4TH INTERNATIONAL CONFERENCE
OF COMPOSITES TESTING & MODEL IDENTIFICATION
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FRACTURE ANALYSIS FOR BONDLINES AND INTERFACES OF COMPOSITE STRUCTURES

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The Boeing Company

Presentation Format

- → Introduction
- Static 2D interface element
- Static 3D interface element
- Interlaminar fatigue element
- Calibration testing
- Summary

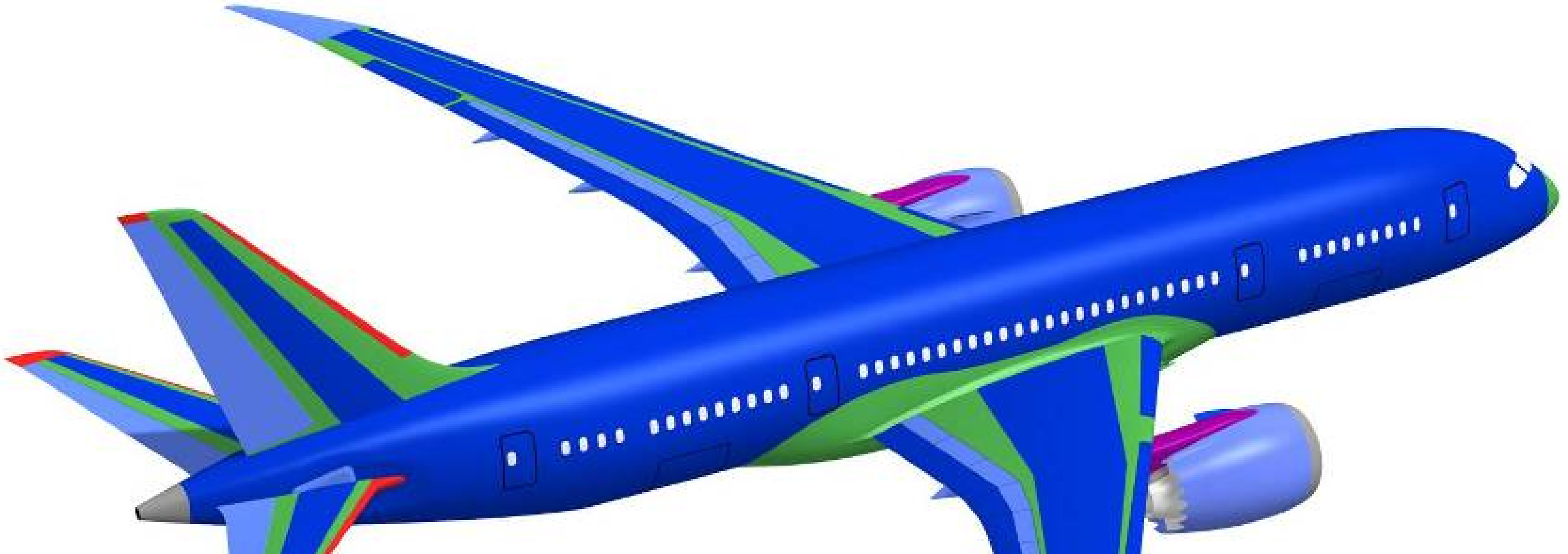
Problem Statement

- To reduce the cost of laminated composite structures, large integrated bonded structures are being considered
  - In primary structures, bondlines and interfaces between plies are required to carry interlaminar loads
  - Damage tolerance requirements dictate that bondlines and interfaces carry required loads with damage

Solution Path

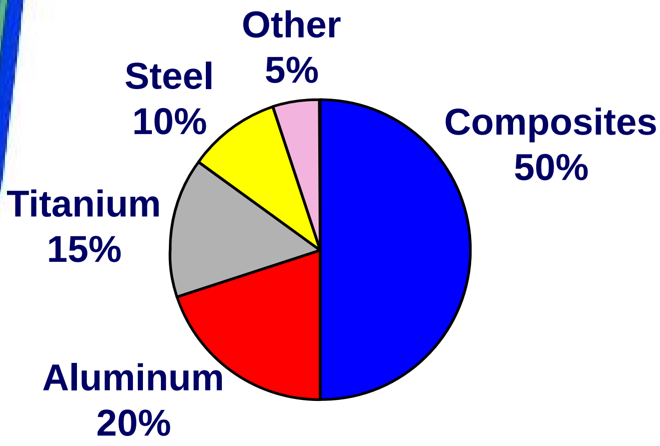
- Apply Linear Elastic Fracture Mechanics (LEFM) to bondlines and interfaces
  - 2D and 3D delaminations
  - Propagation
  - Mode separation
  - Multiple cracks
  - Non-linear behavior (e.g. postbuckling)
  - Composite structure
  - Practical (CPU time, minimum set of models)
  - Static and dynamic solution applicability

Boeing 787
Composites Serve as Primary Structural Material



Boeing 787

- 🟦 **Carbon laminate**
- 🟦 **Carbon sandwich**
- 🟩 **Other composites**
- 🟥 **Aluminum**
- ▨ **Titanium**
- 🟪 **Titanium/steel/aluminum**



787 Section 41

787 Section 43

Completing Drill & Trim

787 Sections 47/48

787 Section 41

Fatigue Test Airplane Component

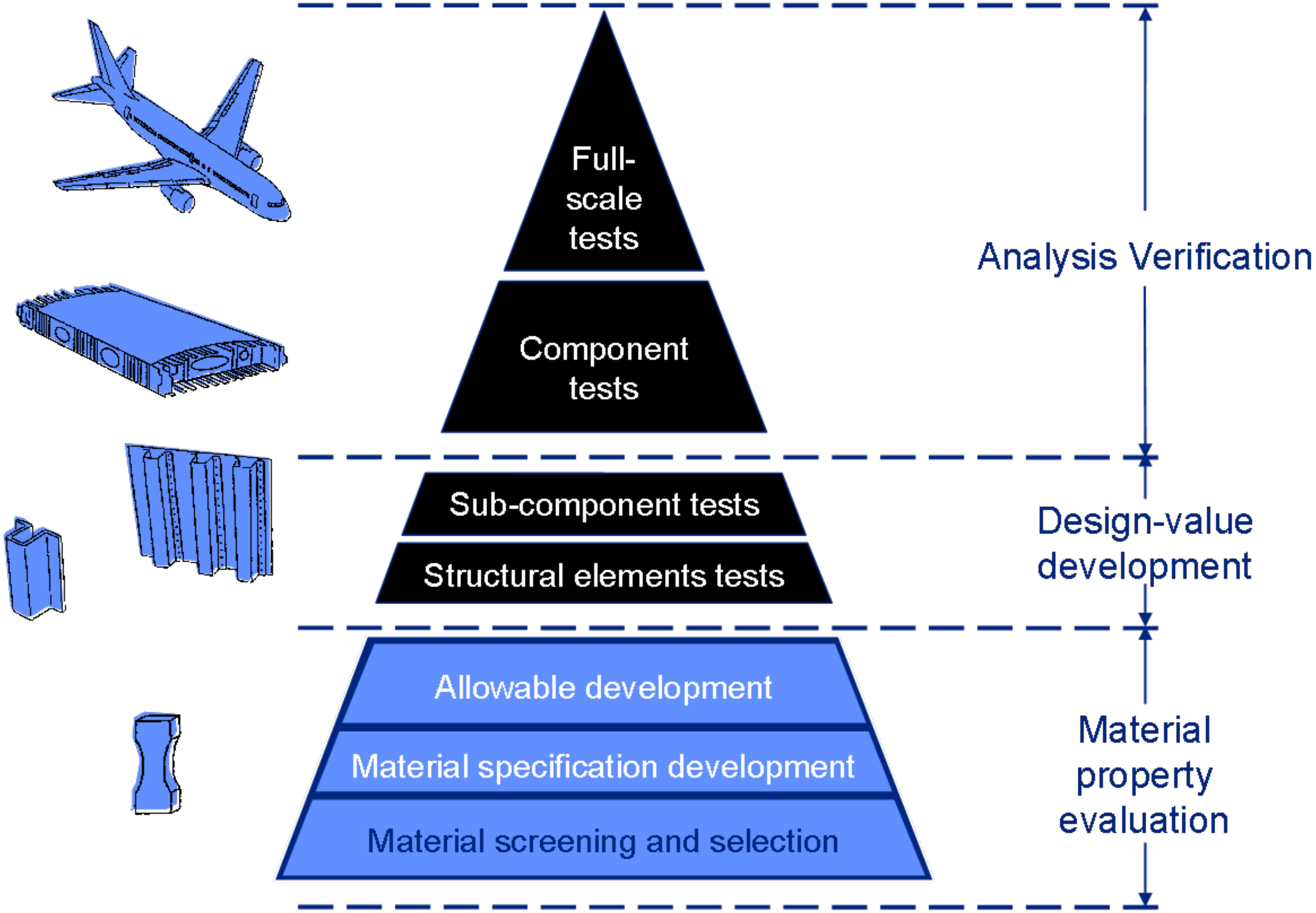
787 Final Assembly

Wing

Wing-to-Body Join

Structural Analysis and Certification Approach

Certified by analysis, supported by test evidence



Full-scale tests

Component tests

Sub-component tests

Structural elements tests

Allowable development

Material specification development

Material screening and selection

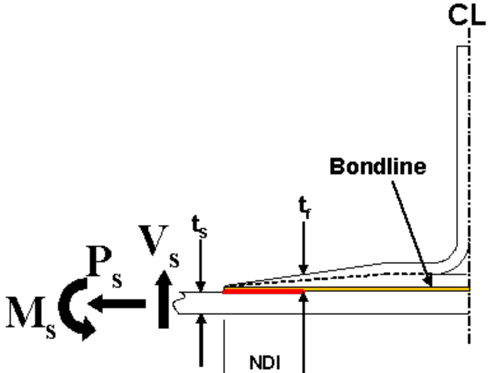
Analysis Verification

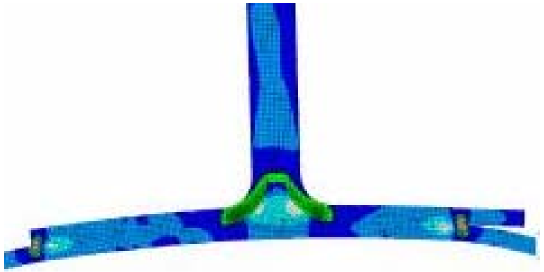
Design-value development

Material property evaluation

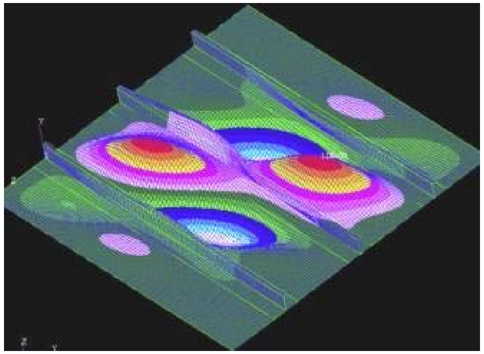
Advances in Analysis Methods Applied to 787

- Extensive use of bonded structures in applications with out of plane loading (pressure, postbuckling)
  - Direct use of interlaminar fracture mechanics for bond lines and interfaces



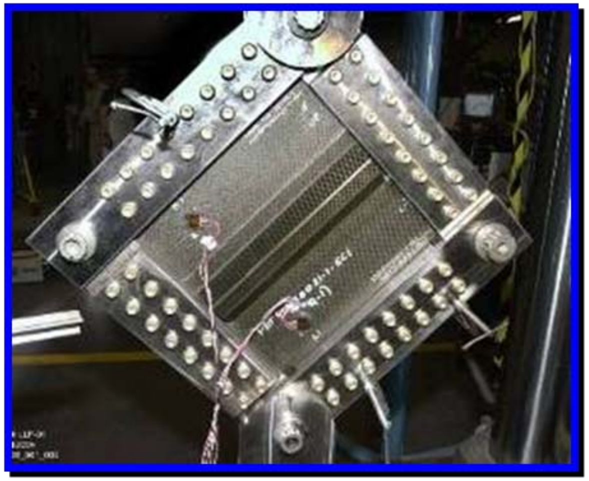


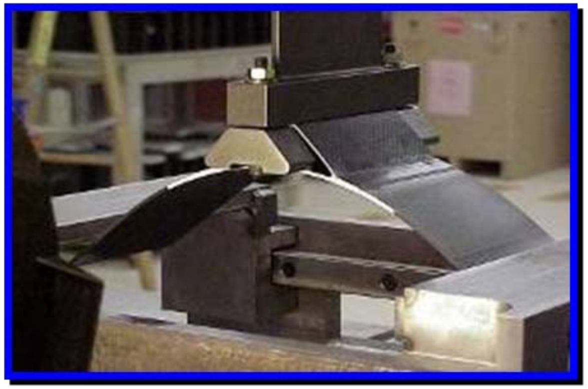
- Extensive use of non linear finite element analysis in preliminary and detailed design



Structural Test

Skin and Stringer Elements





Post Buckling

Visible Impact Damage

Compression

Large Damage

- Tension
- Compression

Shear

Freeze-Thaw

Large Notch Y-Factor

Tension

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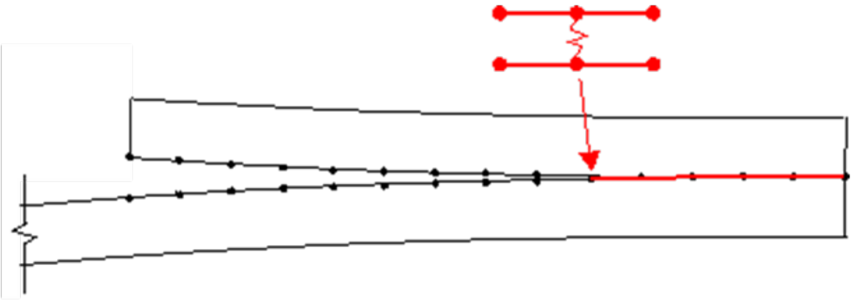
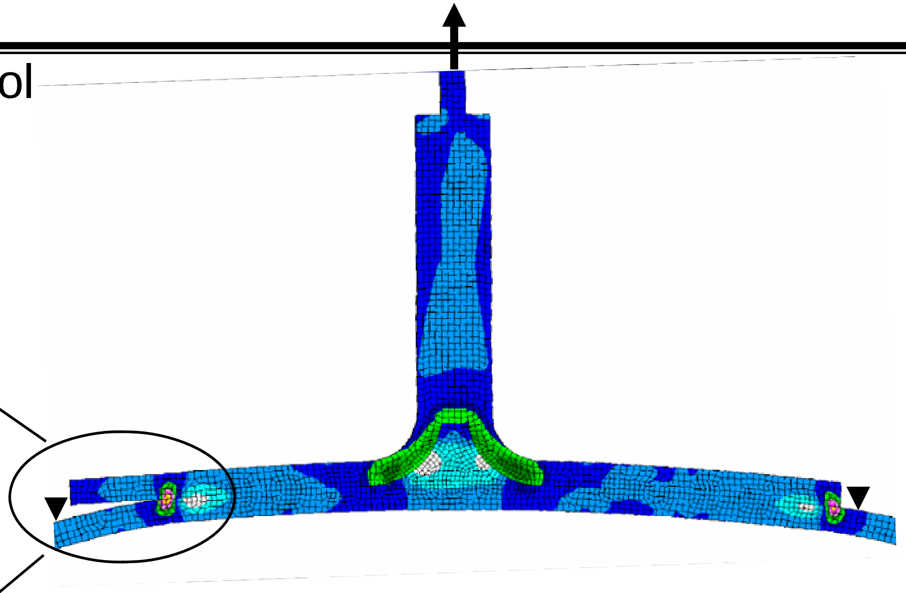
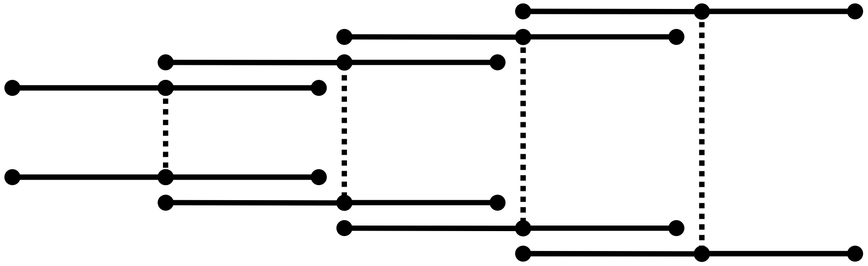
2D Interface Element Usage

Fracture mechanics interface elements control growth of delamination into new material





Interface elements located along plane of delamination

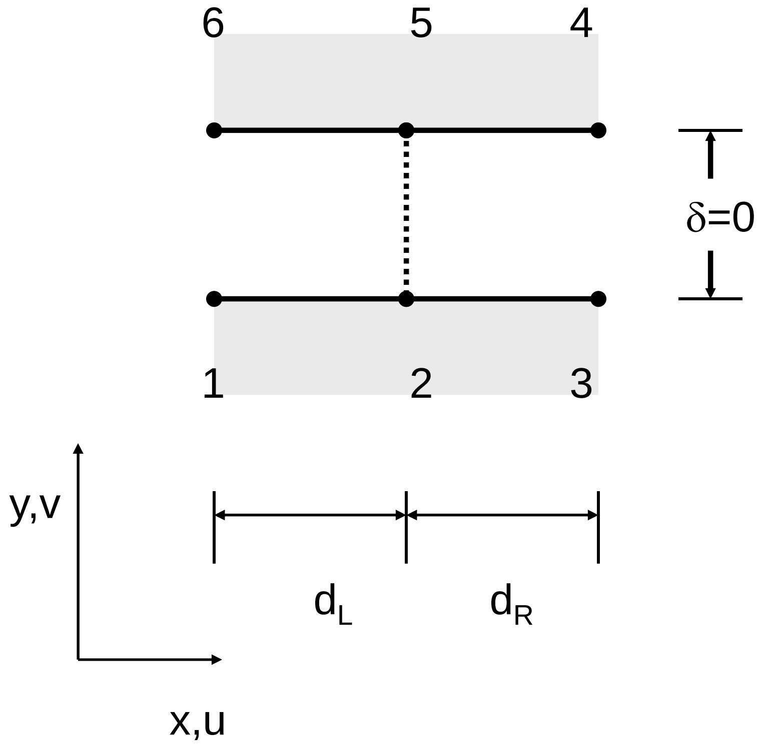


By using a series of overlapping interface elements, delaminations can be propagated along a path in either direction.

Direction of propagation is not pre specified.

Patent pending

Interface Element for Mixed Mode Fracture Analysis



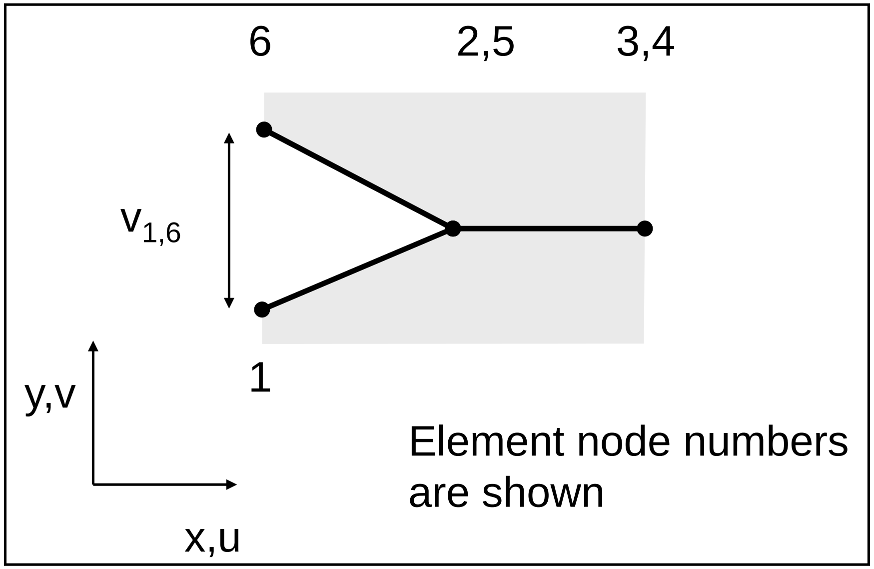
Element node numbers
are shown

- Nodes 2 and 5 are initially bound together (stiffness is virtually infinite)
- Stiffness between all other nodes is zero
- Antennae node pairs 1,6 and 3,4 sense approaching crack, provide displacement and area in VCCT calculation.
- Constrained node pair 2,5 provide force in VCCT calculation, initiate release and follow strain softening law based on fracture energy calculation.

Patent pending

Modified Virtual Crack Closure (VCCT) Implementation

For Pure Mode I



Element node numbers are shown

Nodes 2 and 5 will start to release when :

$$\frac{1}{2}\frac{v_{1,6}F_{v,2,5}d_R}{bd_L^2} = G_I \geq G_{IC}$$

where

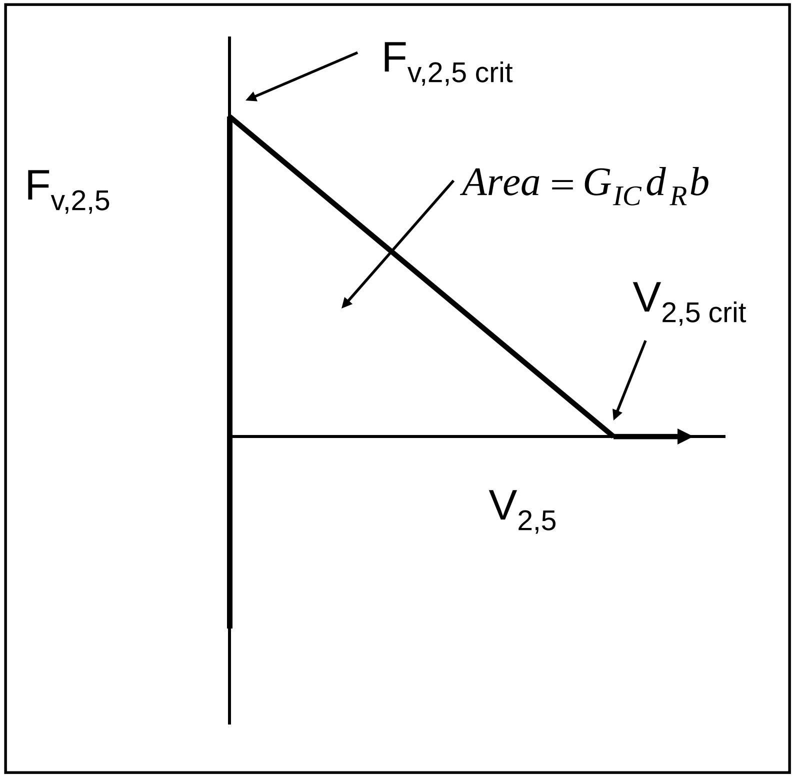
G_I = mode I energy release rate

G_{IC} = Critical mode I energy release rate

b = width

$F_{v,2,5}$ = Vertical force between nodes 2 and 5

$v_{1,6}$ = Vertical displacement between nodes 1 and 6

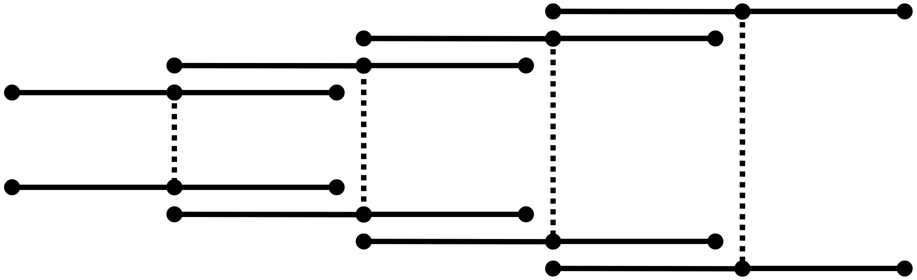


Mode II treated similarly

Patent pending

2D Interlaminar Fracture Elements - Propagation

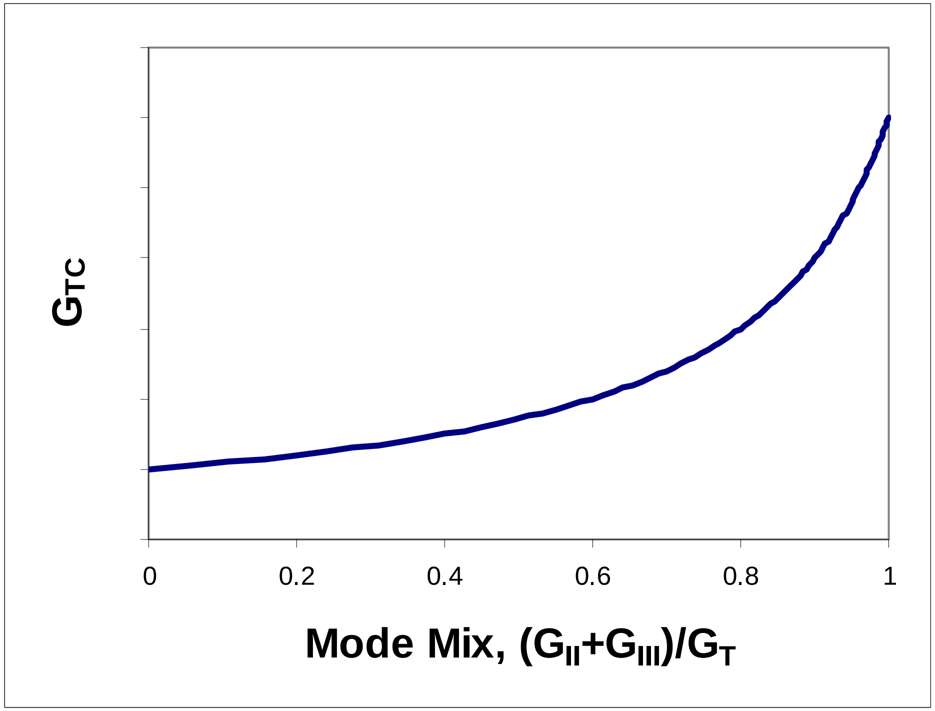
By using a series of interface elements, delaminations can be propagated along a plane in either direction.



Patent pending

Mixed Mode Fracture Criteria

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n + \left(\frac{G_{III}}{G_{IIIC}}\right)^p \geq 1, \text{ for crack propagation}$$



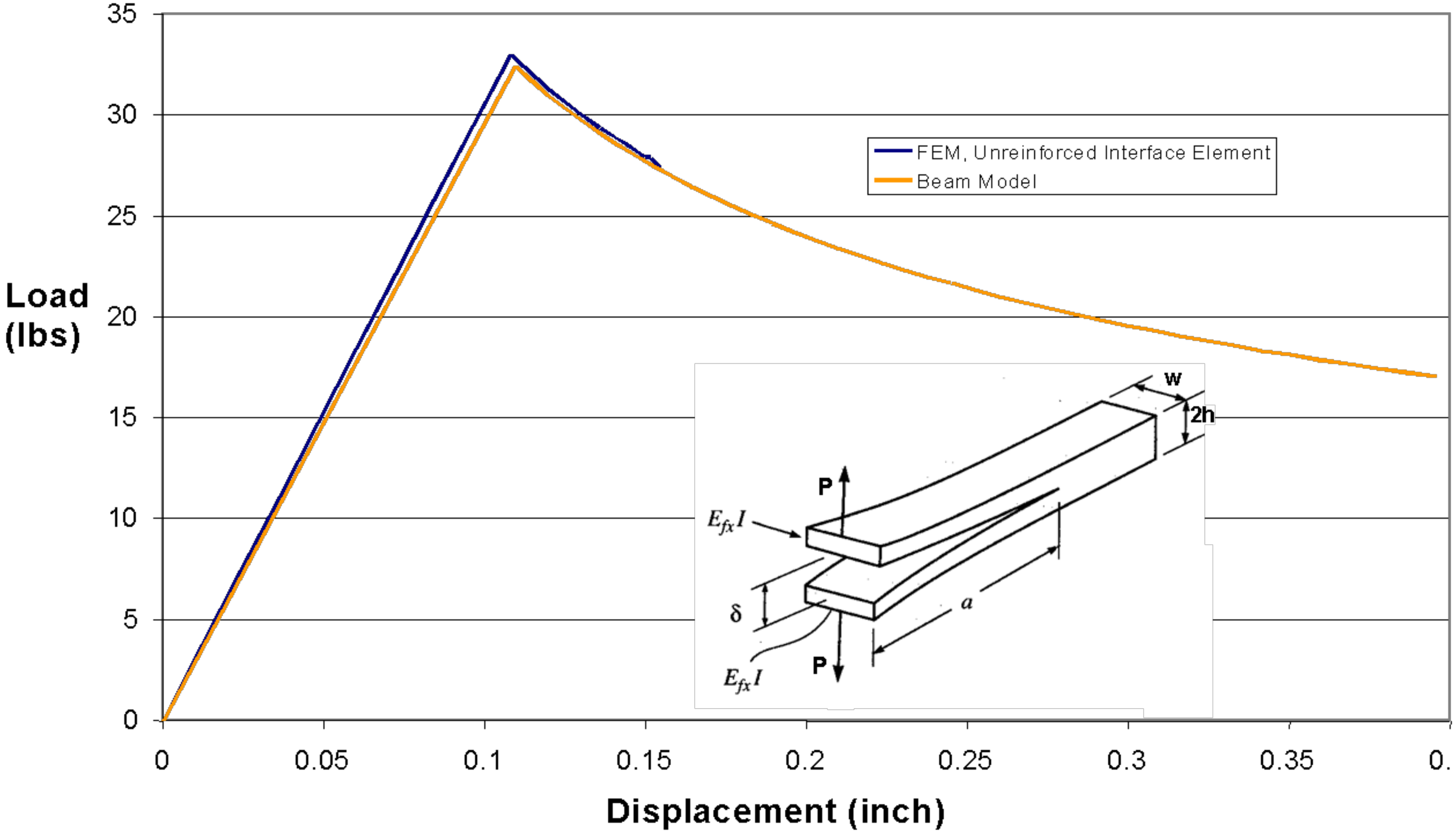
user specified parameters: $m, n, p, G_{IC}, G_{IIC}, G_{IIIC}$

Other mode mix equation forms have been easily incorporated

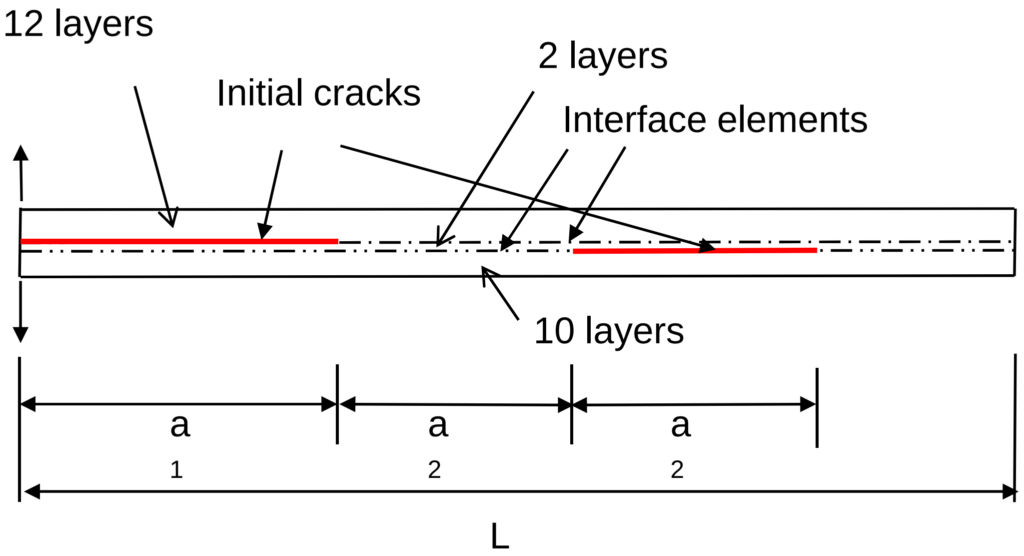
Fracture Interface Element Advantages

- Initiation of node release based on fracture
  - Unlike cohesive failure models
- Relatively mesh size independent
  - Unlike direct techniques based on local displacement or stress fields
- Intermediate crack tip location
  - Typically not available when VCCT applied manually
- Mode separation
- Remeshing not necessary
  - Assumed crack interface, not crack direction

Double Cantilever Beam (DCB) Analysis Comparison



Non-Symmetric Multi-Delamination Analysis



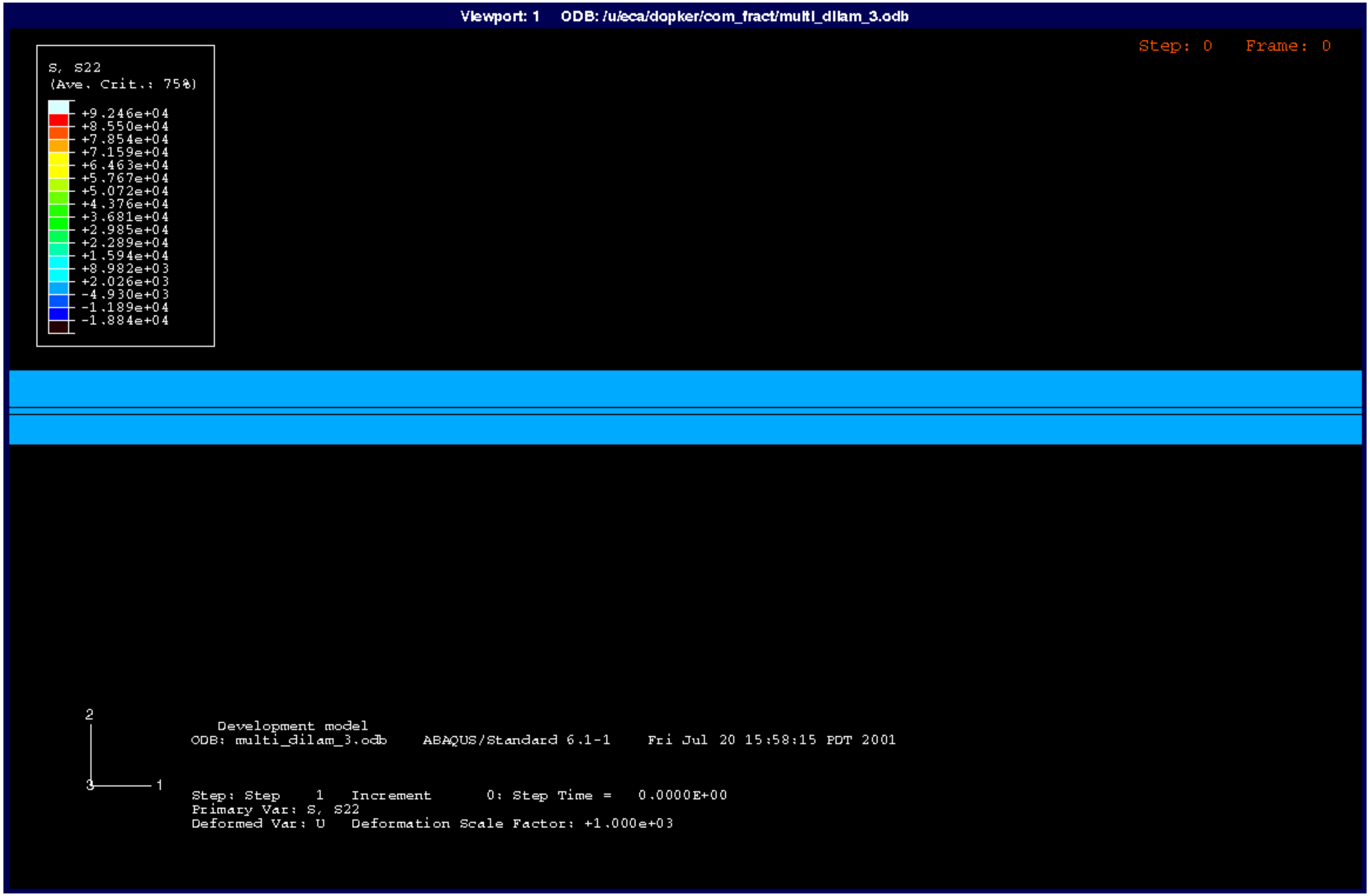
E_{11} = 115.0 GPa
E_{22} = 8.5 GPa
E_{33} = 8.5 GPa
G_{12} = 4.5 Gpa
ν_{12} = 0.29
ν_{13} = 0.29
ν_{23} = 0.3

G_{c1} = 0.33 N/mm
G_{c2} = 0.80 N/mm

L = 100 mm
a_1 = 40 mm
a_2 = 40 mm
width = 20 mm
Layer thickness=0.1325 mm

From Alfano and Crisfield 2001

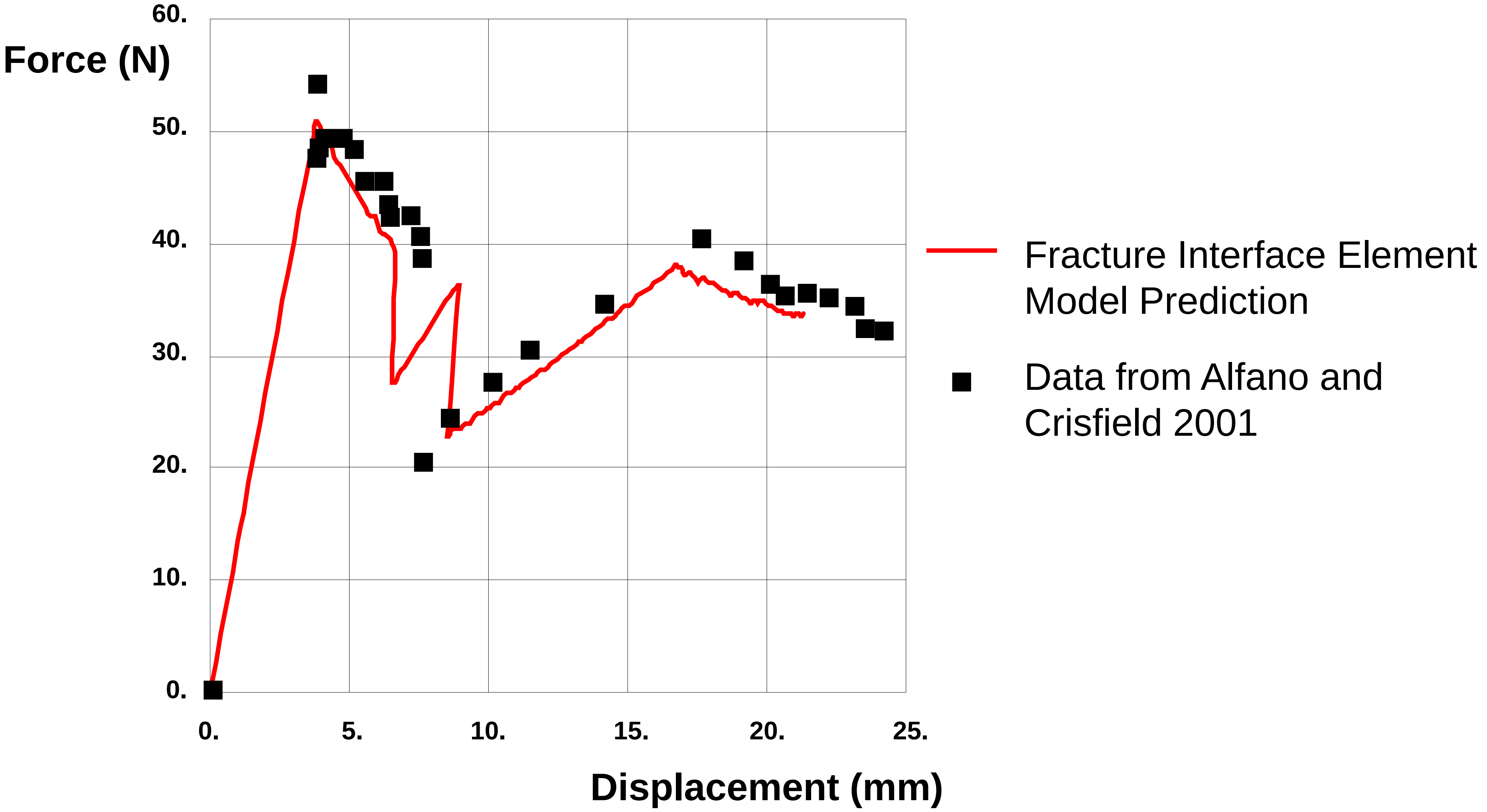
Multi-Delamination Analysis Results



```
Development model
ODB: multi_dilam_3.odb    ABAQUS/Standard 6.1-1    Fri Jul 20 15:58:15 PDT 2001

Step: Step    1   Increment      0: Step Time =    0.0000E+00
Primary Var: S, S22
Deformed Var: U   Deformation Scale Factor: +1.000e+03
```

Non-Symmetric Multi-Delamination - Comparison with Test and Analyses



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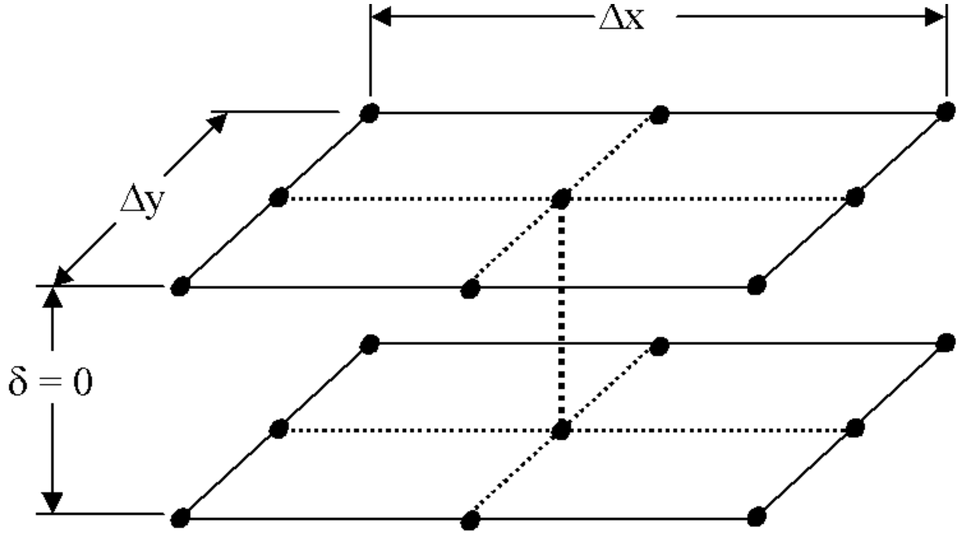
18-noded 3D Interface Element for Composite Delamination Modeling

- Finite size delaminations
- Unreinforced interface fracture



Practical application of VCCT
No remeshing of FE model

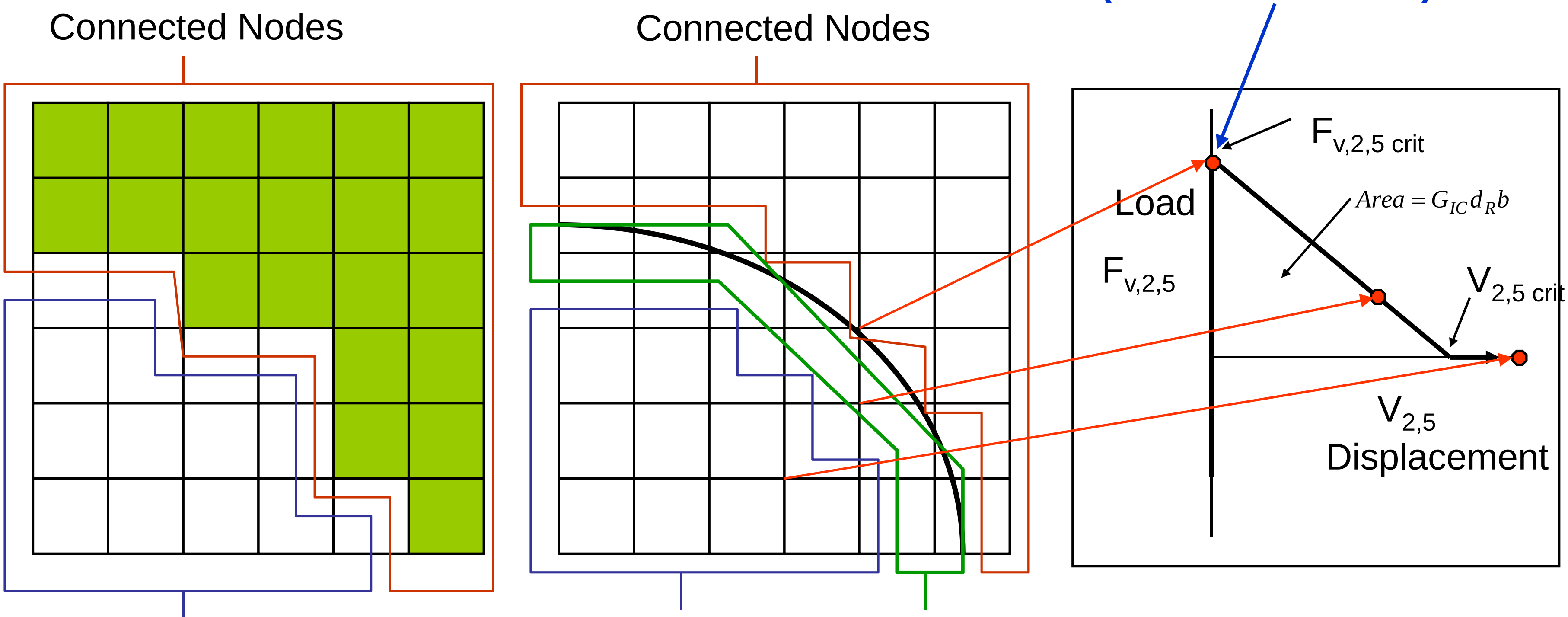
Patent pending

Crack Front with 3D Fracture Interface Elements

A. Manual Crack Front Interrogation

B. Interface Element Automatic Crack Front Interrogation

Release force calculated by mixed-mode modified VCCT (Not stress based!)



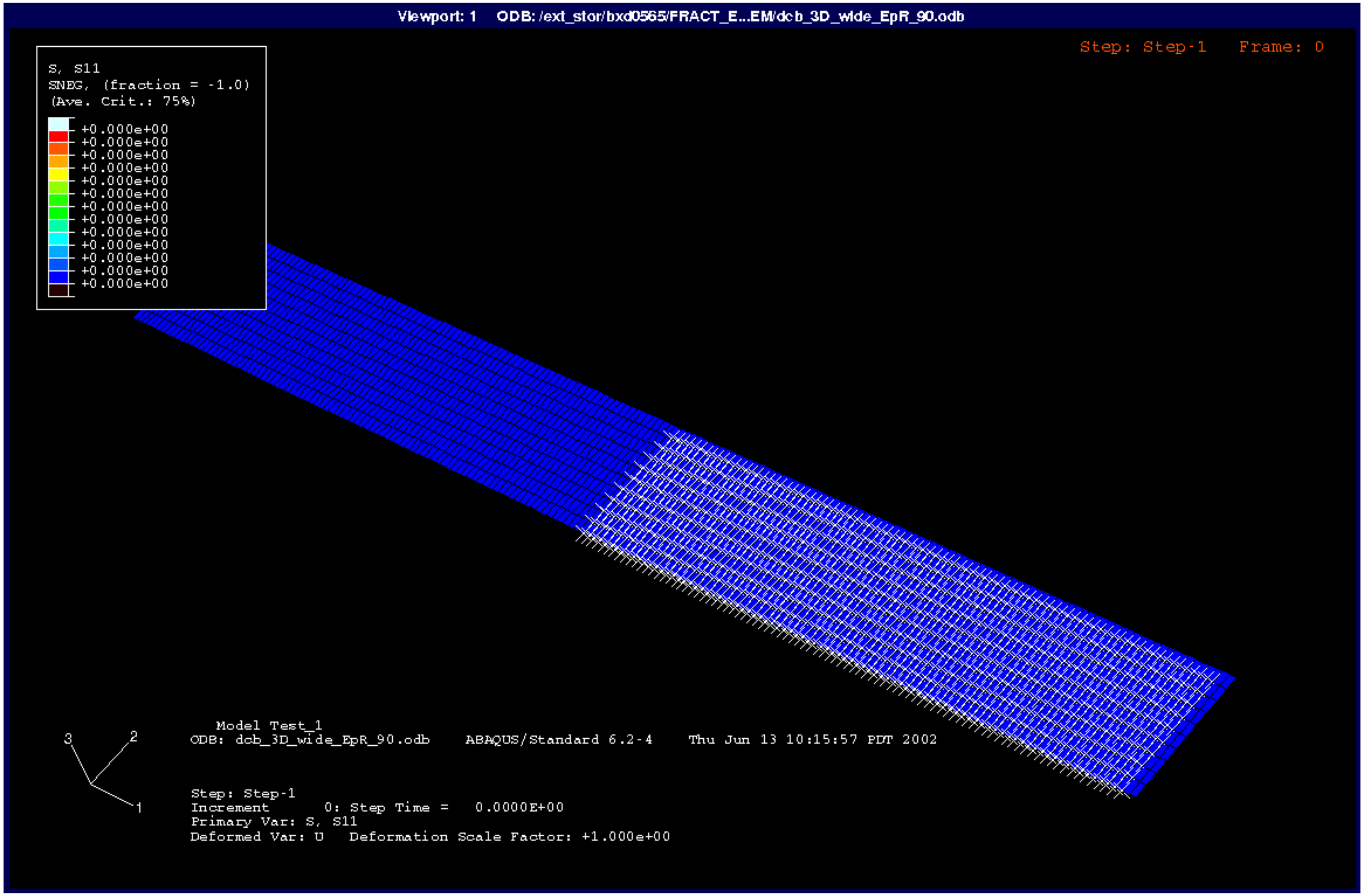
Disconnected Nodes
Zero residual force

Disconnected Nodes
Zero residual force

Disconnected Nodes
Residual force

Patent pending

Finite Width DCB Analysis
– Straight Initial Crack Front

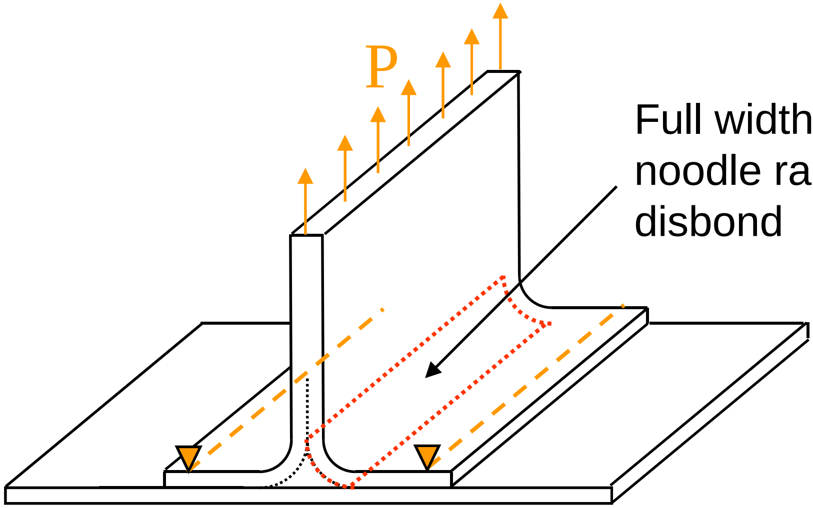


```
   Model Test_1
ODB: dcb_3D_wide_EpR_90.odb    ABAQUS/Standard 6.2-4    Thu Jun 13 10:15:57 PDT 2002


Step: Step-1
Increment      0: Step Time =    0.0000E+00
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

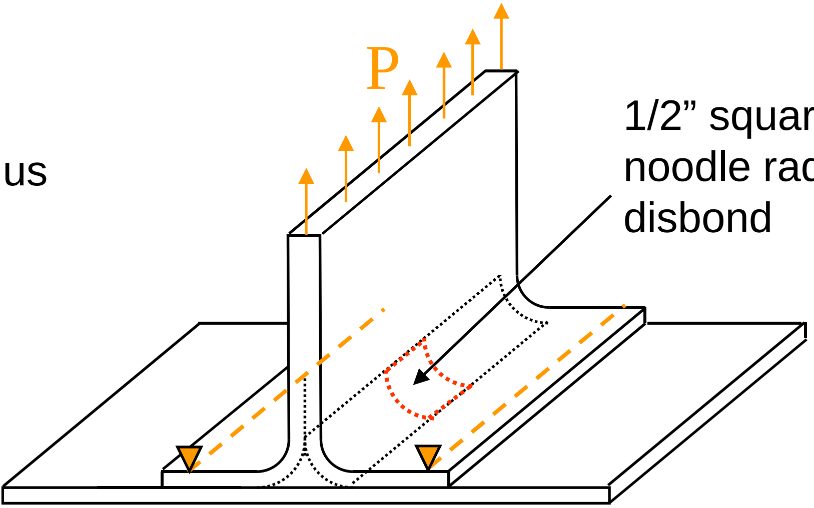
Noodle Radius Disbond Analysis

<u>Full Width Disbond</u>



Full width
noodle radius
disbond

<u>1/2” Square Finite Sized Disbond</u>

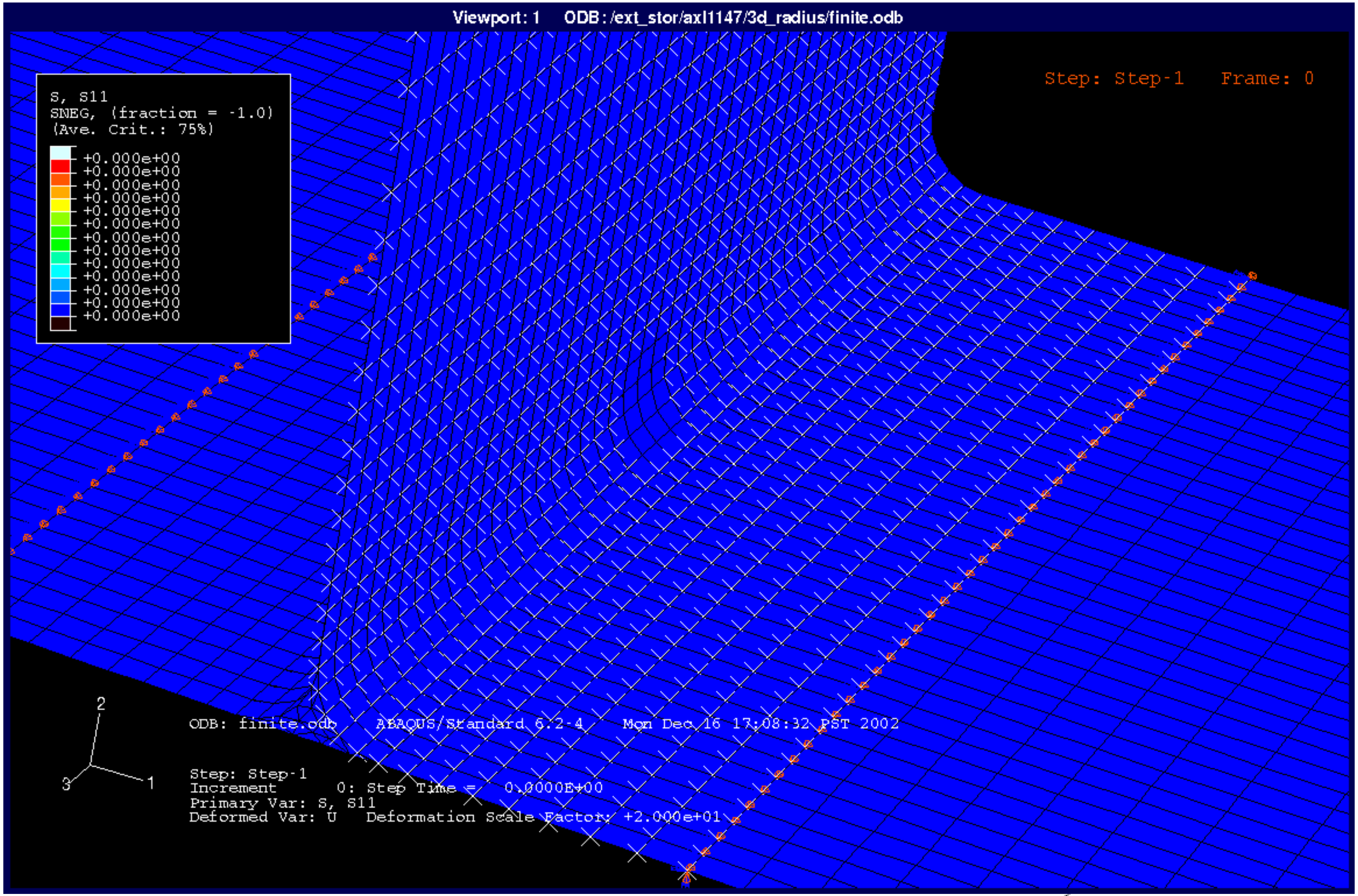


1/2” square
noodle radius
disbond

- Light gauged bonded stiffener design
- Narrow span Tpull test to interrogate noodle region
- Complex progression of failure observed in test
- Comparison of test and analysis results
- Modeled using 3D fracture interface element
- Full width disbond case modeled using 2D interface element

Noodle Radius Disbond Analysis

½” Square Disbond Animation



Viewport: 1 ODB: /ext_stor/axl1147/3d_radius/finite.odb

```
S, S11
SNEG, (fraction = -1.0)
(Ave. Crit.: 75%)
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
+0.000e+00
```

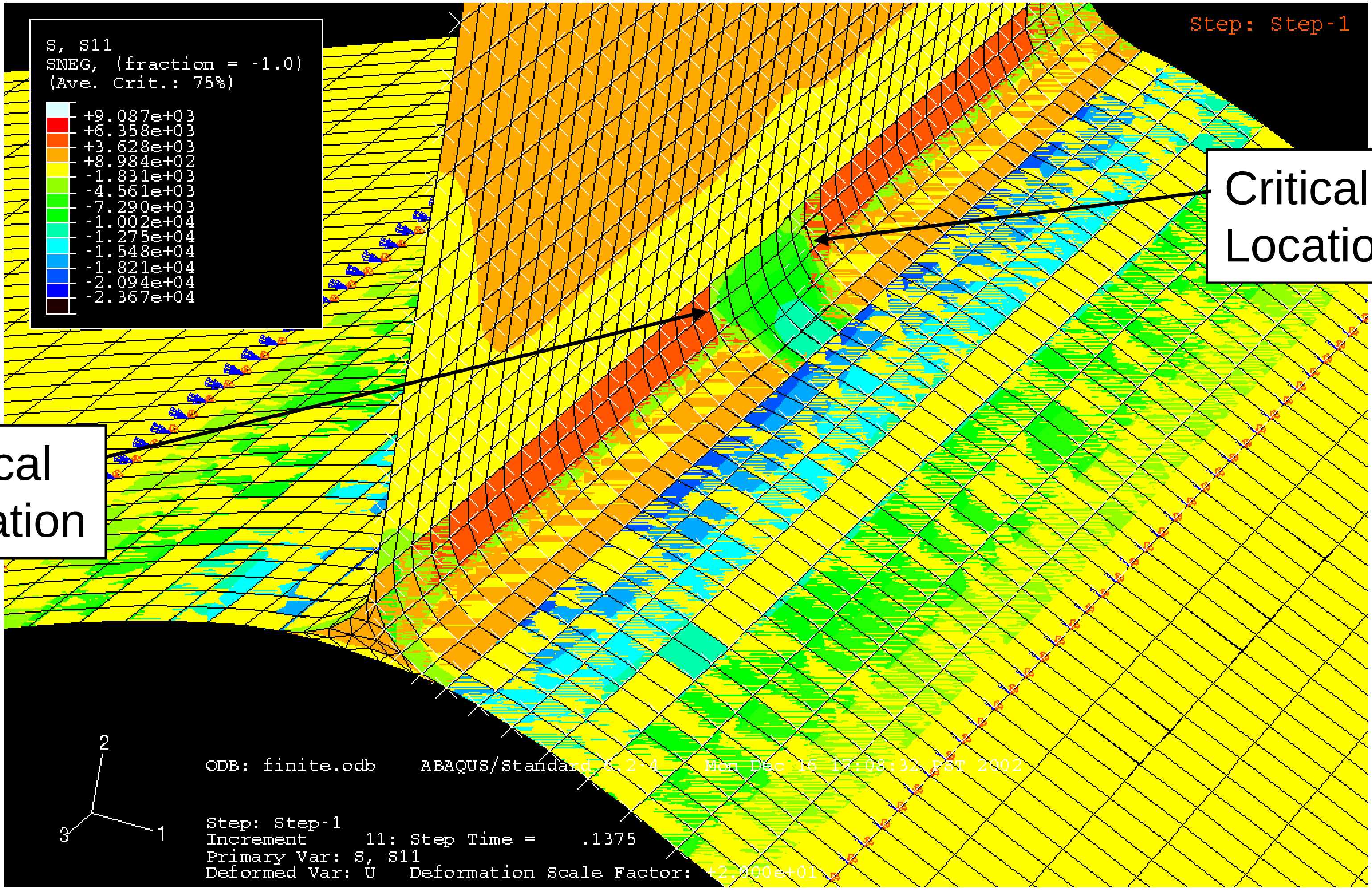
```
Step: Step-1    Frame: 0
```

```
ODB: finite.odb    ABAQUS/Standard 6.2-4    Mon Dec 16 17:08:32 PST 2002

Step: Step-1
Increment      0: Step Time =     0.0000E+00
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +2.000e+01
```

Noodle Radius Disbond Analysis

Onset of Disbond Growth from ½” Square Disbond

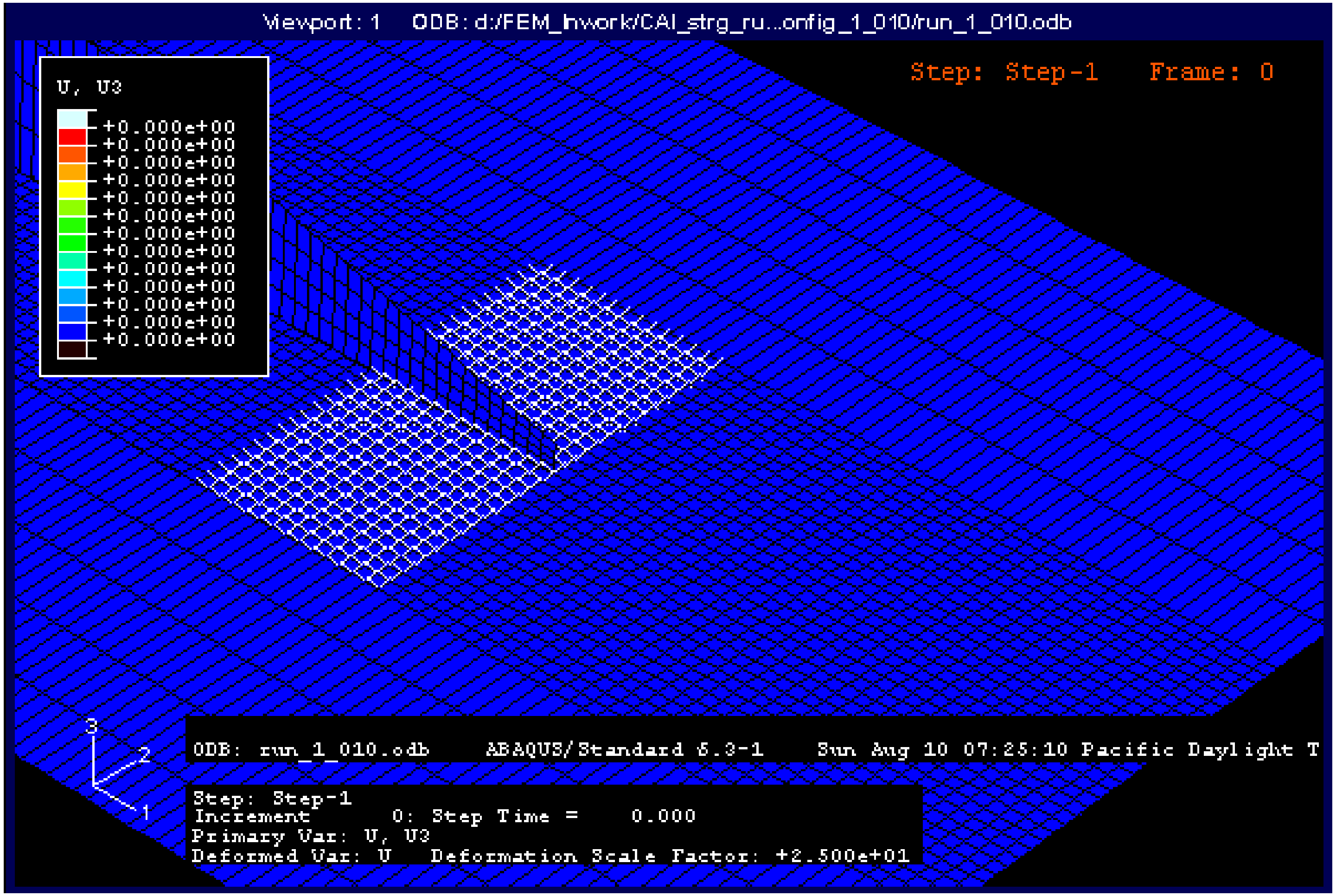


Critical Location

Critical Location

Delamination Analysis of Bonded Stiffener Termination

Load-path eccentricity causes delamination



```
Viewport: 1    ODB: d:/FEM_hwork/CAI_strg_ru...onfig_1_010/run_1_010.odb
```

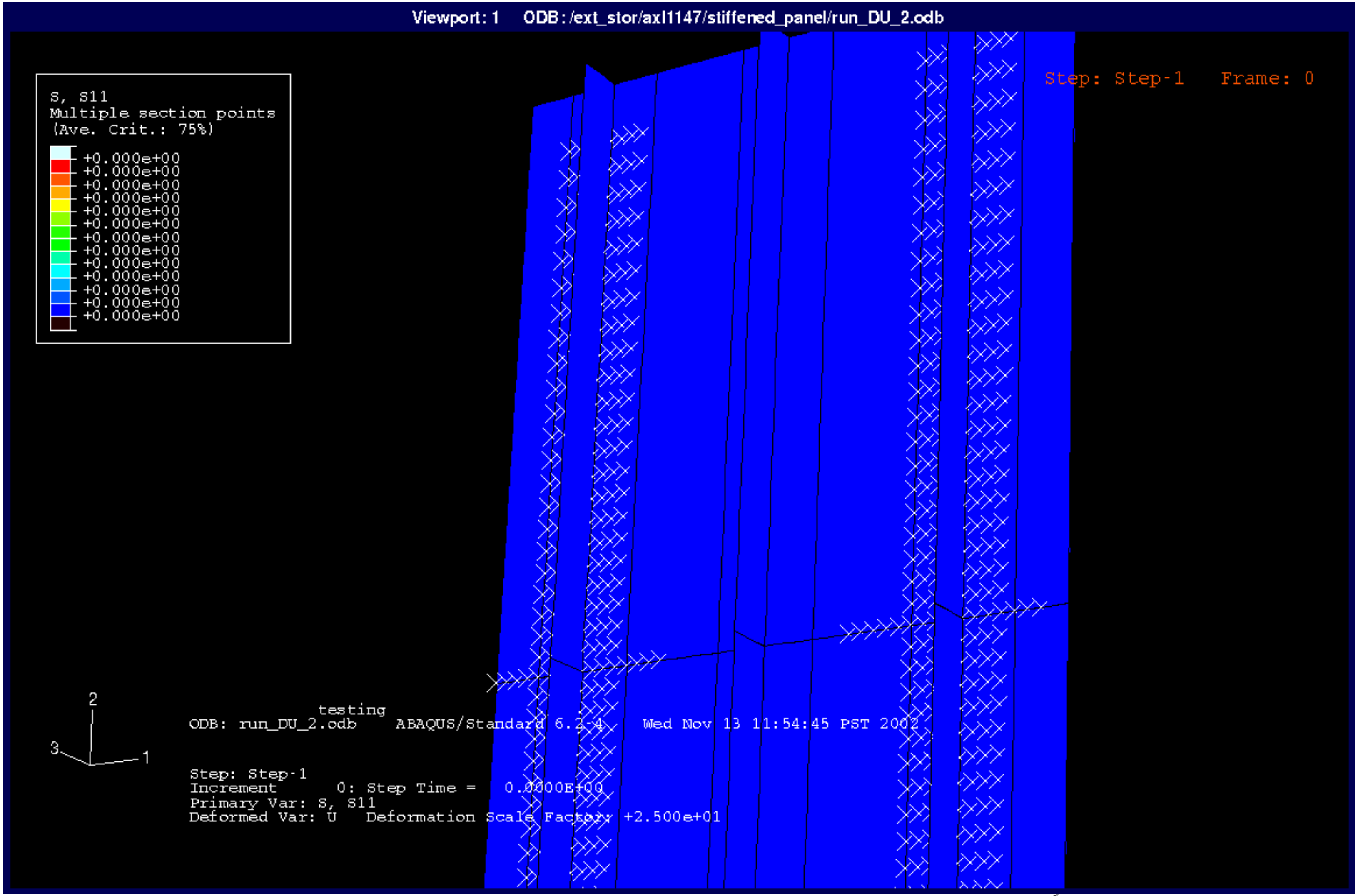
```
Step: Step-1    Frame: 0
```

```
ODB: run_1_010.odb    ABAQUS/Standard 6.3-1    Sun Aug 10 07:25:10 Pacific Daylight T

Step: Step-1
Increment      0: Step Time =     0.000
Primary Var: U, U3
Deformed Var: U   Deformation Scale Factor: +2.500e+01
```

Bonded Stiffener Separation Caused By Approaching Through Penetration

Heavy Gauge Stiffeners



```
Viewport: 1     ODB: /ext_stor/axl1147/stiffened_panel/run_DU_2.odb

S, S11
Multiple section points
(Ave. Crit.: 75%)
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00
 +0.000e+00

Step: Step-1    Frame: 0

                testing
ODB: run_DU_2.odb    ABAQUS/Standard 6.2-4    Wed Nov 13 11:54:45 PST 2002

Step: Step-1
Increment      0: Step Time =    0.0000E+00
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +2.500e+01
```

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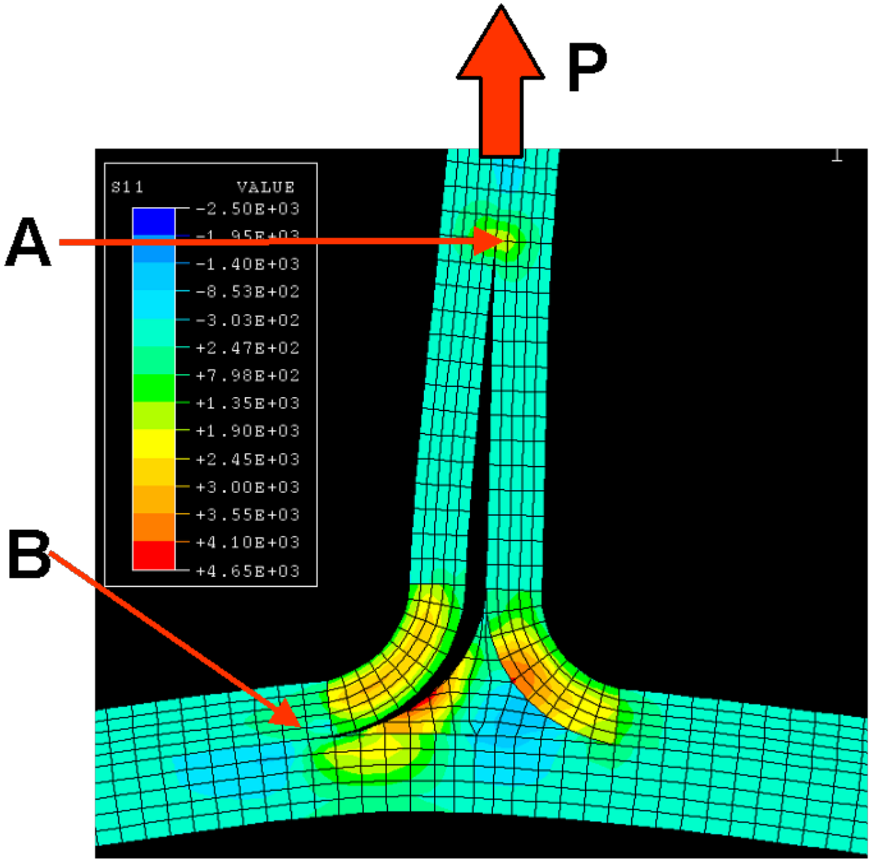
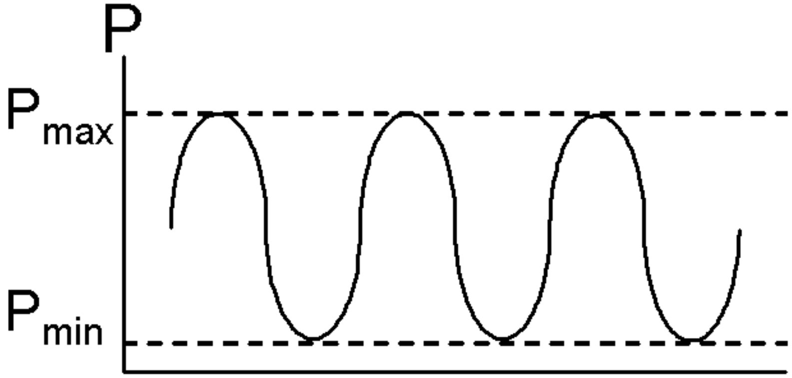
Interlaminar Fatigue Problem



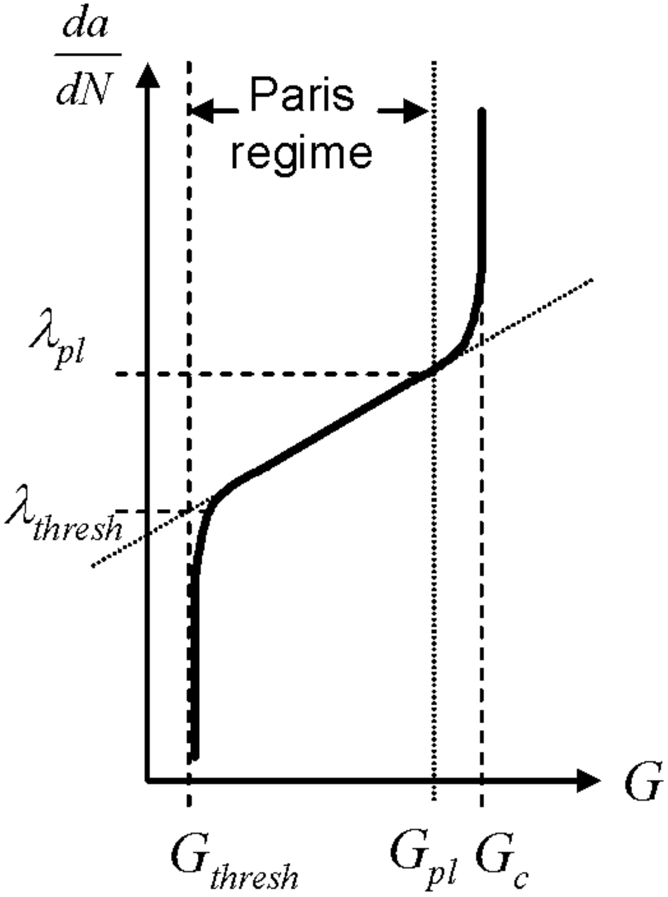


Interlaminar Fatigue Element

- VCCT-based interface element contains functionality necessary for a progressive interlaminar fatigue element.

- Three fatigue analysis approaches
  - Short growth based on Paris Law Growth and total G
  - Short growth based on mixed-mode Paris Law
  - Onset of growth based on measured 5% growth in DCBs and a crack tip Energy Release Rate, G.

Paris Law Fatigue Growth



G_{Ipl}, G_{IIpl} = Energy release rates in mode I and II defining upper limit of the Paris regime

(Note: *pl* refers to “Paris limit”)

G_{thresh} = Fatigue threshold energy release rate

or

λ_{pl} = Crack opening rate (*da/dN*) at the upper end of the Paris regime

for

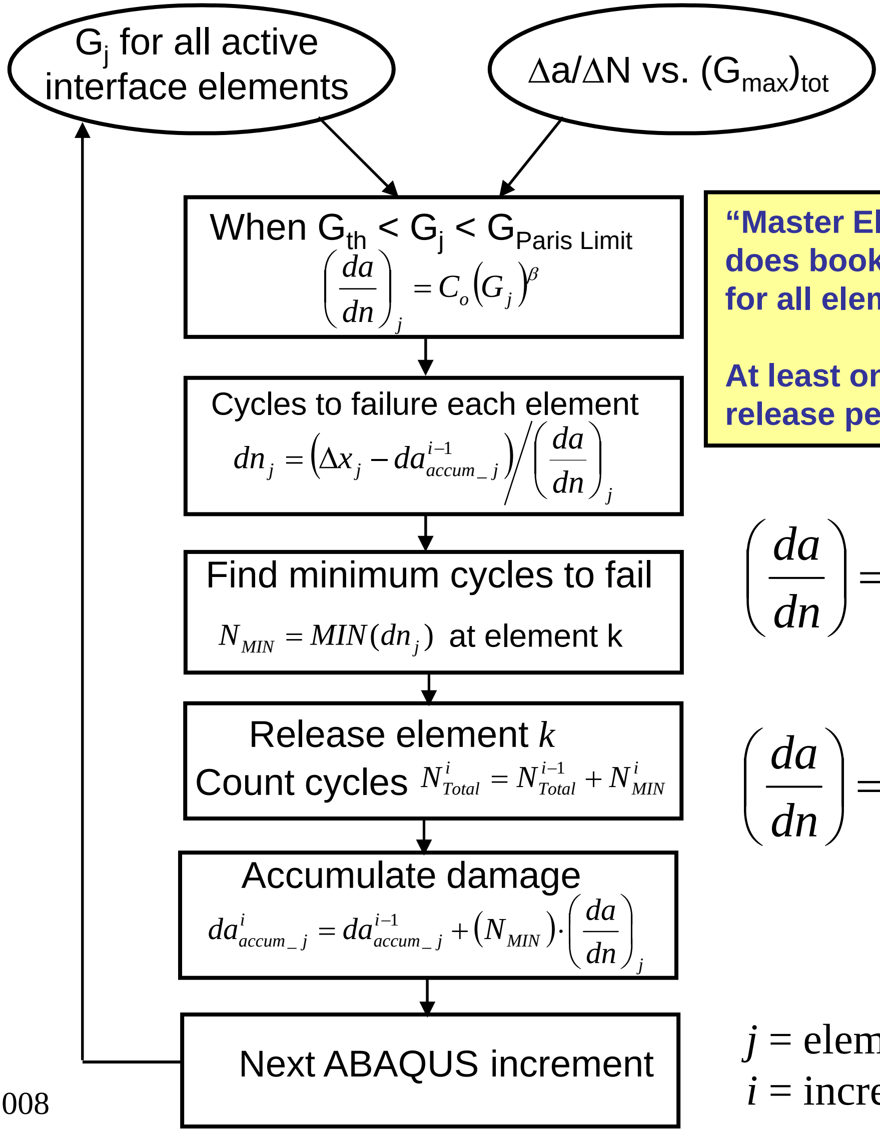
λ_{thresh} = Crack opening rate at the fatigue threshold

$$\frac{da}{dN} = c \cdot G_{\max}^{\beta} \text{ or } \frac{da}{dN} = c \cdot (\Delta G)^{\beta}$$

where

$$G > G_{threshold} \text{ and } G < G_C$$

Simplified 2D Interlaminar Fatigue Element



G_j for all active interface elements

$\Delta a/\Delta N$ vs. $(G_{max})_{tot}$

When $G_{th} < G_j < G_{Paris\ Limit}$

$$\left(\frac{da}{dn}\right)_j = C_o\left(G_j\right)^{\beta}$$

Cycles to failure each element

$$dn_j = \left(\Delta x_j - da^{i-1}_{accum\_j}\right) \Big/ \left(\frac{da}{dn}\right)_j$$

Find minimum cycles to fail

$N_{MIN} = MIN(dn_j)$ at element k

Release element *k*

Count cycles $N^i_{Total} = N^{i-1}_{Total} + N^i_{MIN}$

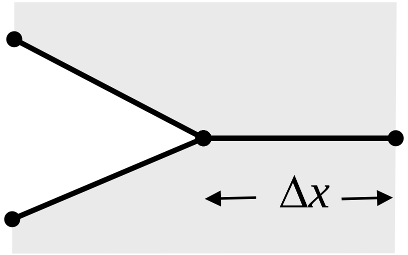
Accumulate damage

$$da^i_{accum\_j} = da^{i-1}_{accum\_j} + \left(N_{MIN}\right) \cdot \left(\frac{da}{dn}\right)_j$$

Next ABAQUS increment

“Master Element” does bookkeeping for all elements

At least one element release per increment



$$\left(\frac{da}{dn}\right) = C_o\left(\Delta G\right)^{\beta}$$

or

$$\left(\frac{da}{dn}\right) = C_o\left(G_{Max}\right)^{\beta}$$

Implemented as ABAQUS UEL

j = element index

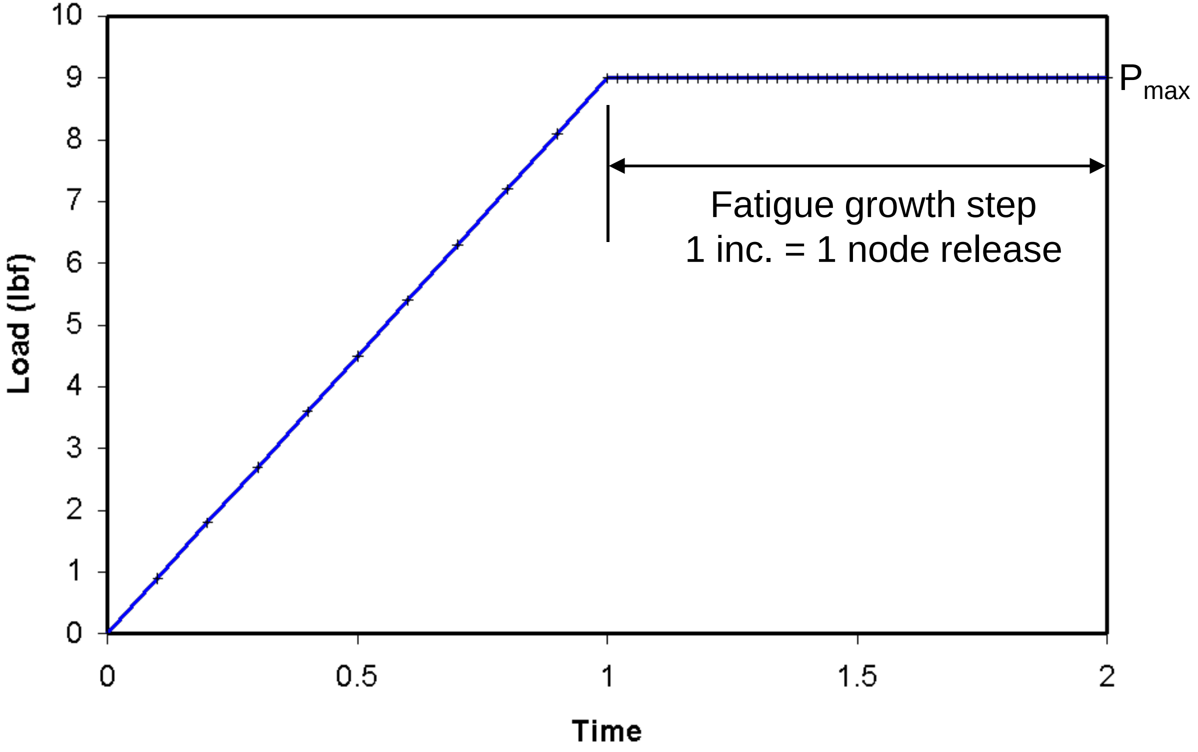
i = increment number

2D Fatigue in DCB

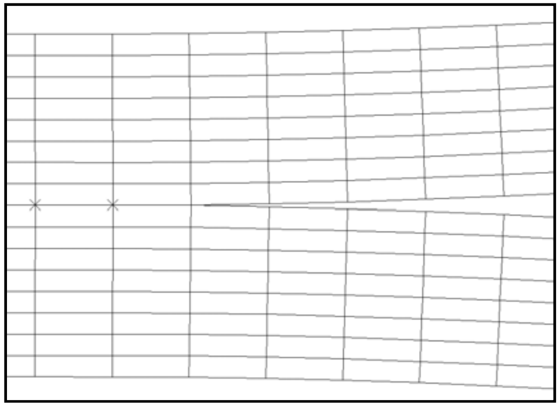
User Defined Load Step History

Load = P_{max} = constant

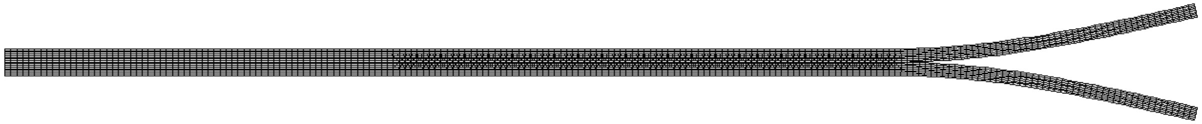
Assume Linearity, R = P_{min}/P_{max}

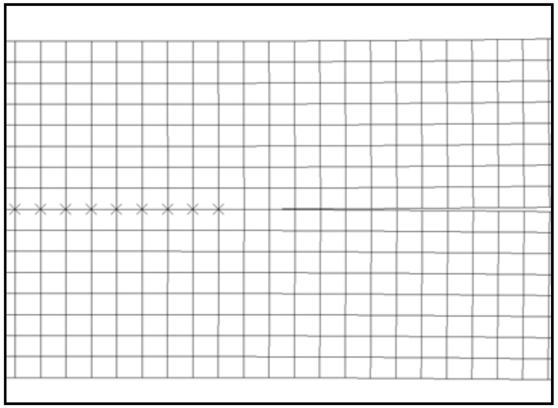


Interlaminar Fatigue Analysis



Coarse Mesh DCB



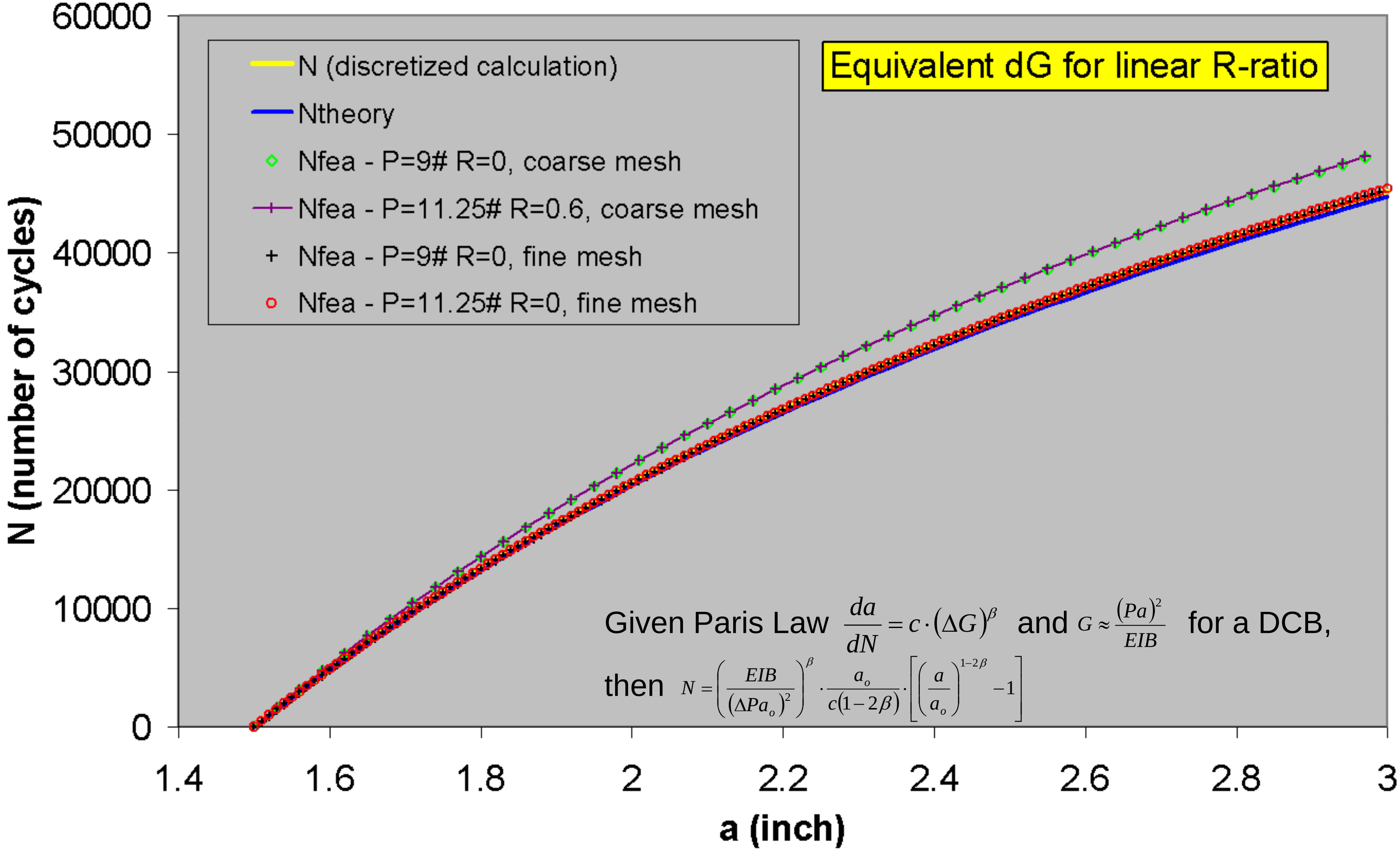


FE Models Used in Development

Fine Mesh DCB

2D Fatigue Element in DCB Model

Paris Law Growth



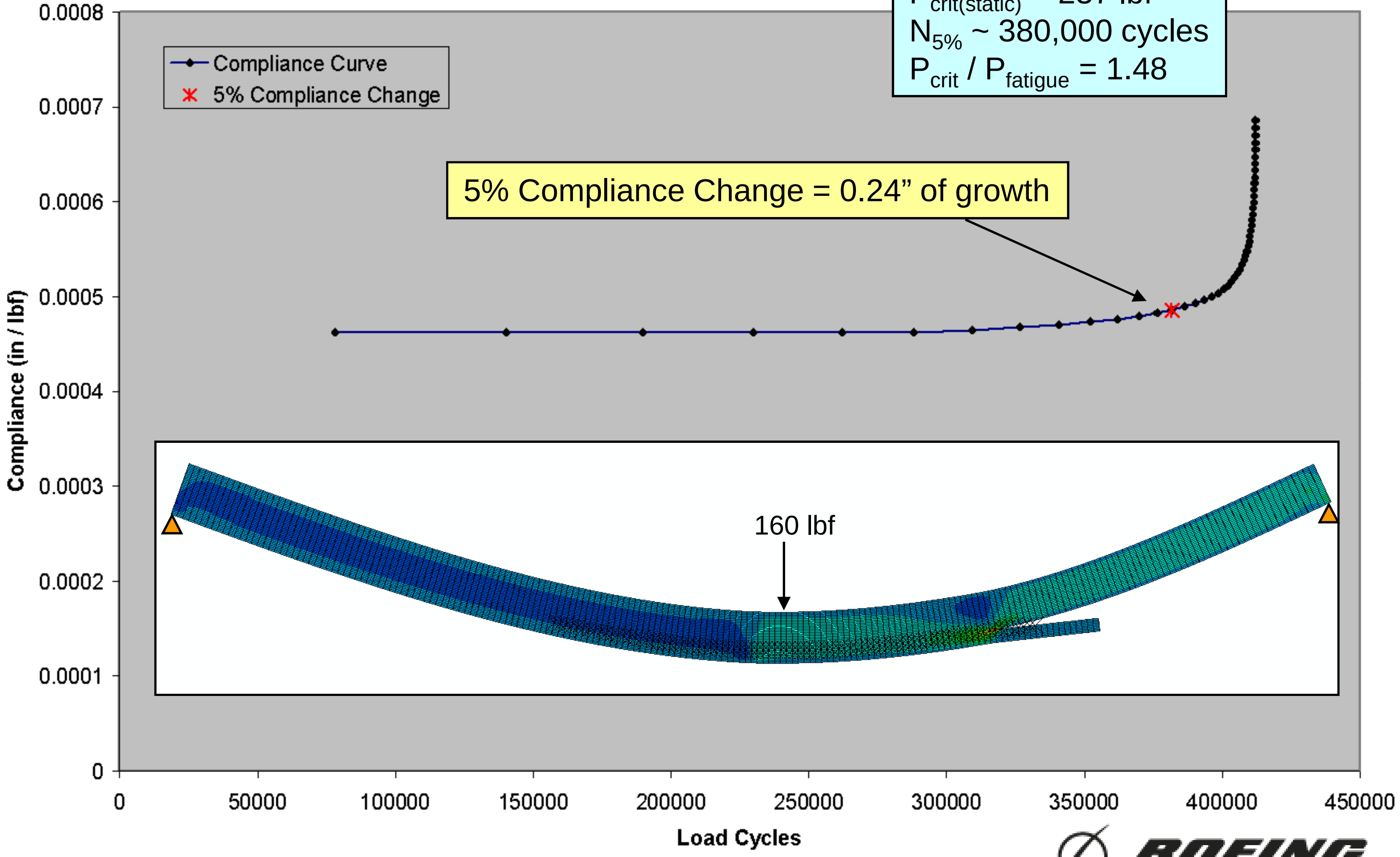
Equivalent dG for linear R-ratio

Given Paris Law $\frac{da}{dN} = c \cdot (\Delta G)^{\beta}$ and $G \approx \frac{(Pa)^2}{EIB}$ for a DCB,

then $N = \left(\frac{EIB}{(\Delta P a_o)^2}\right)^{\beta} \cdot \frac{a_o}{c(1-2\beta)} \cdot \left[\left(\frac{a}{a_o}\right)^{1-2\beta} - 1\right]$

Single Leg Bend Model and Mixed Mode Paris Law

Single Leg Bend Fatigue
Applied Load = 160 lbf



$P_{fatigue}$ = 160 lbf
$P_{crit(static)}$ = 237 lbf
$N_{5\%}$ ~ 380,000 cycles
P_{crit} / $P_{fatigue}$ = 1.48

5% Compliance Change = 0.24” of growth

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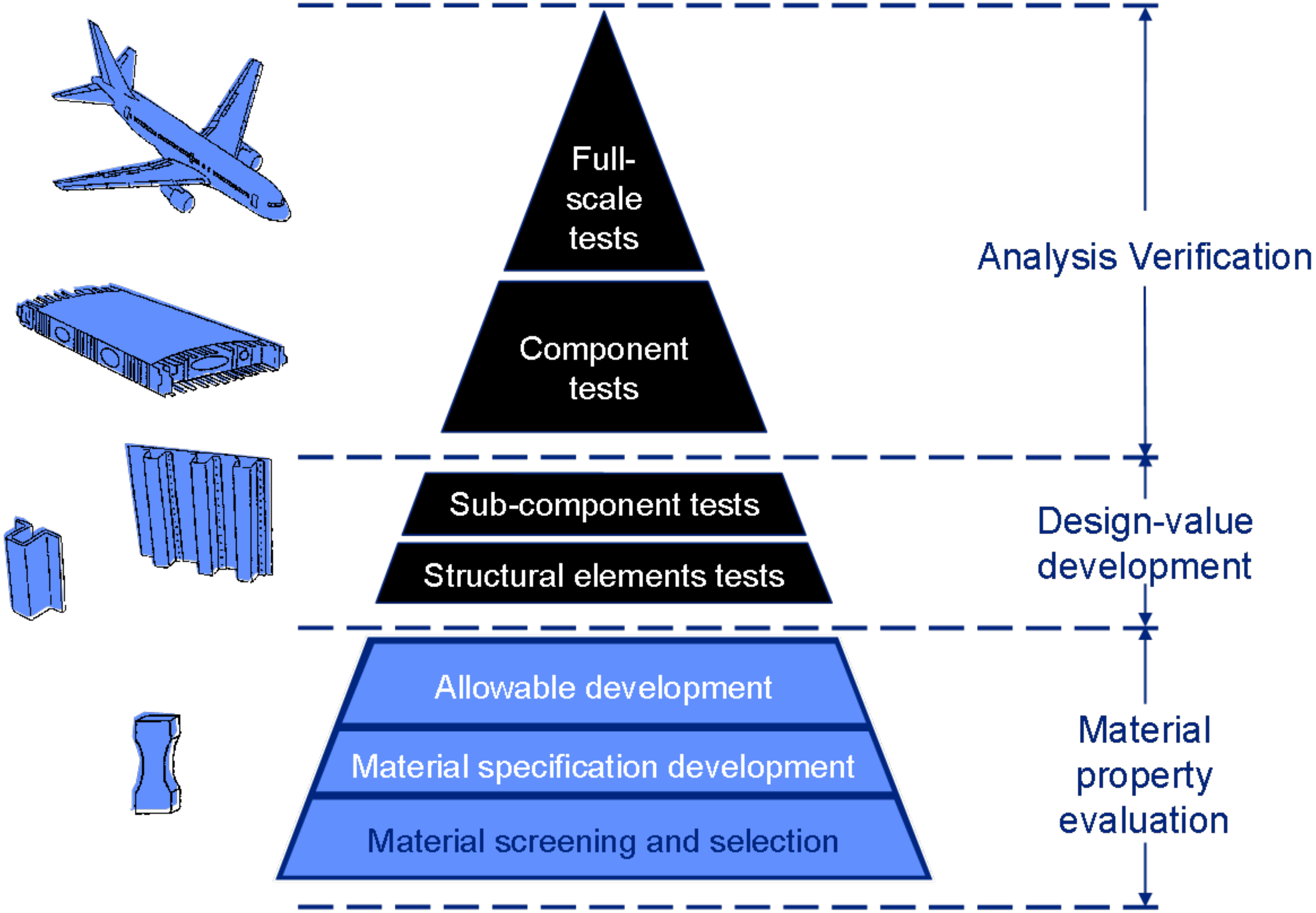
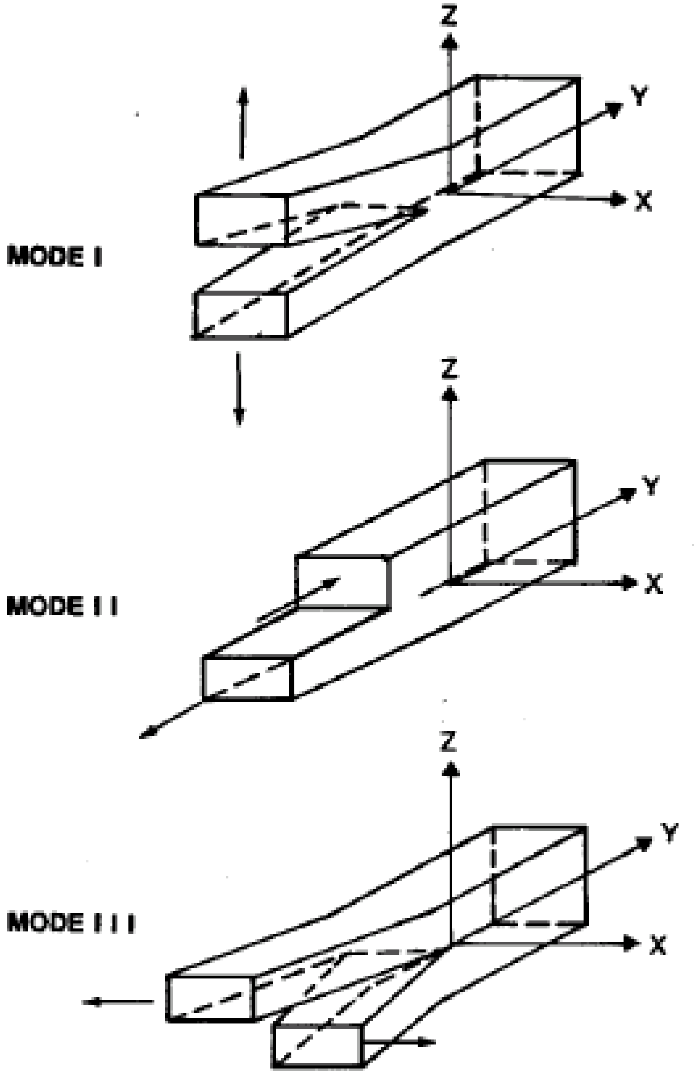
Structural Analysis and Certification Approach

Certified by analysis, supported by test evidence

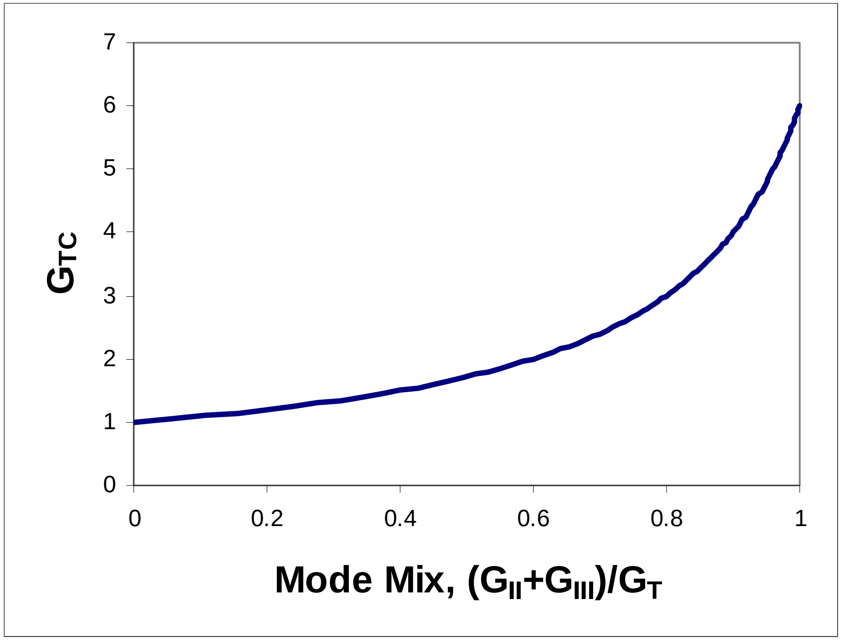


Fracture Mechanics - Crack Loading Modes

- Crack propagation modes



Mixed Mode Fracture Criteria



Traditional Interaction

For crack propagation:

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n + \left(\frac{G_{III}}{G_{IIIC}}\right)^p \geq 1$$

user specified parameters:

$m, n, p, G_{IC}, G_{IIC}, G_{IIIC}$

BKR Interaction

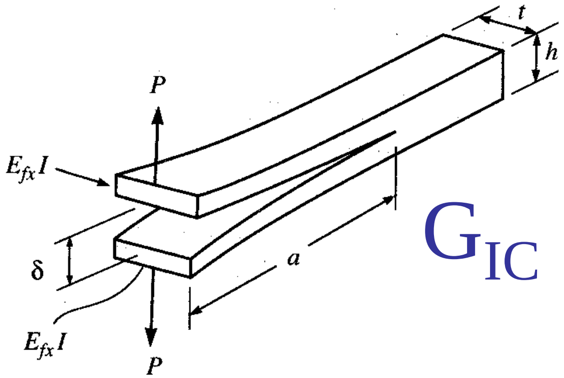
For crack propagation $G_T \geq G_{TC}$, where

$$G_{TC} = G_{IC} + \left[G_{IIIC}\frac{G_{III}}{G_T} + G_{IIC}\frac{G_{II}}{G_T} - G_{IC}\left(\frac{G_{III}}{G_T} + \frac{G_{II}}{G_T}\right)\right]\left(\frac{G_{II}+G_{III}}{G_T}\right)^{n-1}$$

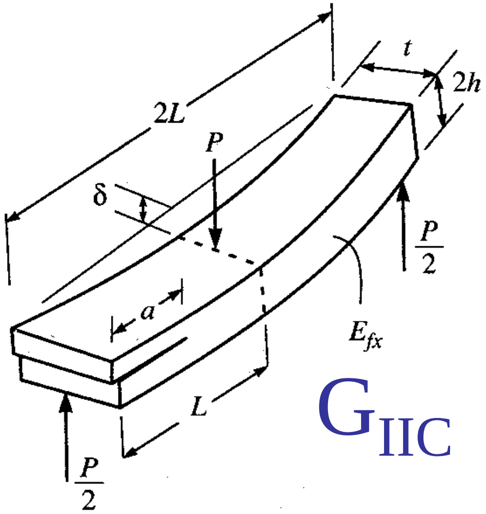
user defined parameters:

$n, G_{IC}, G_{IIC}, G_{IIIC}$

Fracture Calibration Tests
Material Property Test Standards



Double Cantilever Beam (DCB) Coupon, Mode I



End Notch Flexure (ENF) Coupon, Mode II

ASTM Standards

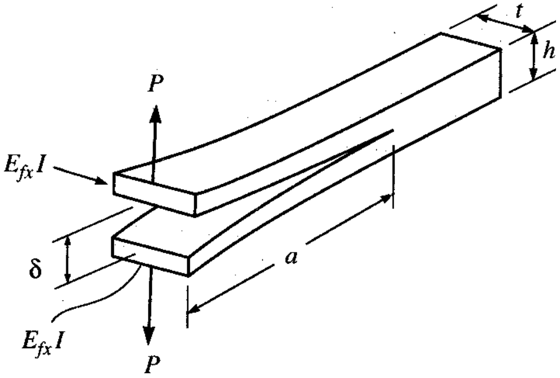
- existing

- D5528 Static DCB (also ISO standard)
- D6115 Fatigue Onset DCB
- D6671 Static Mixed mode

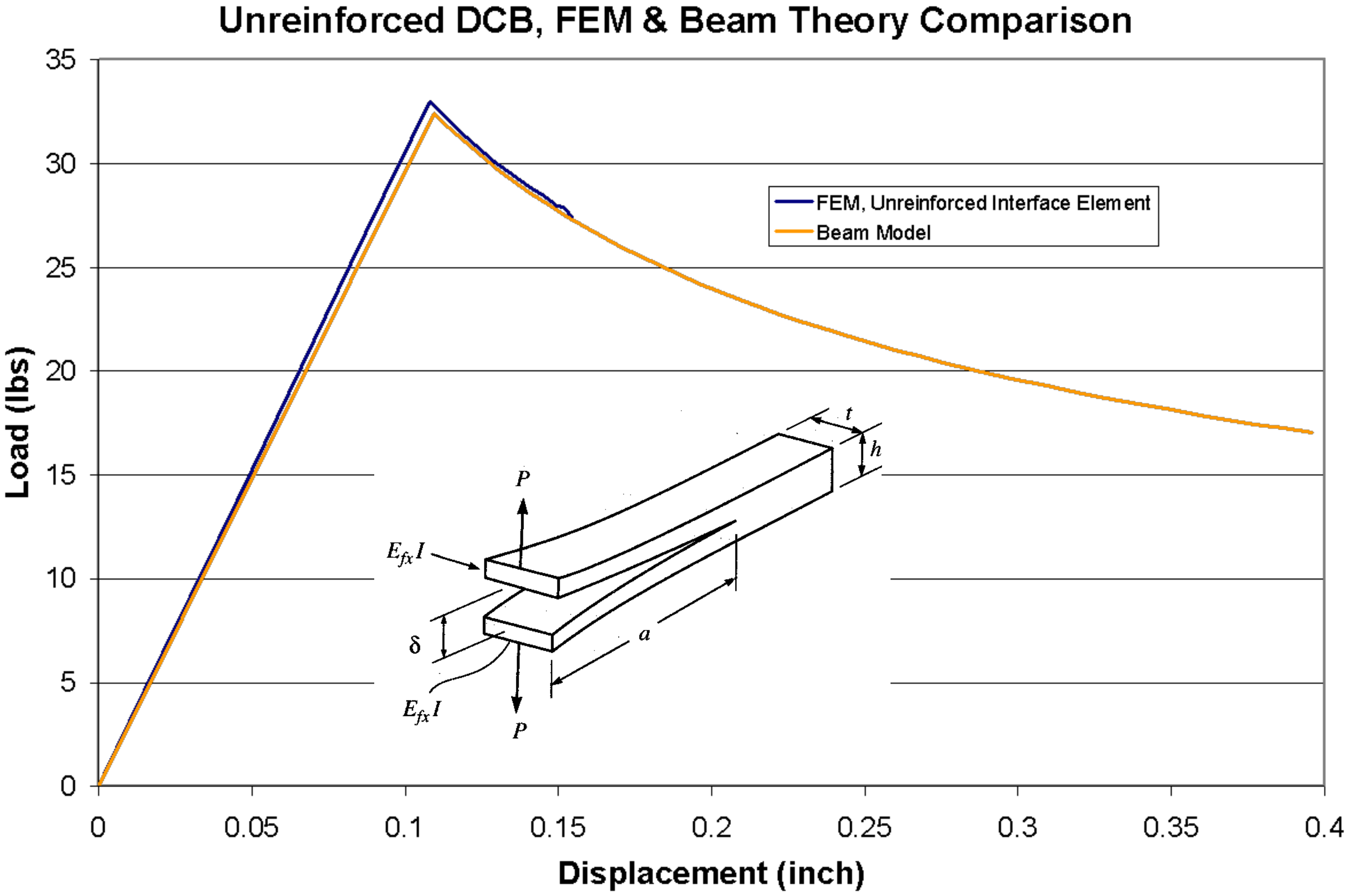
-in work

- Mode II static (3ENF)
- Mode III static
- Mode I fatigue propagation
- Mode II fatigue onset
- Mode III fatigue onset

Double Cantilever Beam Test

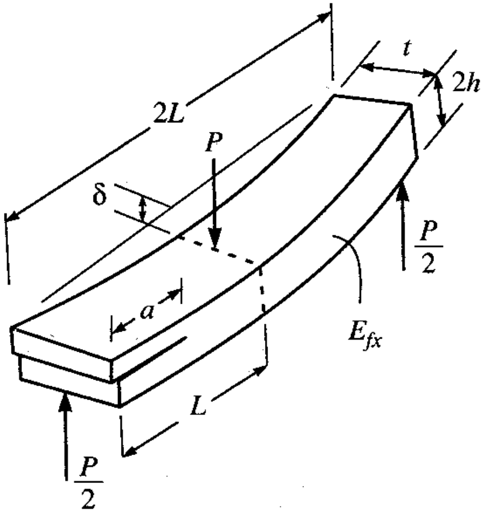


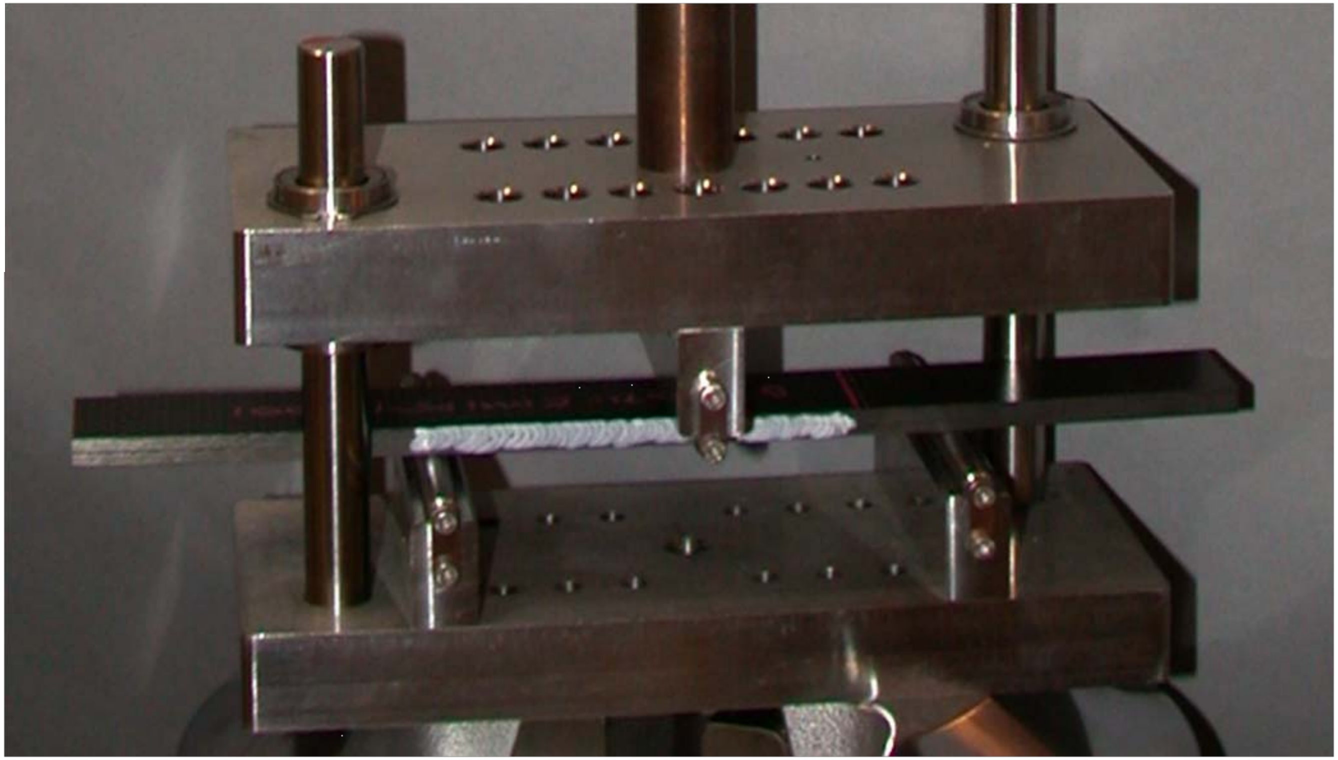
Functionality Check FEM vs Theory Unreinforced DCB Coupon



Unreinforced DCB, FEM & Beam Theory Comparison

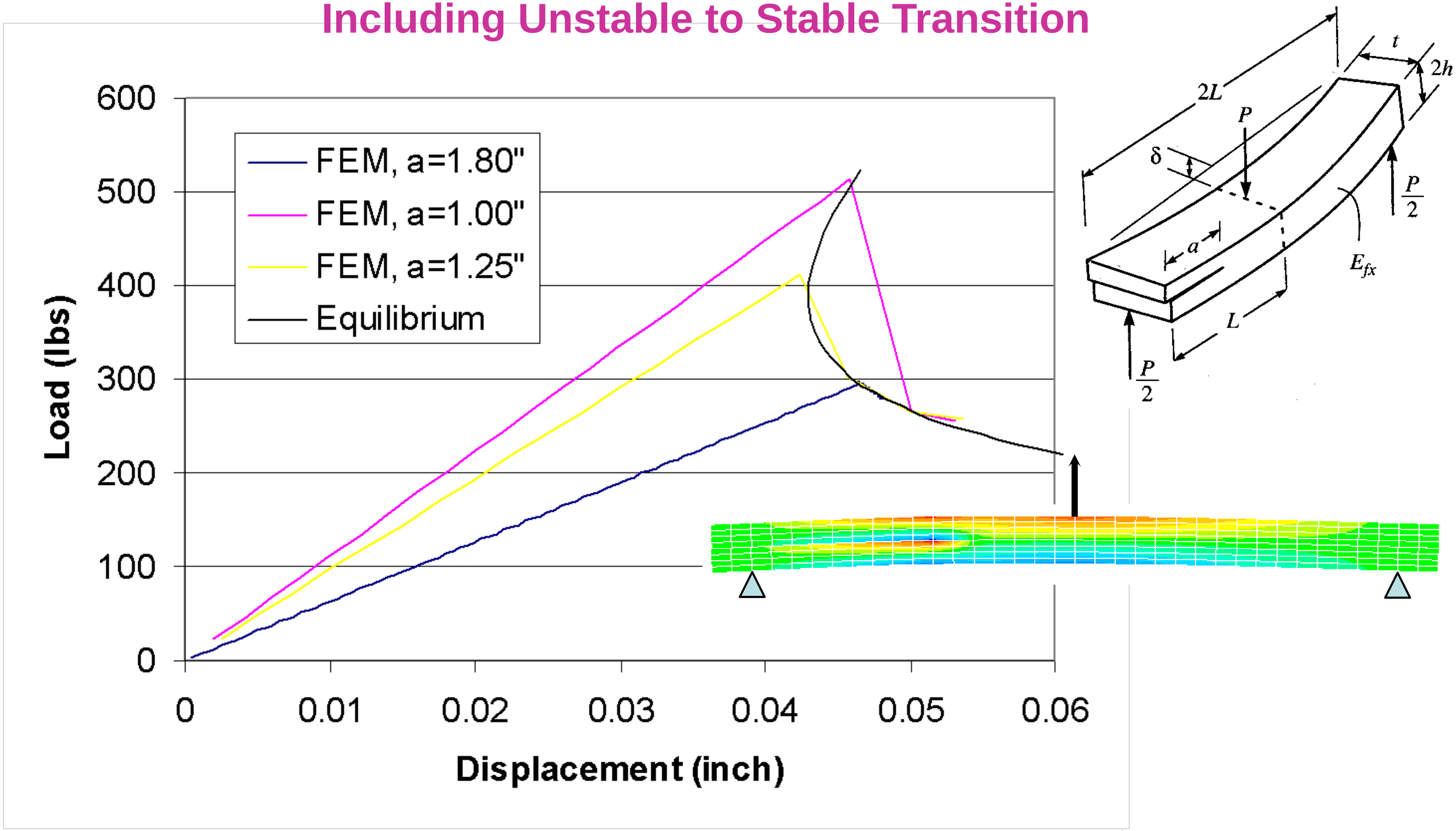
End Notch Flexure Test





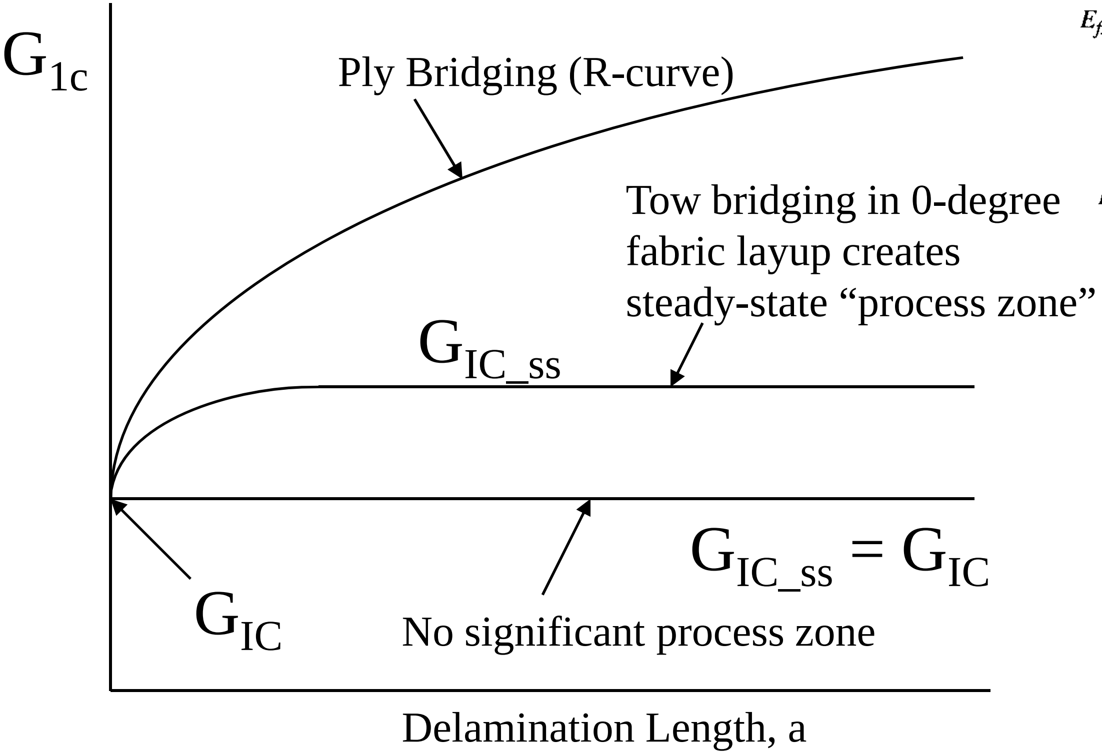
Functionality Check FEM vs Theory ENF Coupon

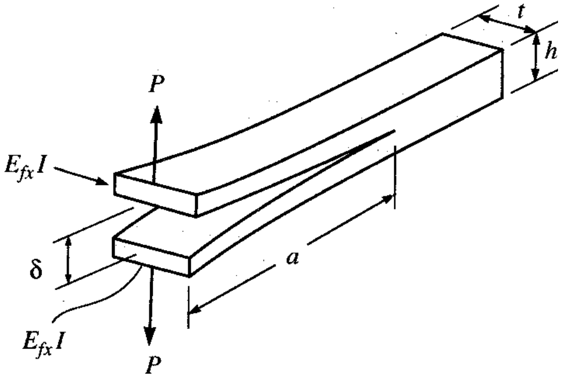
Including Unstable to Stable Transition



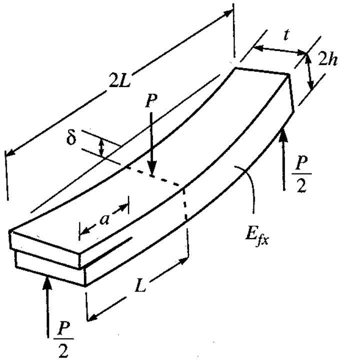
Delamination Length Effects on Apparent G_C

G_{IC} and G_{IC_ss} Defined (Mode I)





Similar definitions for Mode II G_{IIC} and G_{IIC_ss} Defined



Presentation Format

- Introduction
- Static 2D interface element
- Static 3D interface element
- Interlaminar fatigue element
- Calibration testing
- → Summary

Summary - Static

- 2D and 3D static fracture interface elements have been developed
- Multiple crack tips/fronts can be modeled simultaneously
- Strength based initiation capability is available for 2D and 3D fracture interface elements
- This technology is available in Abaqus Standard.

Summary - Fatigue

- VCCT-based elements provide excellent platform to implement automatic interlaminar fatigue analysis based on Paris Law
- 2D Progressive crack growth in FE models is numerically stable
- Better results for fine mesh due to energy release rate calculated at beginning of node release.
- Error if mode mix not considered

Future Enhancements - Analysis

- Crack branching
- Improve efficiency and stability
- Application to explicit finite element formulation

- Routine analysis of multiple delaminations (barely visible impact damage)

Future Enhancements - Testing

- Need industry standard methods for both static and fatigue
  - Mode II, mode III, mixed mode
- Practical in service NDI for delaminations

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- Composite Affordability Initiative Program
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- Al Miller

Thank you

Building the Dream

787 DREAMLINER