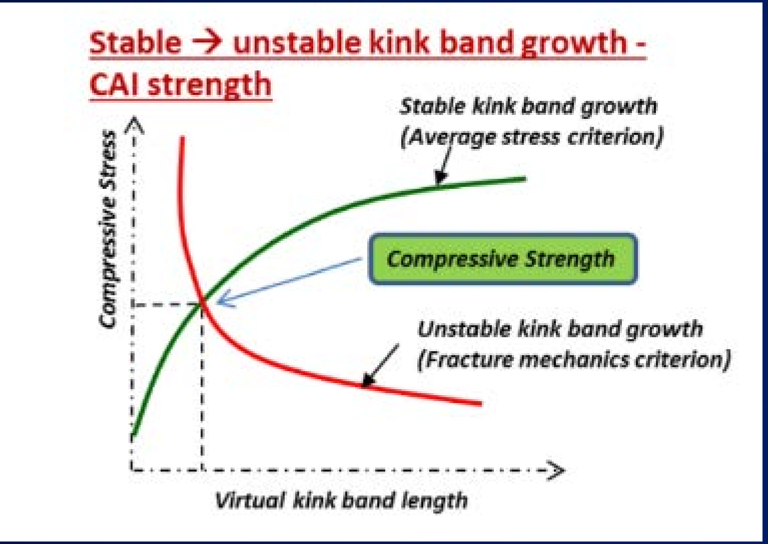
$$K_{Ic} = Laminate\ fracture\ toughness$$

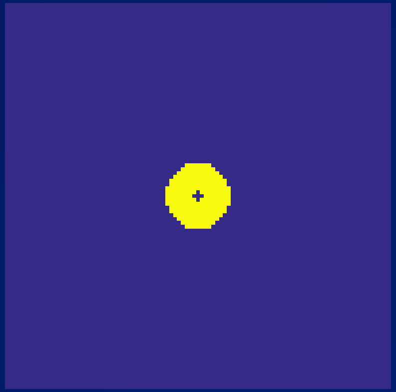
Damage Assessment Tool

Delamination –Compression After Impact Strength Tool (CAIST) (developed under NASA-ACC)

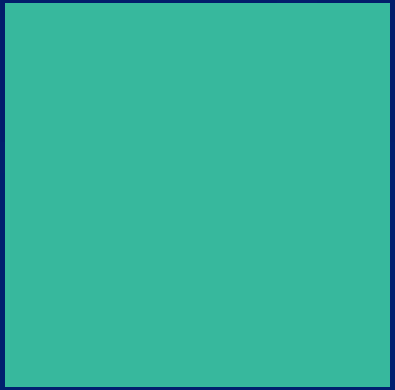


Predicted Impact Damage Size (Inch)	Predicted CAI Failure Strain	Test Result (Damage Size, Inch)	Test Result (CAI Failure Strain)
0.84	6.71E-03	1.1	6.75E-3

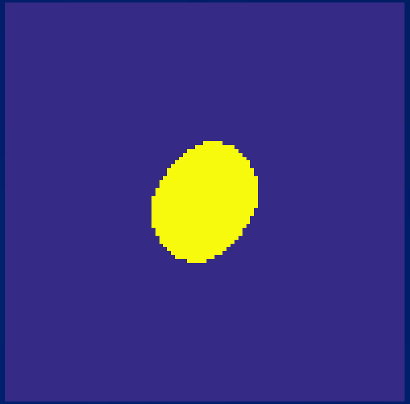




ILS Damage
Predicted size = 0.84”

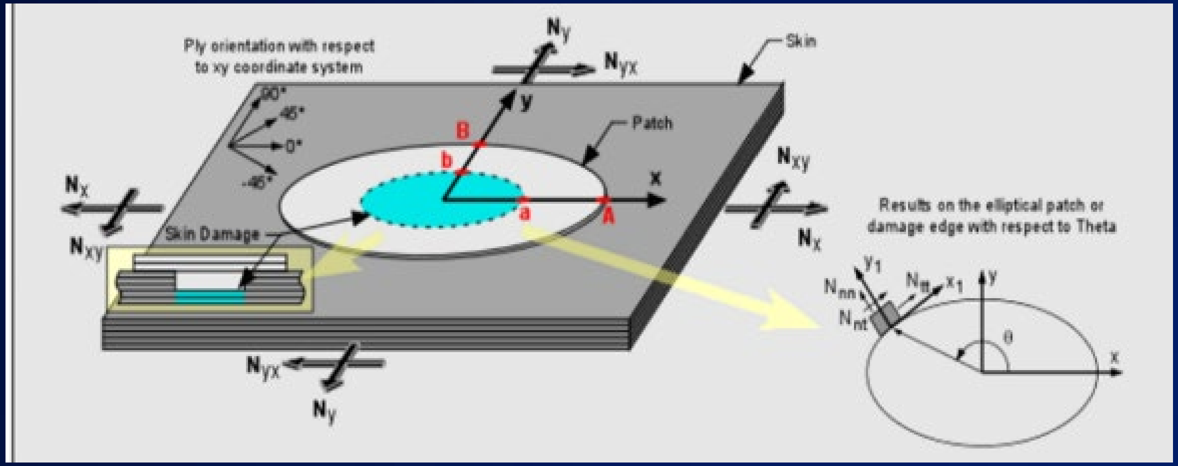


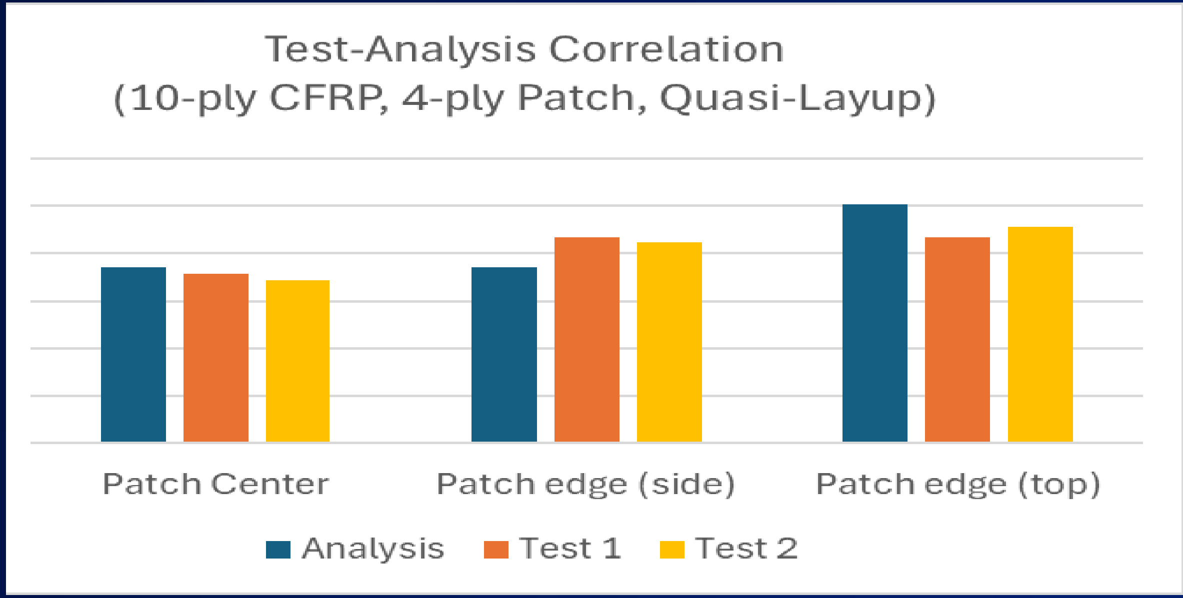
In-plane Fiber Damage
Predicted: None

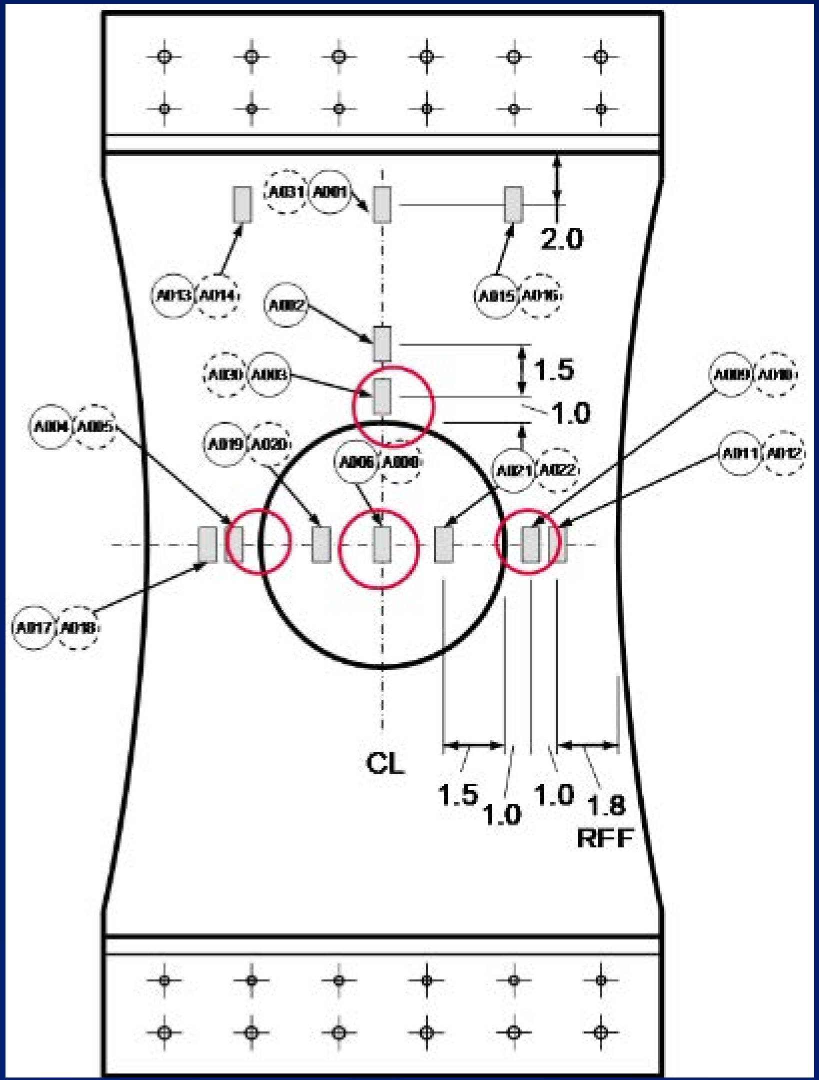


In-plane
Matrix Damage

Bonded Doubler Repair Analysis

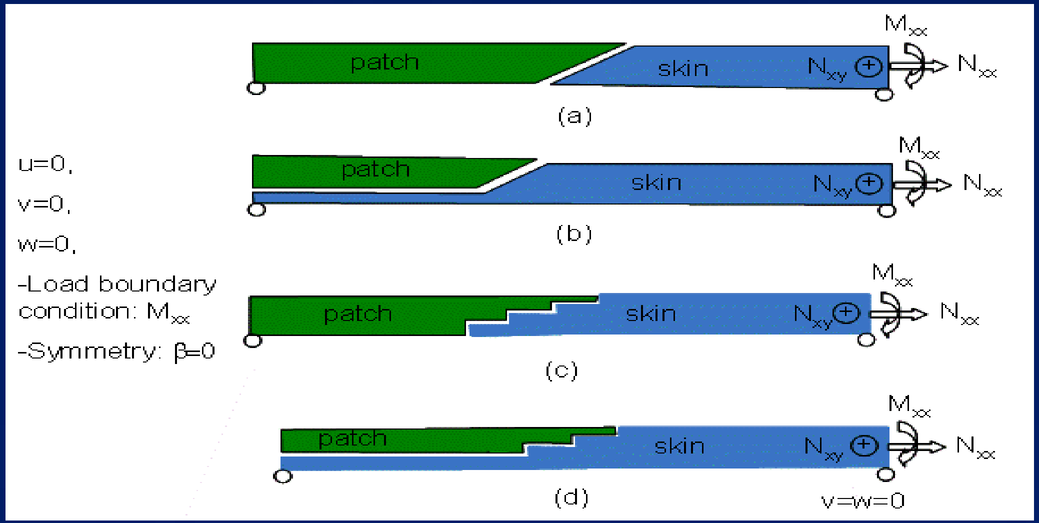


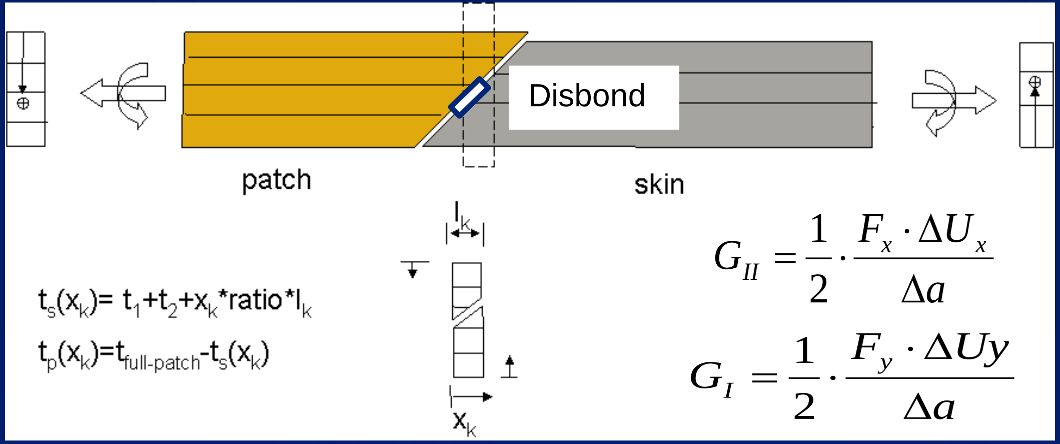




Scarf Joint Method (SJM)

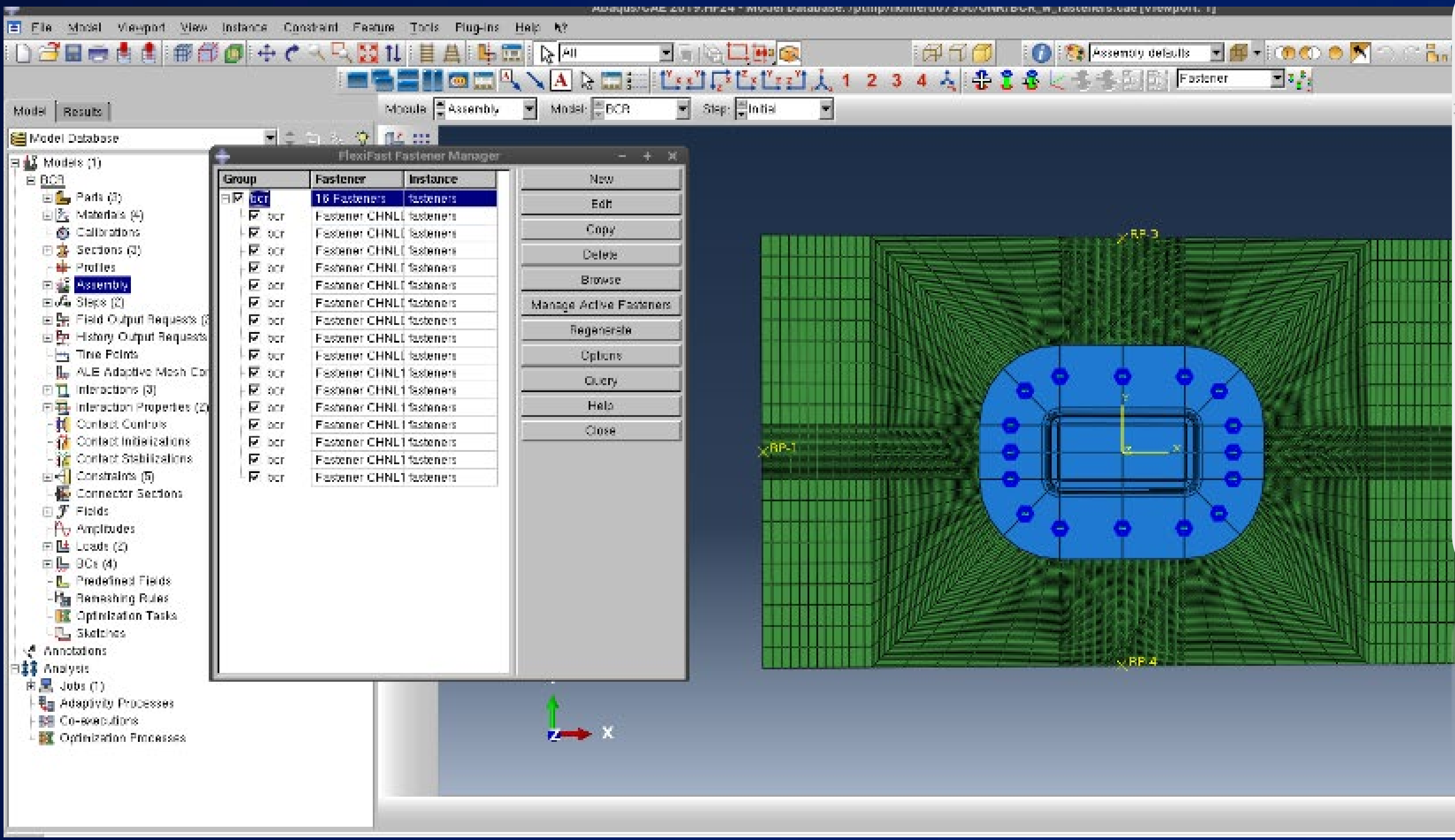
- Category: Closed-Form
- Application: Bondline analysis (strength and damage tolerance) of a **scarf** or **multiple step joint/repair**
- New capabilities:
  - Peel and shear ***Coupling*** (beyond A4EI capabilities)
  - ***Disbond/delamination*** (beyond VCTeM capabilities)
  - Non-matching patch/parent material or thickness



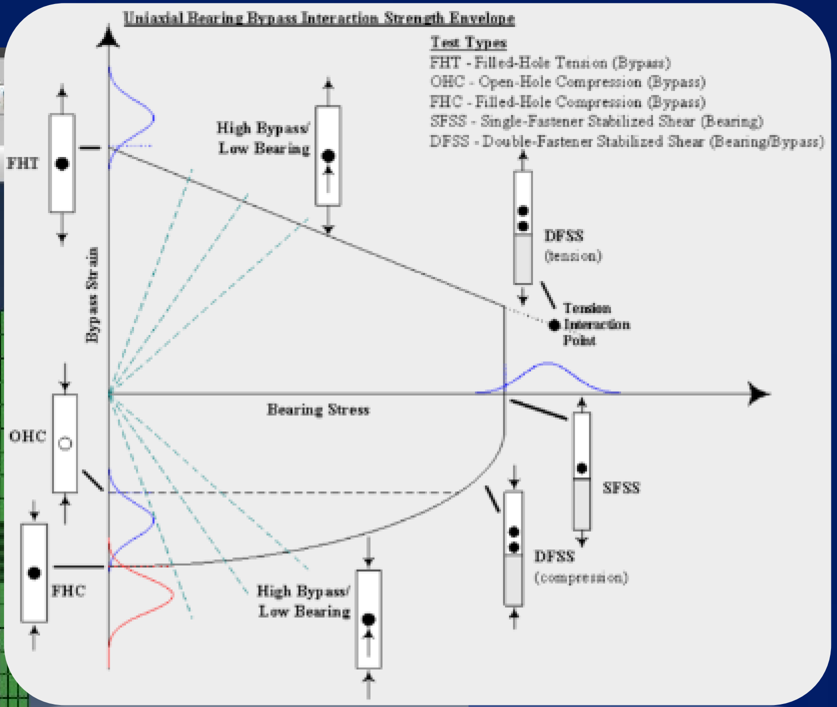


Bolted Doubler Example –

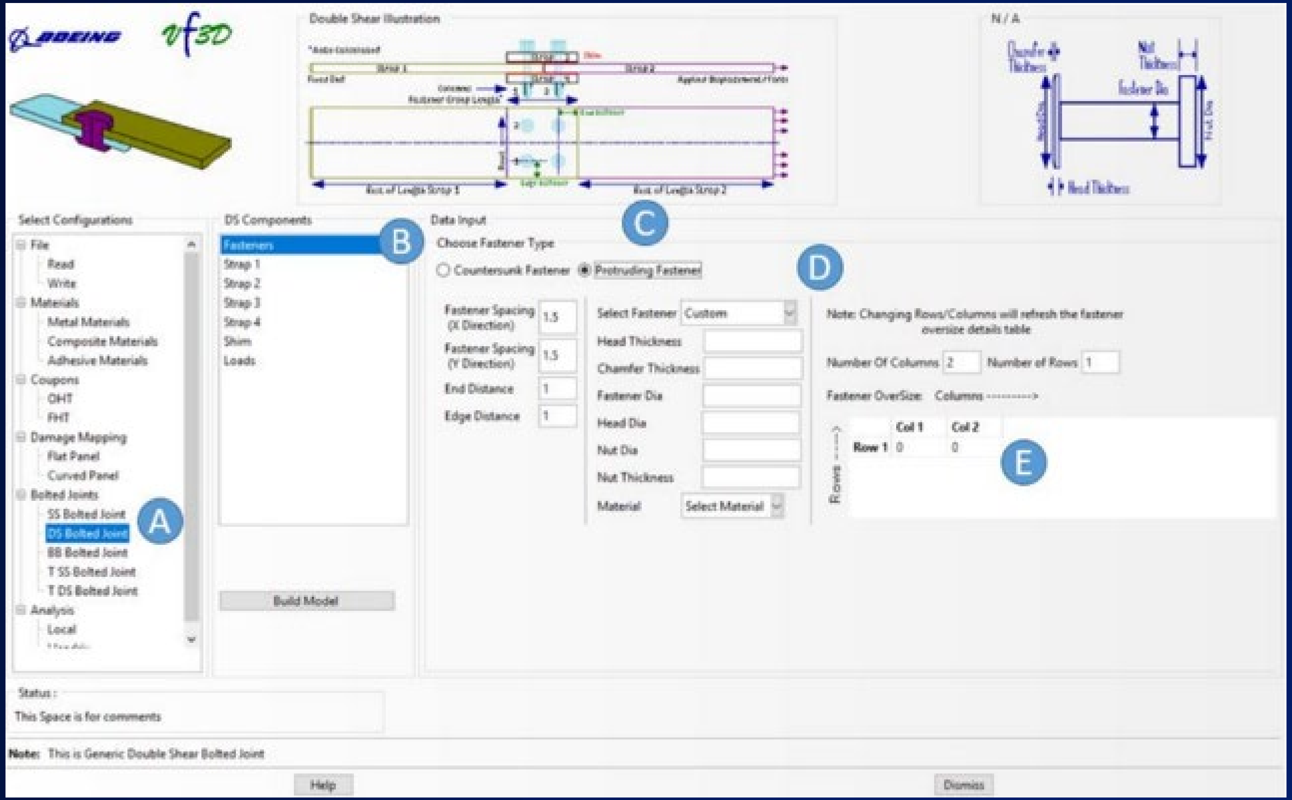
Automated fastener modeling, analysis and bearing bypass loads extraction and margin calculation

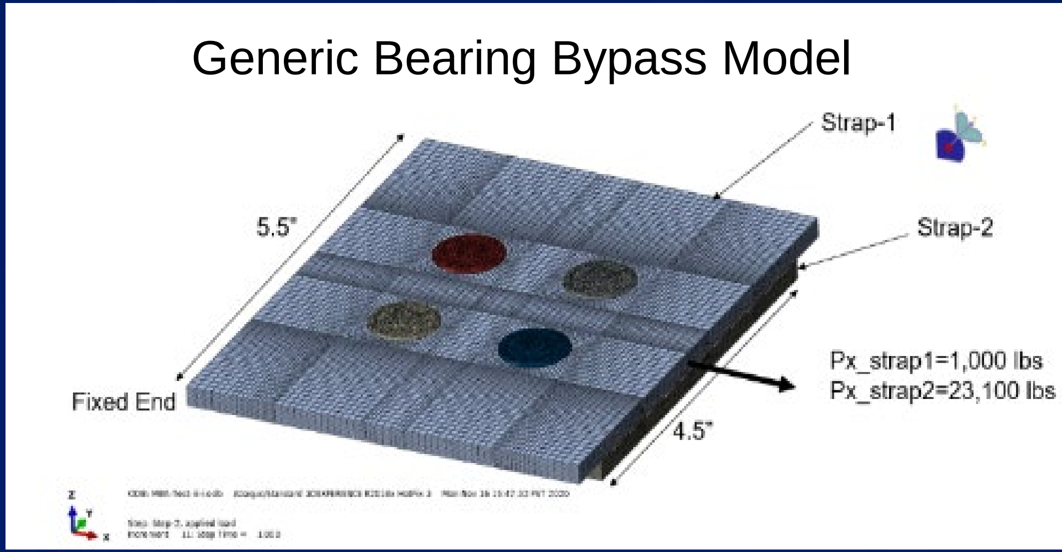


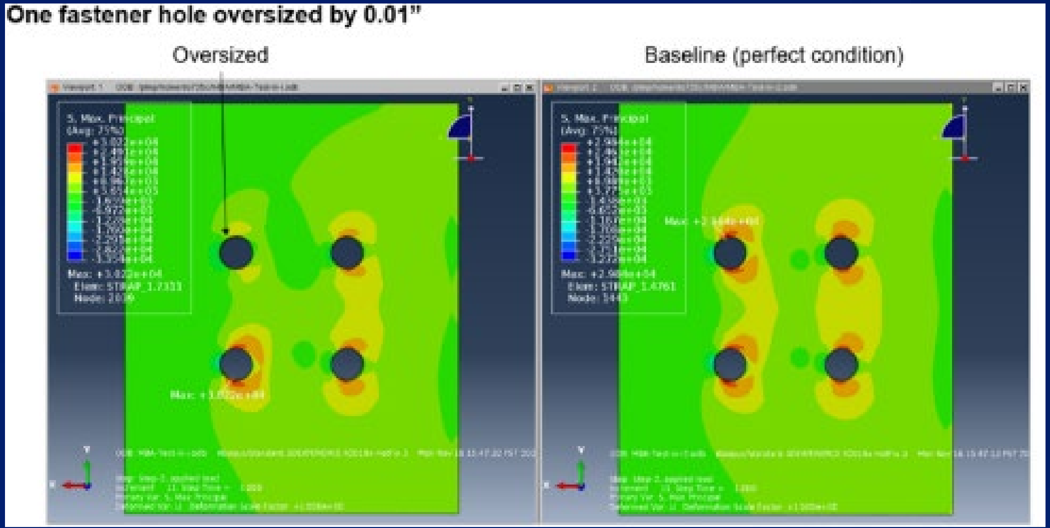
Generic Bearing Bypass Envelope



Fully Parameterized Bolted Joint Model – *Vari-Fast3D*

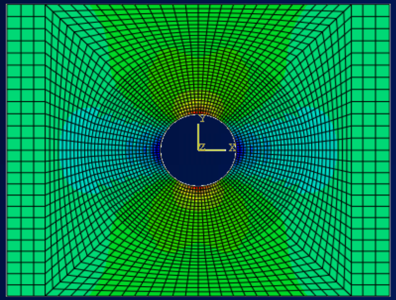


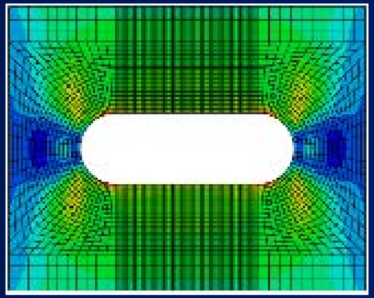


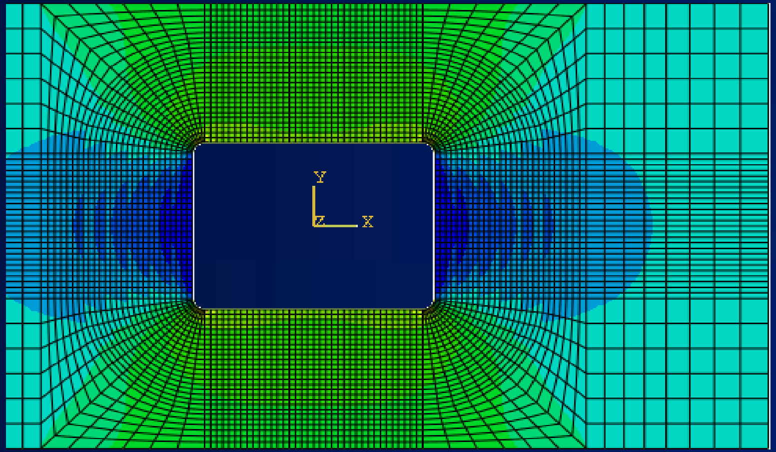


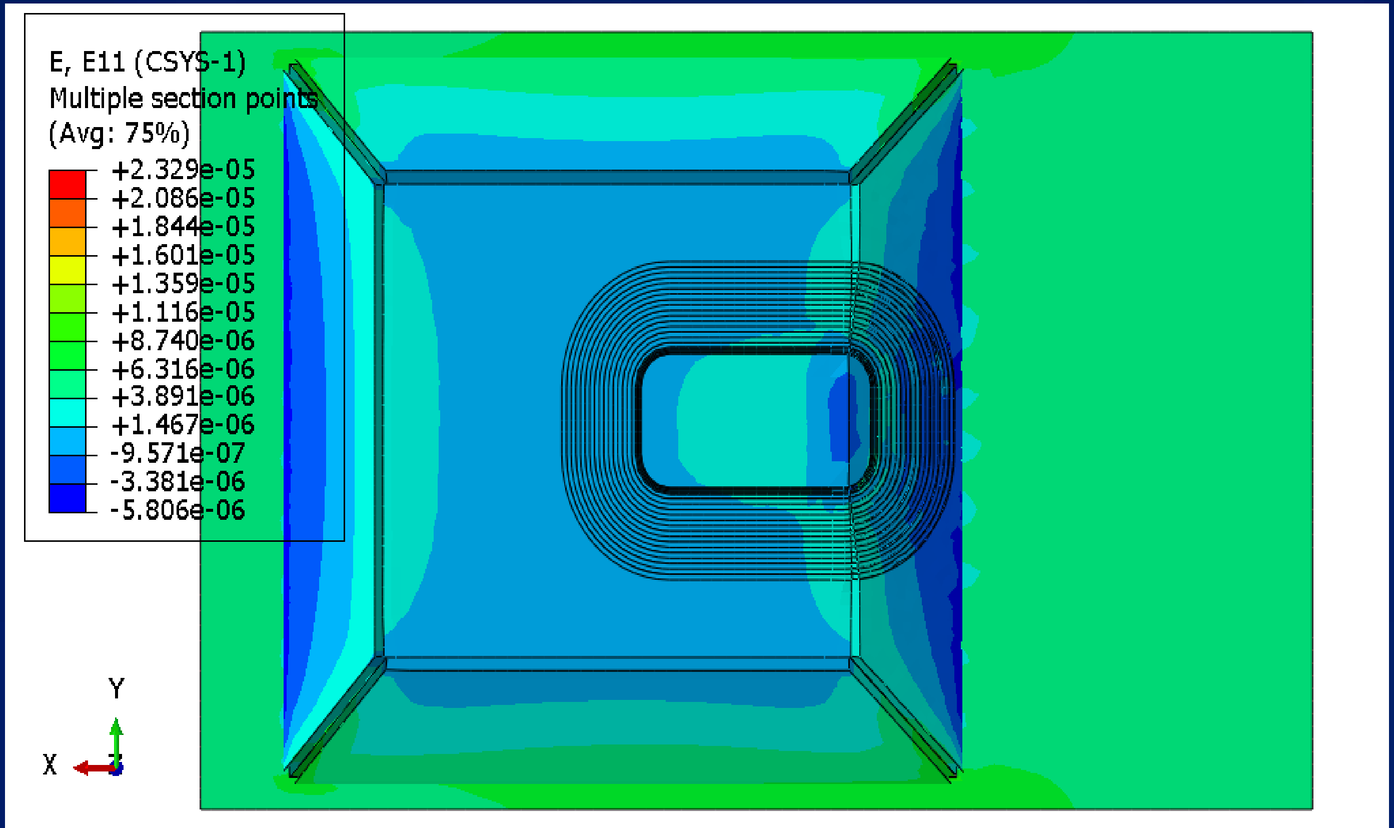
A. Joint Configuration (SS, DS, Tapered Joint, generic bearing bypass)
B. Joint Component Definition (two straps + shim)
C. Fastener Library/Custom (Protruding Head, Counter-sink)
D. Fastener Pattern (up to 4 x 4 array)
E. Oversizing (Pre-load included, specifiable hole/fastener)

Automated FEA for Trim-outs when patches fell off



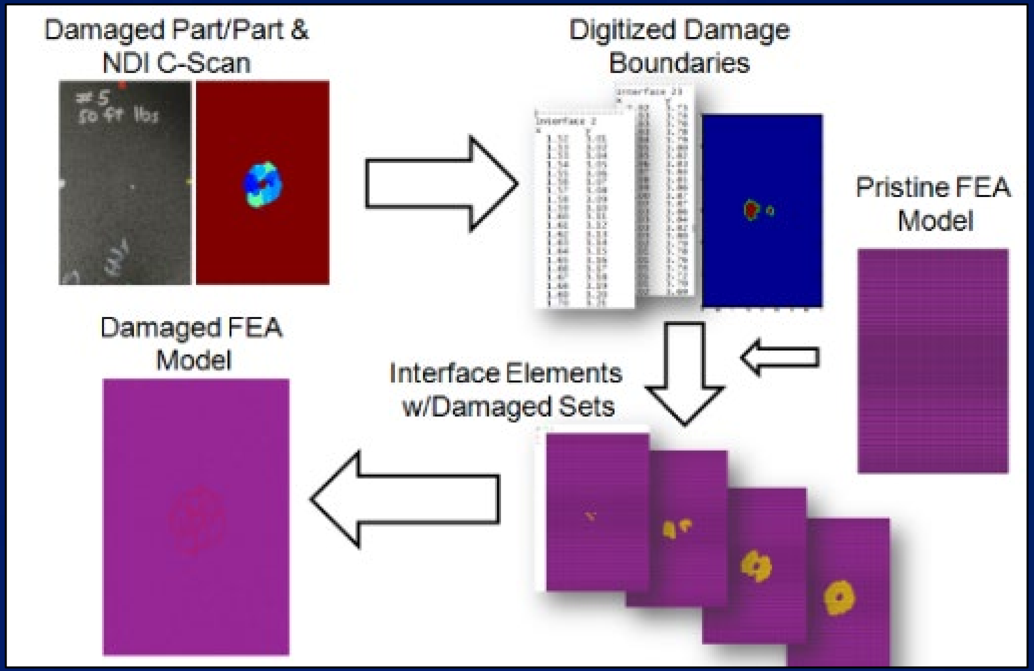


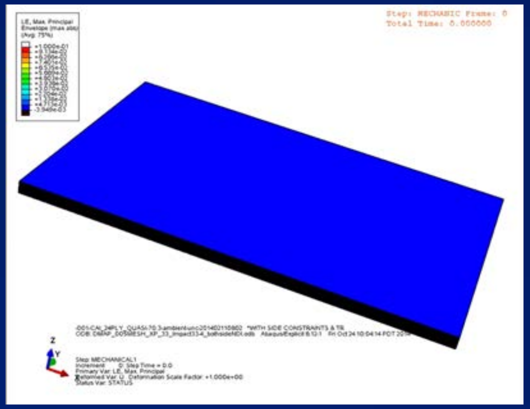




Damage Mapping Technique

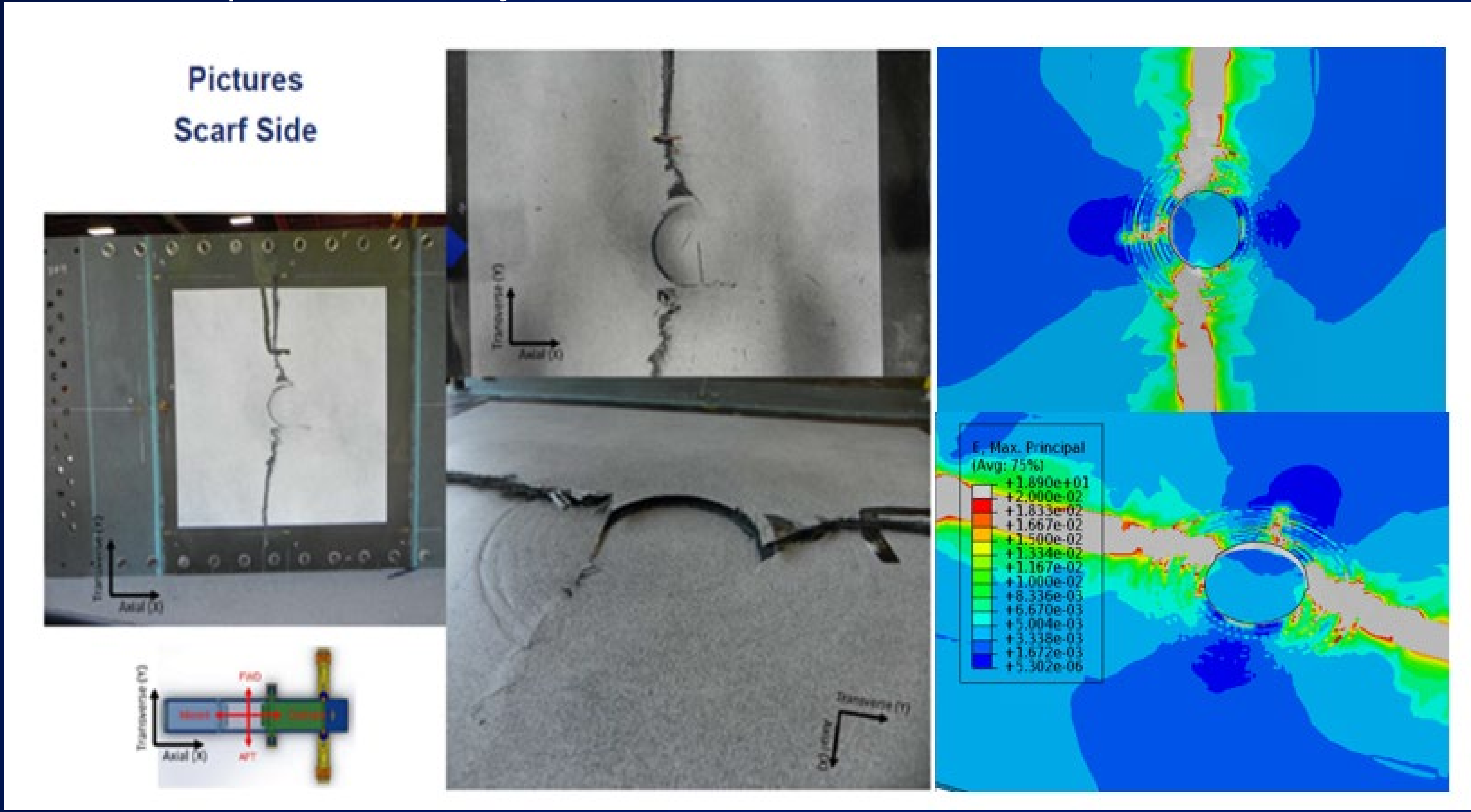
- Customer/Need
  - Reduce testing cost for barely visible impact damage (BVID)
- Outcome
  - Innovative solution combining real NDI data and FEM-based progressive failure analysis (PFA). Patent pending.
  - Damage mapping tool integrated with parametric FEA tool
  - Validated by Compression After Impact (CAI) tests
- Impact
  - Enable condition-based, in-situ damage assessment
  - Enable "Smart Testing" with reduced cost



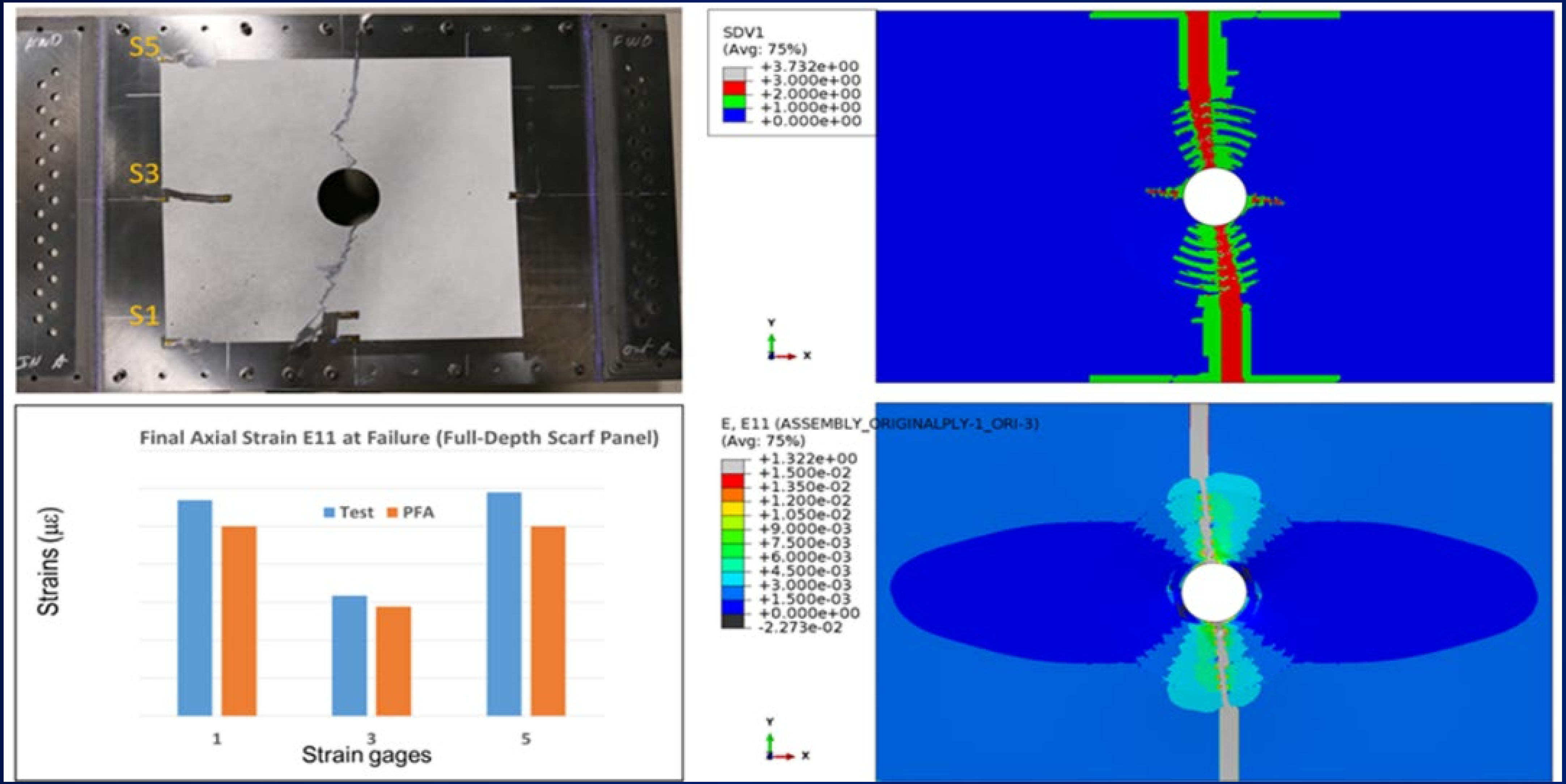


Animation

Double-Sided Repair Fail-Safety – Thermoset CFRP



Single-sided Full-Depth Scarf Repair



Summary

- ABDR requires simple & rapid repair design and analysis
- A full suite of rapid-executing analysis tools have been developed and validated:
  - Loads query
  - Damage disposition
  - Bonded Repair
  - Bolted Repair
  - Repair Fail-Safety