AN APPROACH FOR ASSESSING DELAMINATION PROPAGATION CAPABILITIES IN COMMERCIAL FINITE ELEMENT CODES

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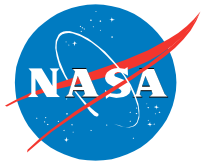
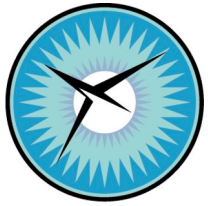
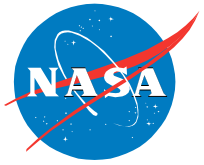
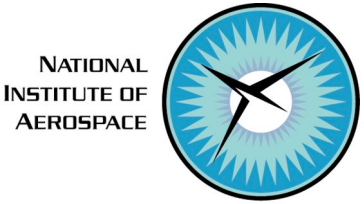


NASA Aviation Safety Technical Conference, St. Louis, Missouri, 2007





OUTLINE



- Overview of research task
- Background and motivation
- Fracture mechanics methodology for delamination onset prediction
- Comparison of computed strain energy release rates in a DCB specimen with results from user written post-processing routines
- Propagation analysis for DCB and SLB specimens using VCCT for ABAQUS
  - Creation of benchmark results based on critical load/displacement conditions
  - Comparison of computed load-displacement behavior with benchmark results for various input parameters
  - Comparison of computed displacement-crack length behavior with benchmark results for various input parameters
  - Assessment of computed delamination front shapes
- Concluding remarks

NASA Aviation Safety
Aging Aircraft & Durability Program

NATIONAL INSTITUTE OF AEROSPACE

- **Research Task:**

  Development of a Delamination Fatigue Methodology for Composite Rotorcraft Structure

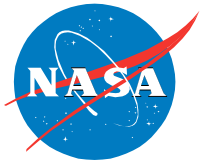
- **Program Goals:**

  Develop Methodologies and Validated Analysis Tools to Predict Fatigue Life and Residual Strength for

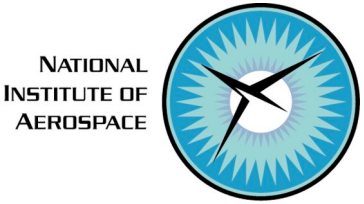
  - **Improved Safety - Certification by Analysis**
  - **Improved Durability - Reduced Life Cycle Costs**
  - **Improved Accept/Reject Criteria**

- **5-Year Program Deliverable:**

  Incorporate Fatigue Life Prediction Methodology into Composite Materials Handbook 17 (CMH-17)



APPROACH



- Collaborative research between NASA and U.S. Rotorcraft Companies through Space Act Agreement with the Center for Rotorcraft Innovation, CRI (formerly RITA)
- NASA Langley in-house CS and contractors to perform experimental characterization and analytical tool development
- CRI to supply characterization test specimens and identify and manufacture validation test articles for testing by NASA and Industry
- Annual milestones established and progress reviewed through periodic IPT meetings/telecons during course of 5-year period of performance (FY07-11)
- External stake holders invited to participate in IPT meetings (Army, FAA, CMH-17, ASTM, Rotorcraft CoE's)

VALIDATION ARTICLE
Durability

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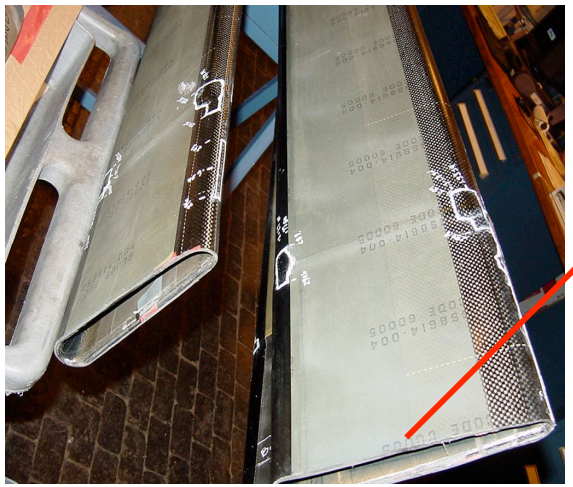
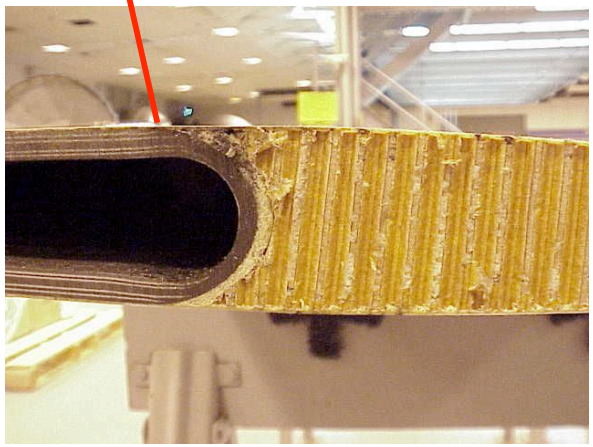
- **S-92 Helicopter main rotor blade spar subjected to tension/torsion fatigue loading**





Airfoil = Spar + Trailing edge

Delamination growth expected at ply drops

VALIDATION ARTICLE
Damage Tolerance

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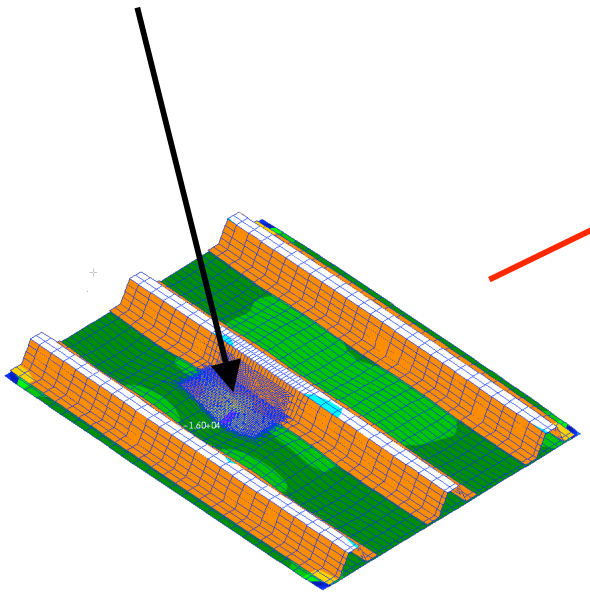
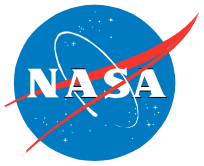
- **Stiffened wing skin panel, post BVID compression fatigue loading**

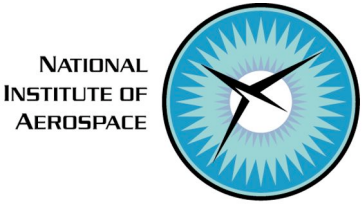
Delamination growth expected after impact



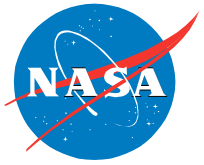
Bell-Agusta BA-609 Civil Tilt Rotor



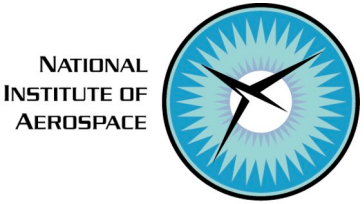
BACKGROUND
Fracture Mechanics Capabilities



- **In the past:**
  - **Fracture mechanics implementations had a focus on J-integral and Virtual Crack Extension**
  - **Virtual Crack Closure Technique (VCCT) implemented only in specialized finite element codes (FRANC2D) or user written post-processing routines**
  - **Crack extension or delamination propagation analyses performed manually which was time consuming.**
- **Today:**
  - **Boeing's VCCT element (commercialized as VCCT for ABAQUS®)**
  - **MSC.Nastran™ SOL 600 and MD Nastran SOL 400 include VCCT options**
  - **Implementation in SAMCEF® is a combination of VCCT and Virtual Crack Extension**
  - **Other codes … (e.g. GENOA, HyperSizer, ESRD Stress Check)**
  - **Automatic propagation analysis is possible**



MOTIVATION AND OVERVIEW



- Develop benchmark cases to gain confidence in the software tools used
- Benchmark cases have to be simple
  - Simple geometry and loading → DCB and SLB specimen
  - Independent of analysis software used
  - Independent of experimental anomalies to avoid unnecessary complications (e.g. fiber bridging, appropriate material input data)
- Create a benchmark in a manual delamination propagation analysis
- Repeat propagation analysis using automated propagation feature
- Assessment based on the comparison of manual and automated propagation
- Comparison with experiments and propagation prediction will follow later

VIRTUAL CRACK CLOSURE TECHNIQUE (VCCT)*

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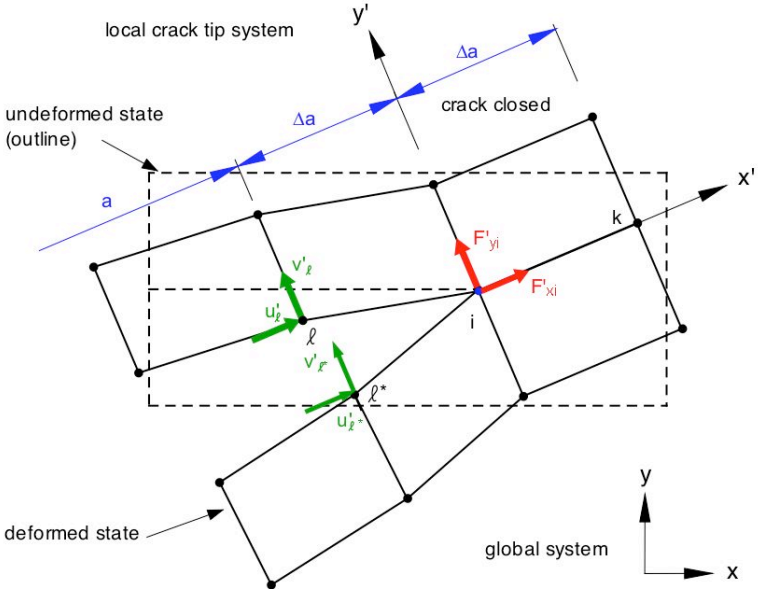
- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front

$$G_I = \frac{1}{2\Delta ab} \cdot F_{yi}' \cdot \left(v'_{\ell} - v'_{\ell^*} \right)$$

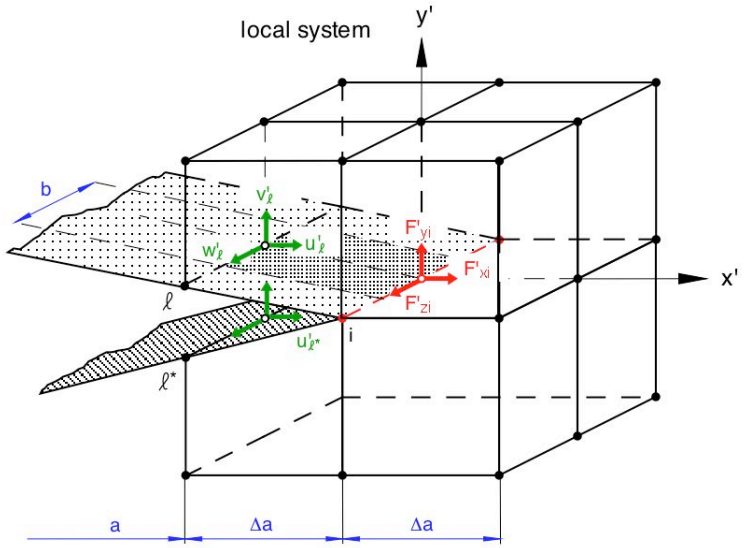
$$G_{II} = \frac{1}{2\Delta ab} \cdot F_{xi}' \cdot \left(u'_{\ell} - u'_{\ell^*} \right)$$



$$G_I = \frac{1}{2\Delta ab} \cdot F_{yi}' \cdot \left(v'_{\ell} - v'_{\ell^*} \right)$$

$$G_{II} = \frac{1}{2\Delta ab} \cdot F_{xi}' \cdot \left(u'_{\ell} - u'_{\ell^*} \right)$$

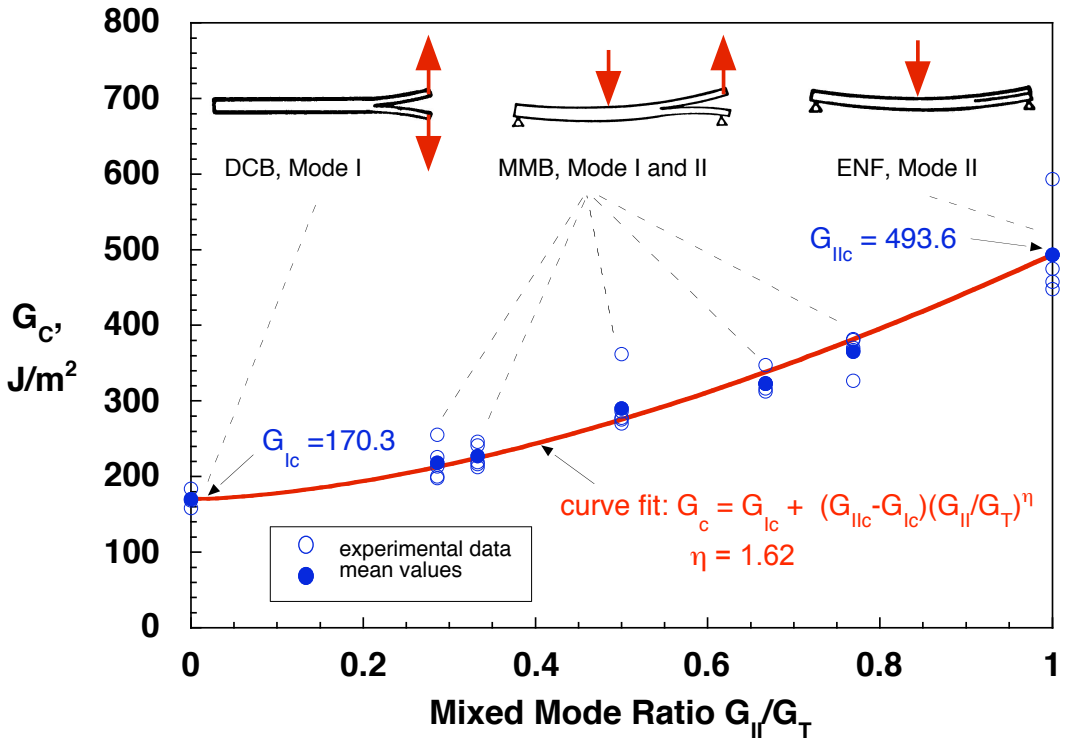
$$G_{III} = \frac{1}{2\Delta ab} \cdot F_{zi}' \cdot \left(w'_{\ell} - w'_{\ell^*} \right)$$



*E. F. Rybicki and M. F. Kanninen, Eng. Fracture Mech., vol. 9, pp. 931-938, 1977.

MIXED-MODE FAILURE CRITERION

- **Establish mixed mode I and II failure criterion (example: T300/914C)**



- **Calculate mixed mode ratio and total energy release rate**

$$G_T = G_I + G_{II} + G_{III}$$
$$G_S = G_{II} + G_{III}$$

- **Obtain critical energy release rate from failure criterion***

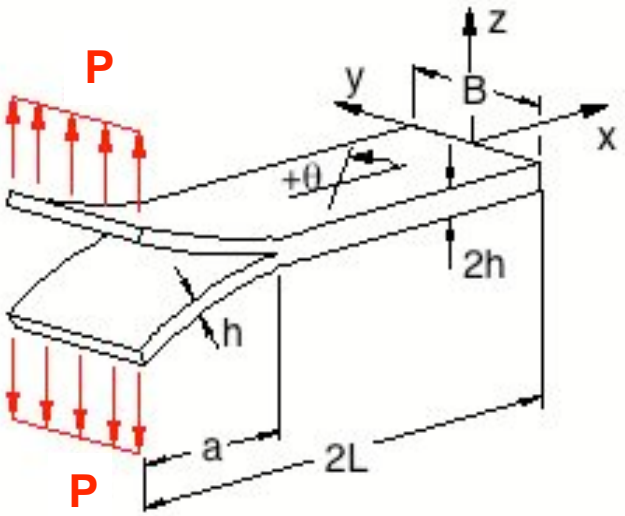
$$G_c = \left(G_{Ic} + \left(G_{IIc} - G_{Ic} \right) \cdot \left(\frac{G_S}{G_T} \right)^{\eta} \right)$$

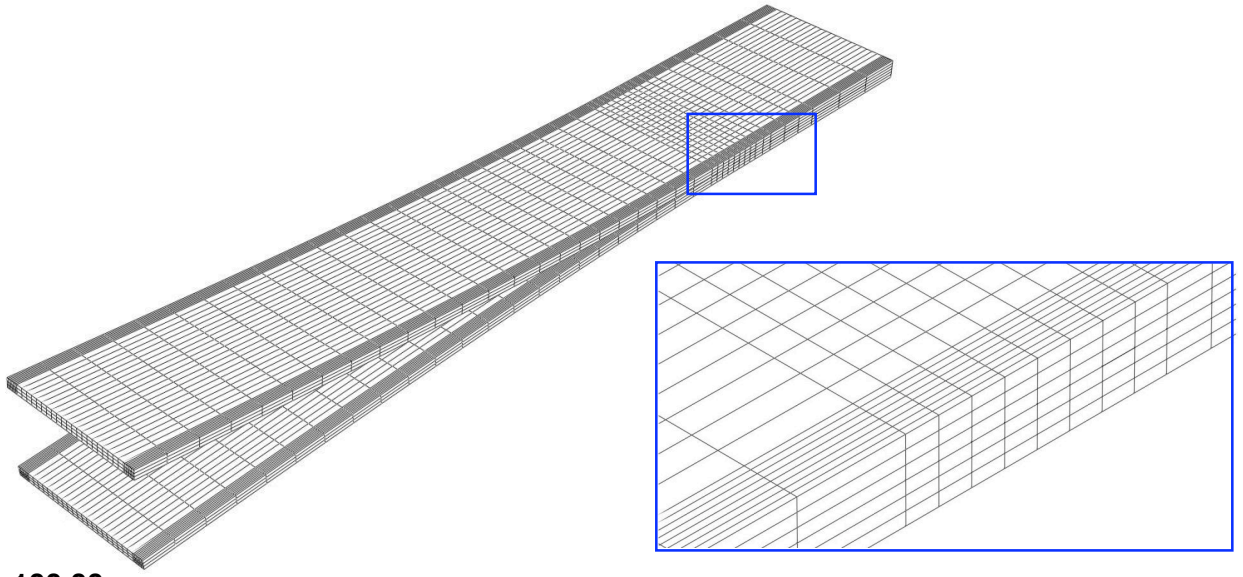
- **Calculate failure index**

$$\frac{G_T}{G_c} \geq 1$$

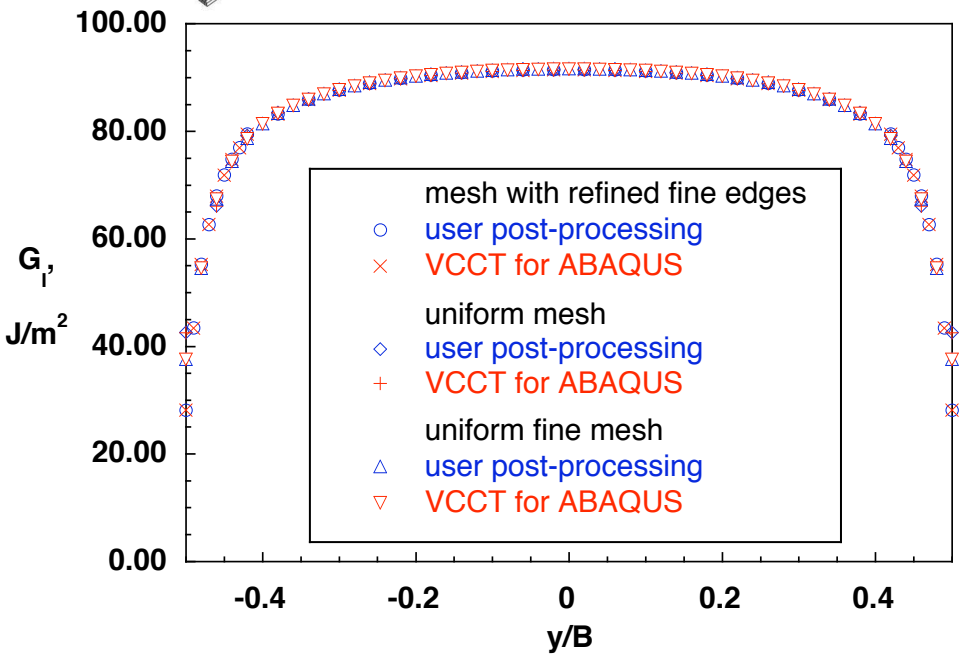
*Benzeggagh, Kenane, 1996

FRACTURE TOUGHNESS SPECIMENS
DCB Specimen - Mode I





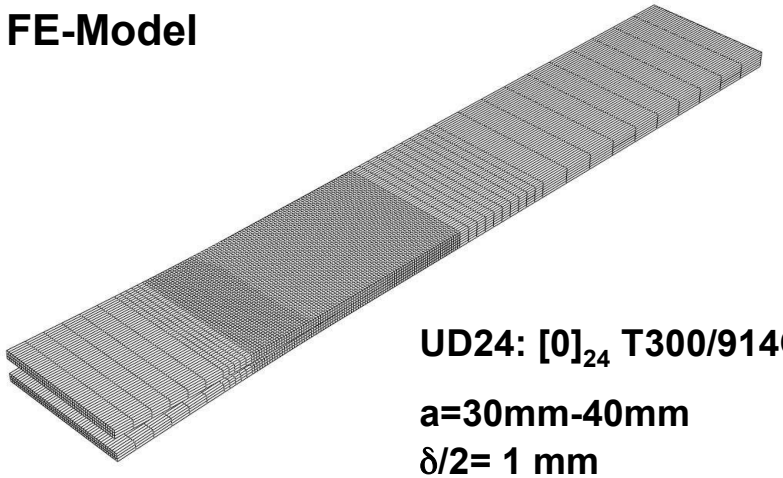
UD24: $[0]_{24}$ T300/914C



R. Krueger and D. Goetze,
Influence of Finite Element Software on Energy Release Rates Computed Using the Virtual Crack Closure Technique,
NIA Report No. 2006-06, NASA/CR-214523, 2006.

MANUALLY CREATING A BENCHMARK SOLUTION - DCB Specimen

- **FE-Model**

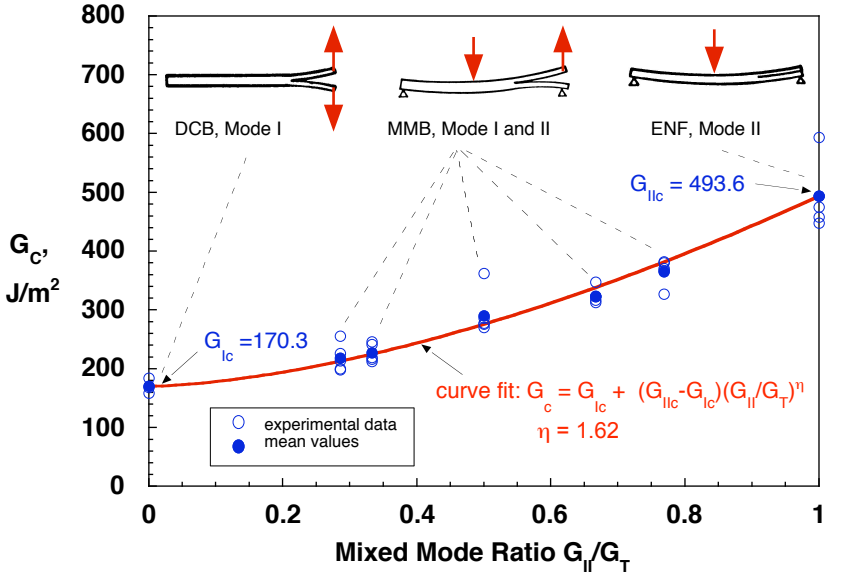


UD24: $[0]_{24}$ T300/914C

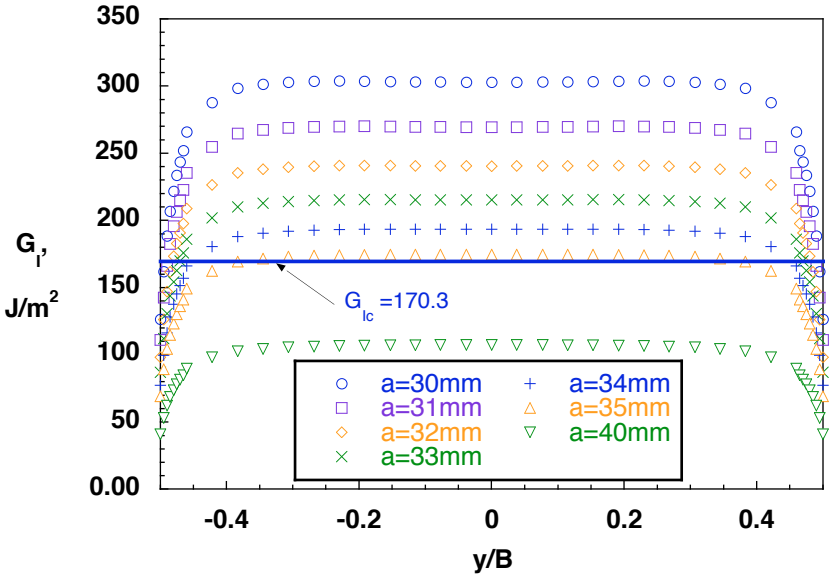
a=30mm-40mm

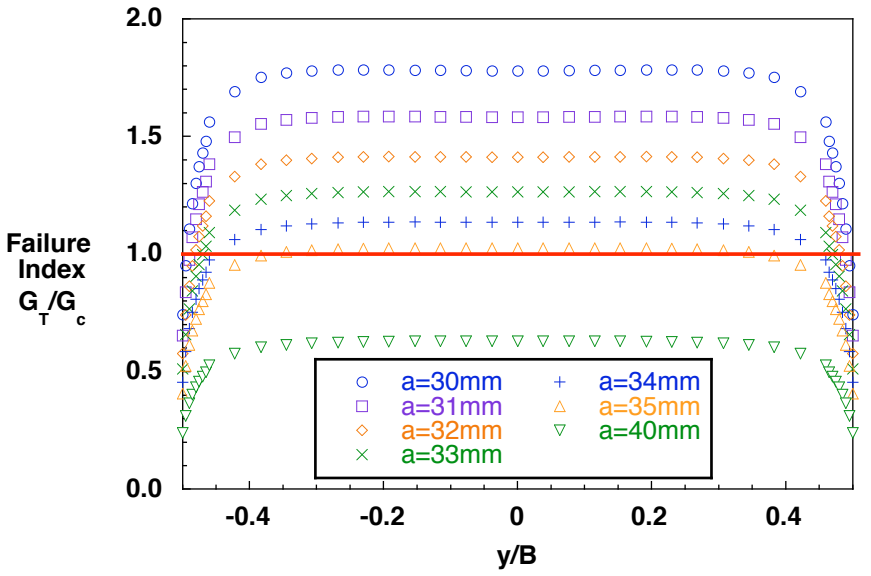
$\delta/2$= 1 mm

- **Mixed mode failure criterion for T300/914C**



- **G_I distribution**





MANUALLY CREATING A BENCHMARK SOLUTION - DCB Specimen

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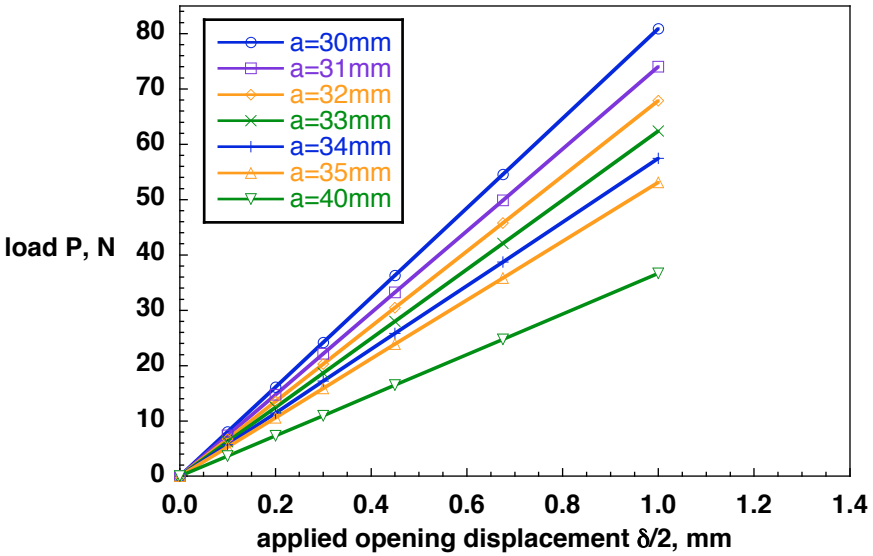
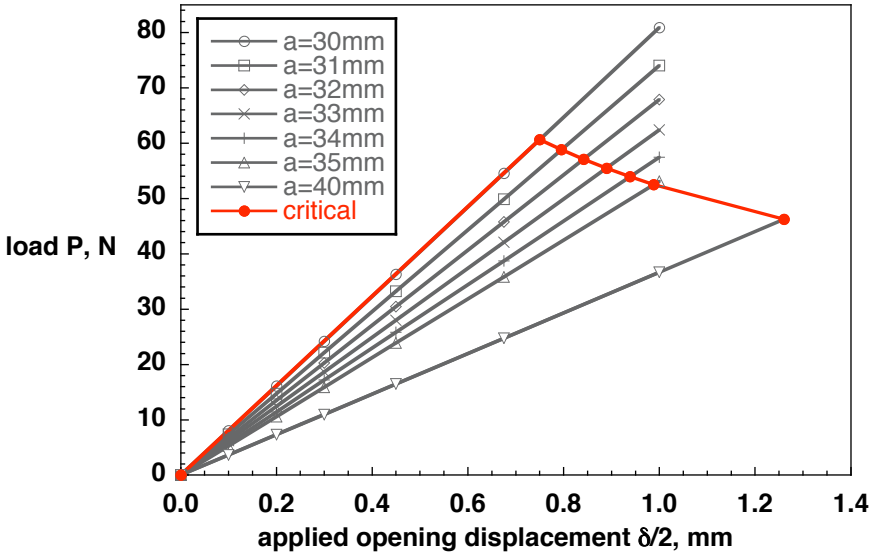
- **Load/displacement plots for different delamination lengths**



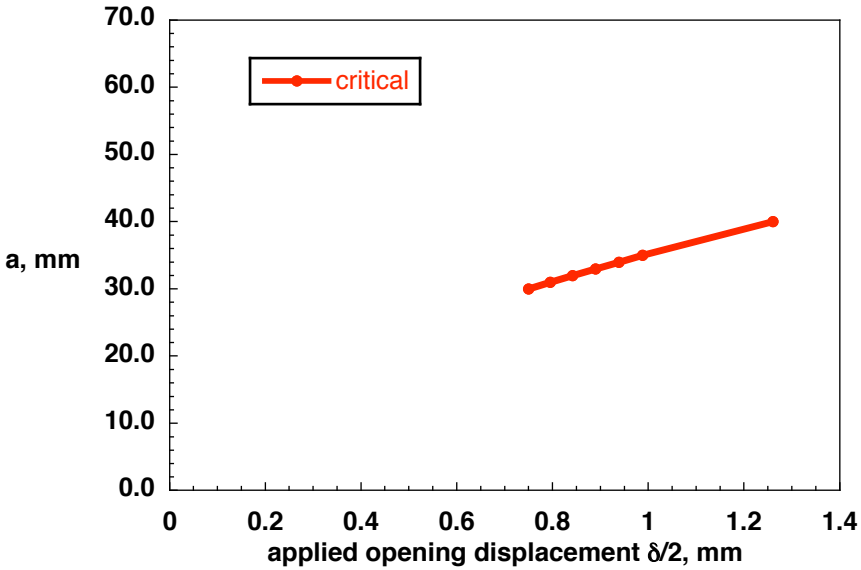
- **Benchmark**

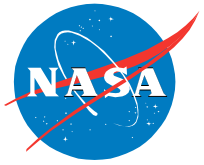


- **Mathematical relationship between load and energy release rate**

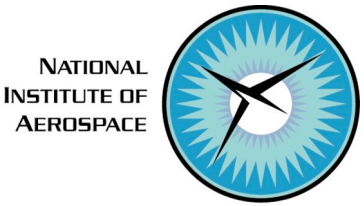
$$G = \frac{P^2}{2} \cdot \frac{\partial C_P}{\partial A} \Rightarrow \frac{G_T}{G_c} = \frac{P^2}{P_{crit}^2}$$

$$\Rightarrow P_{crit} = P\sqrt{\frac{G_c}{G_T}}, \quad \delta_{crit} = \delta\sqrt{\frac{G_c}{G_T}}$$



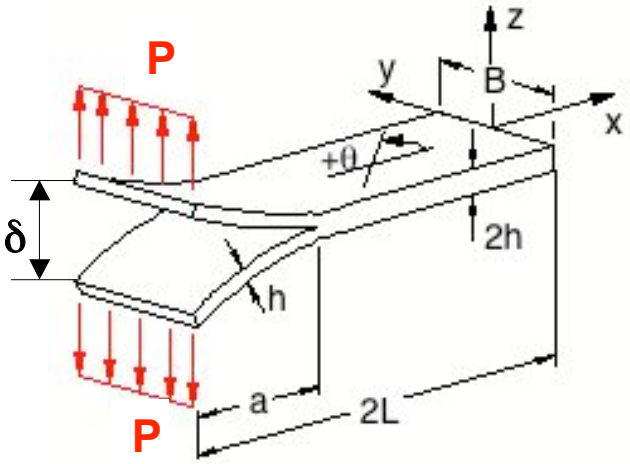


VCCT FOR ABAQUS INPUT PARAMETERS



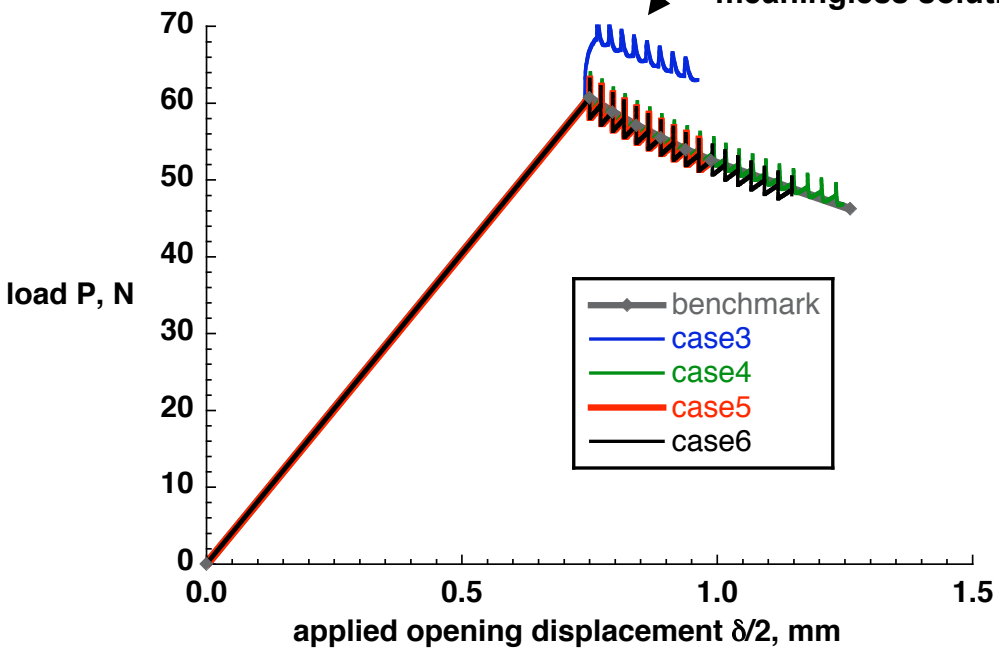
- **Input data for mixed-mode failure criterion (G_{Ic}, G_{IIc}, η) was kept constant for all analyses performed**
- **Initial and maximum increment size was selected at 0.001 *x* final load**
- **To overcome convergence problems, four parameters were adjusted**
  - If the ***release tolerance*** (***relTol***) is exceeded a cutback operation is performed which reduces the time increment**.** The cutback reduces the degree of overshoot and improves the accuracy of the local solution
  - ***Contact stabilization*** which is applied across only selected contact pairs and used to control the motion of two contact pairs while they approach each other in multi-body contact.
  - ***Global stabilization*** which is applied to the motion of the entire model and is commonly used in models that exhibit statically unstable behavior such as buckling.
  - ***Viscous regularization*** (***damv***) which is applied only to nodes on contact pairs that have just debonded. The viscous regularization causes the tangent stiffness matrix of the softening material to be positive for sufficiently small time increments.

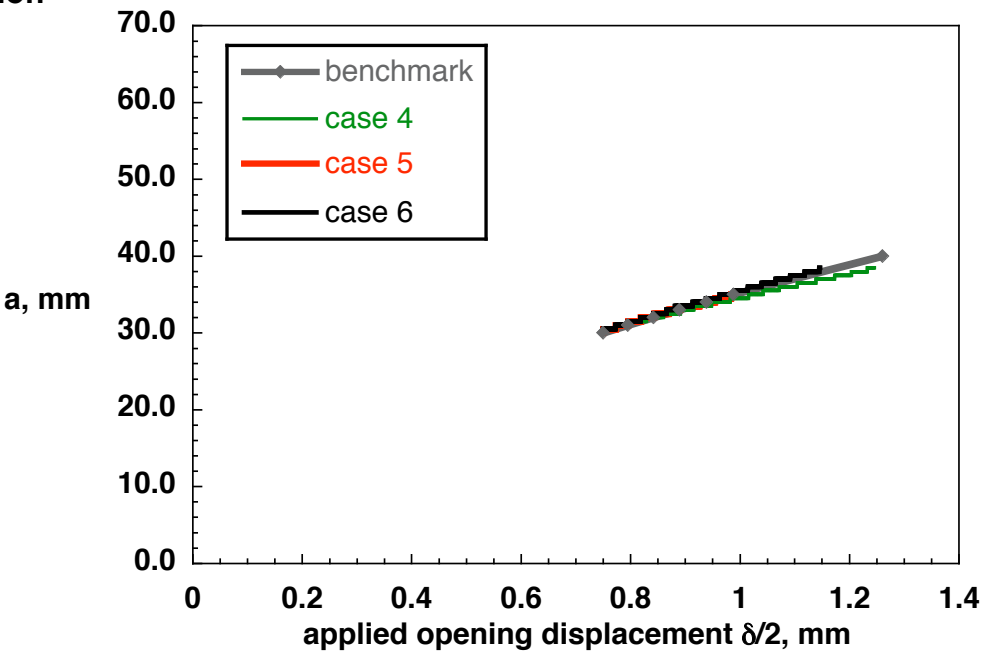
DELAMINATION PROPAGATION IN DCB SPECIMEN - Global Stabilization



case	3	4	5	6	7	8
input	E-5	E-6	E-7	E-8	E-8	E-8
relTol	0.2	0.2	0.2	0.2	0.02	0.002

Default settings converge but yield a meaningless solution





DELAMINATION PROPAGATION IN DCB SPECIMEN

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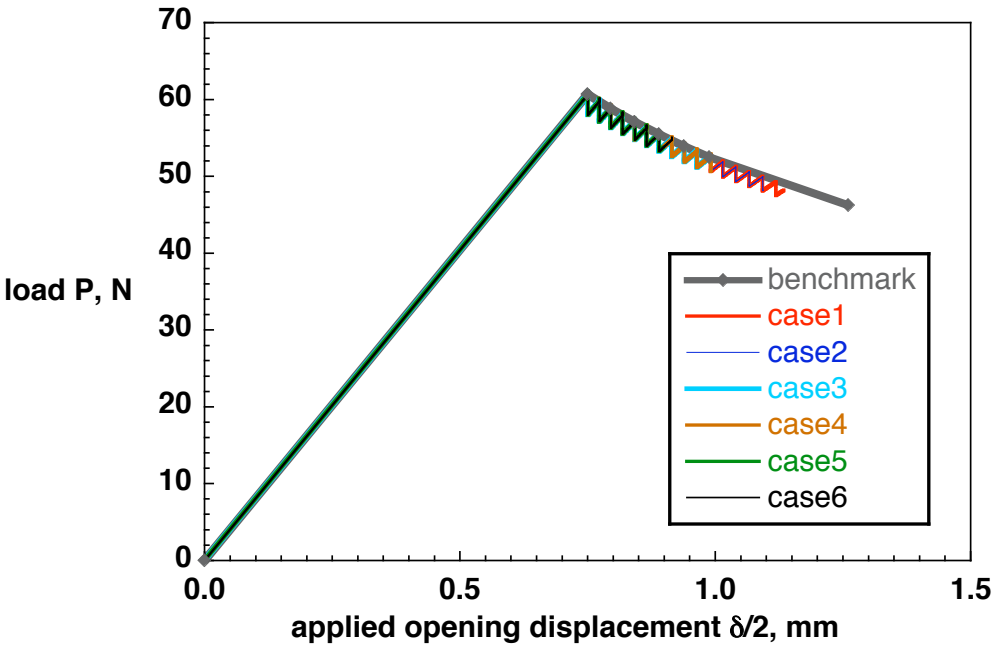
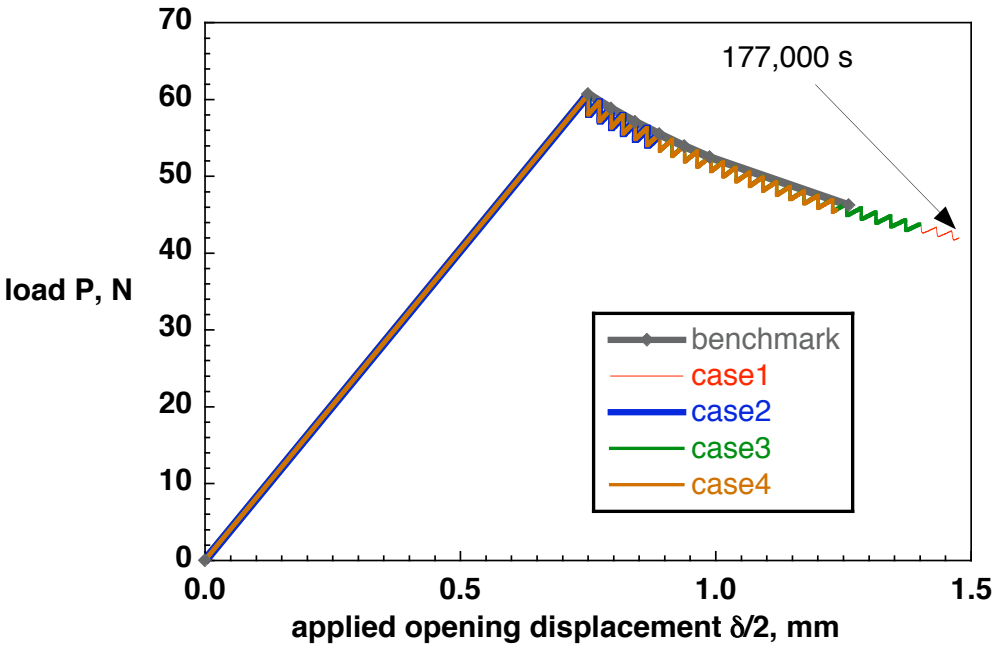
- **Contact Stabilization**

contact	1	2	3	4	5	6
input	E-5	E-6	E-7	E-7	E-7	E-3
relTol	0.2	0.2	0.2	0.02	0.002	0.002

- **Viscous Regularization**

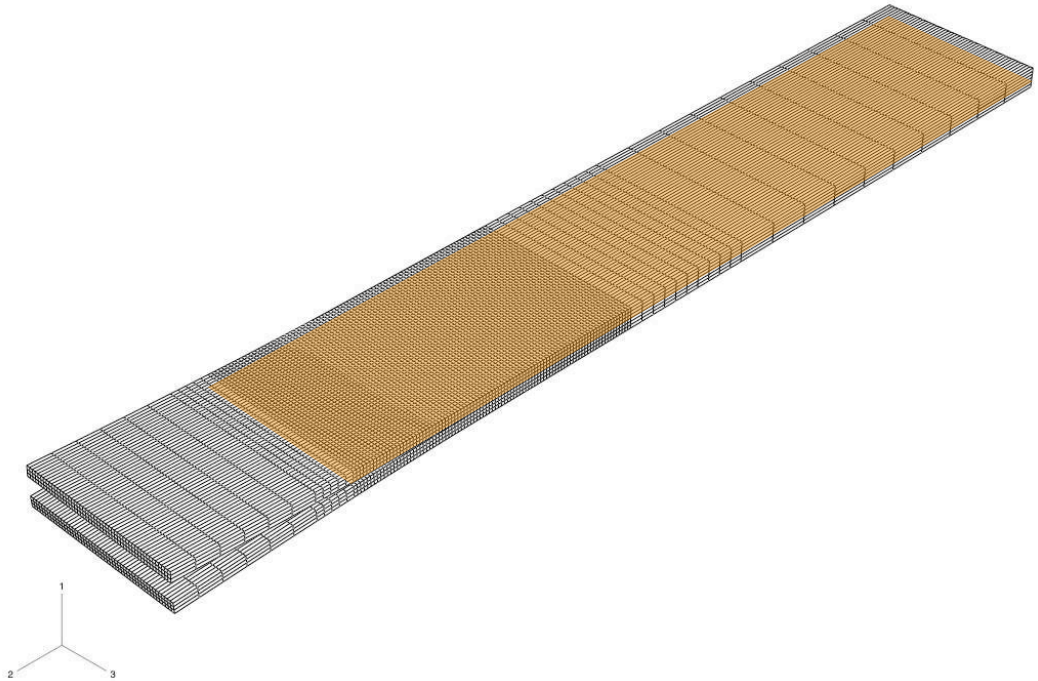
case	1	2	3	4
damv	E-4	E-4	E-5	E-5
relTol	0.5	0.3	0.5	0.3



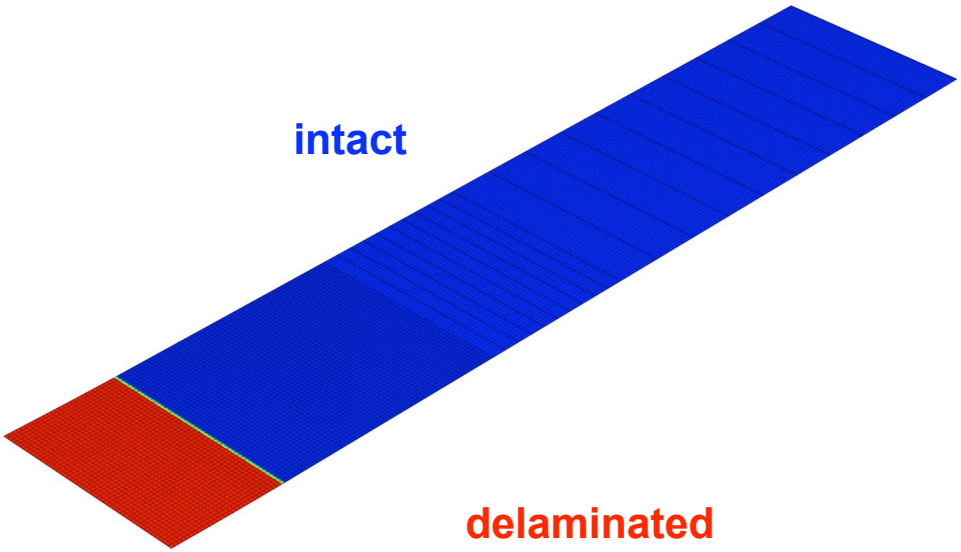


DELAMINATION PROPAGATION IN DCB SPECIMEN - Shape of developing delamination front

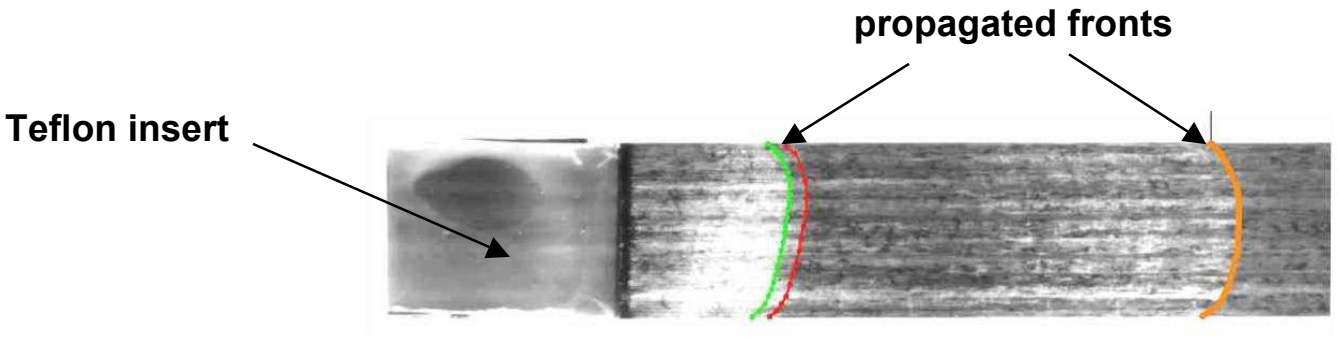
- Deformed model and contact surface



- Bond state after 1000 increments

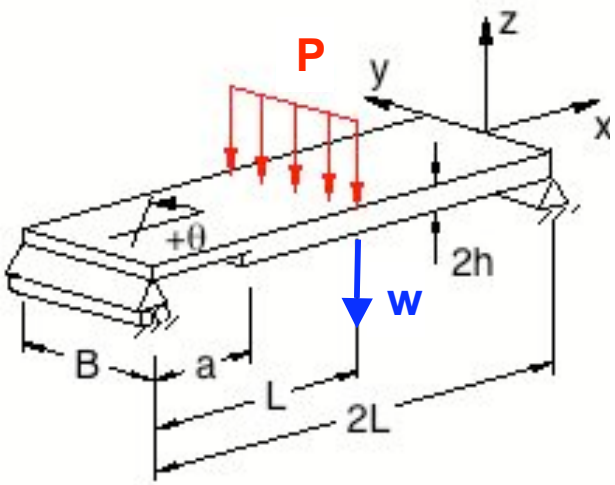


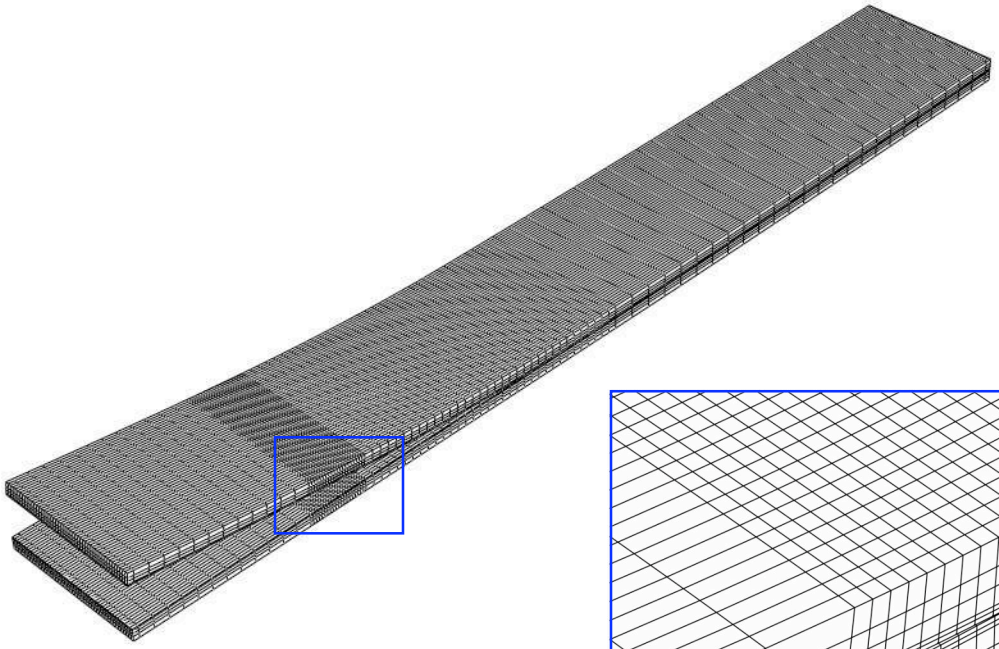
- Experimental observation

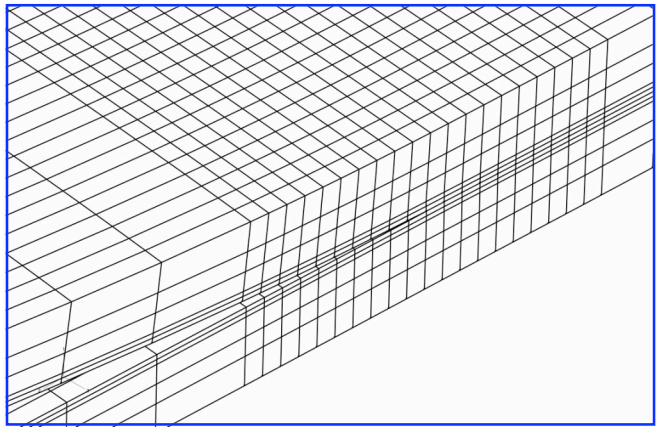


DELAMINATION PROPAGATION

FE Model of SLB Specimen - Mode I/II







D±30: C12K/R6376

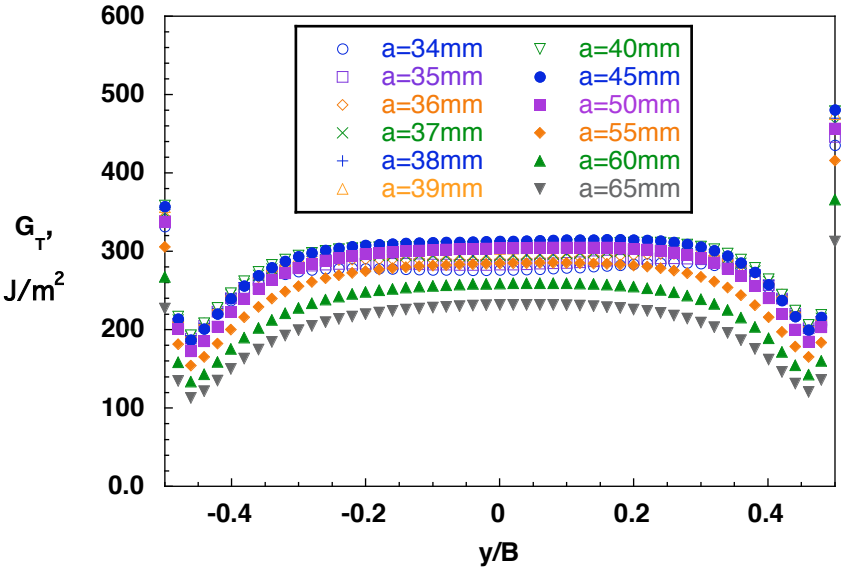
a=34-65 mm
w=2.8 mm

46500 C3D8I elements
57528 user defined nodes
789477 variables in the model

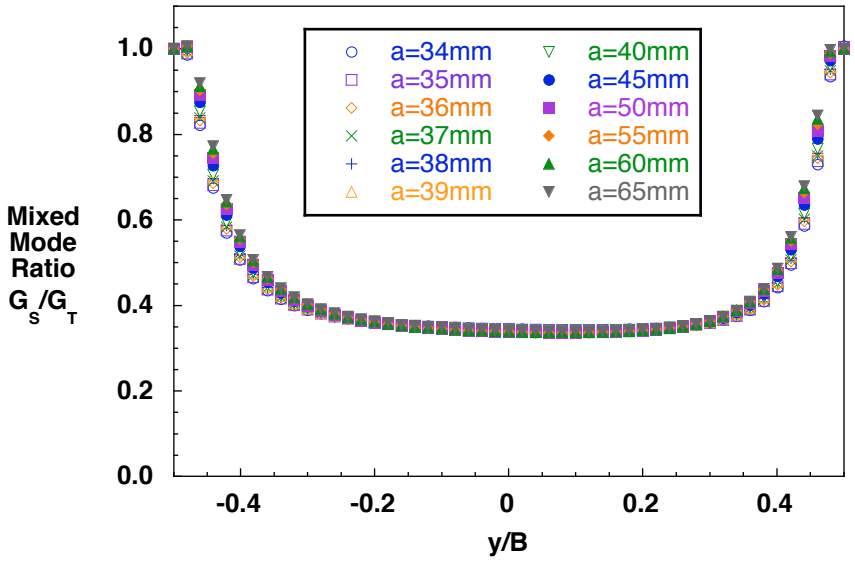
D±30: [±30/0/-30/0/30/0_4/30/0/-30/0/-30/30/ -30/30/0/30/0/-30/0_4/-30/0/30/±30]

MANUALLY CREATING A BENCHMARK SOLUTION - SLB Specimen

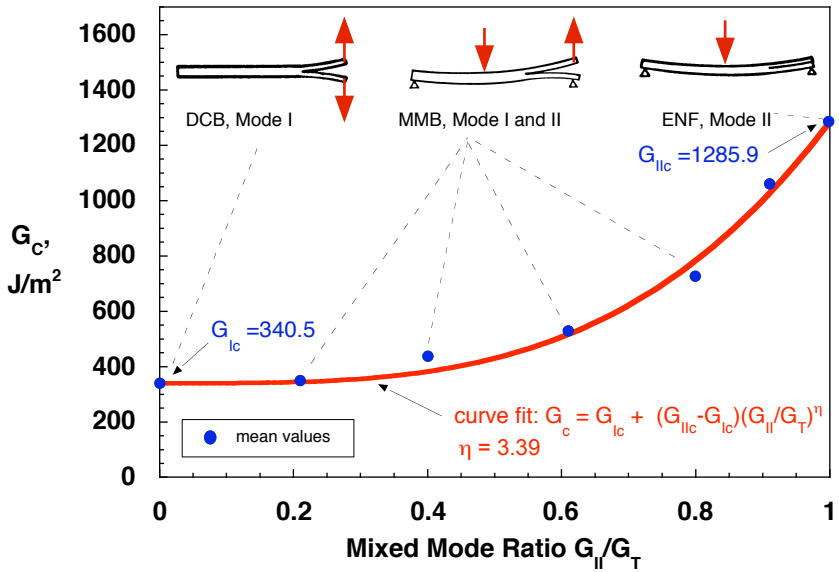
- G_T distribution



- Mixed mode ratio G_S/G_T



- Mixed mode failure criterion for C12K/R6376



MANUALLY CREATING A BENCHMARK SOLUTION - SLB Specimen

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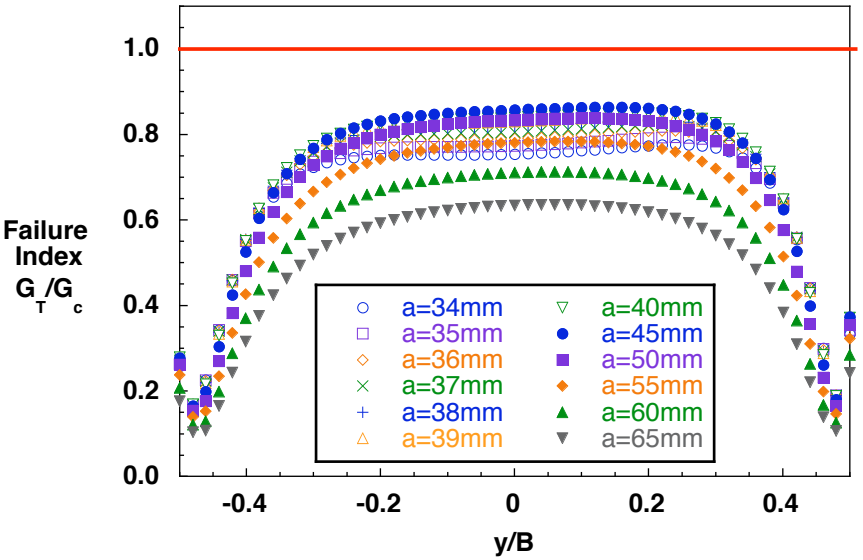
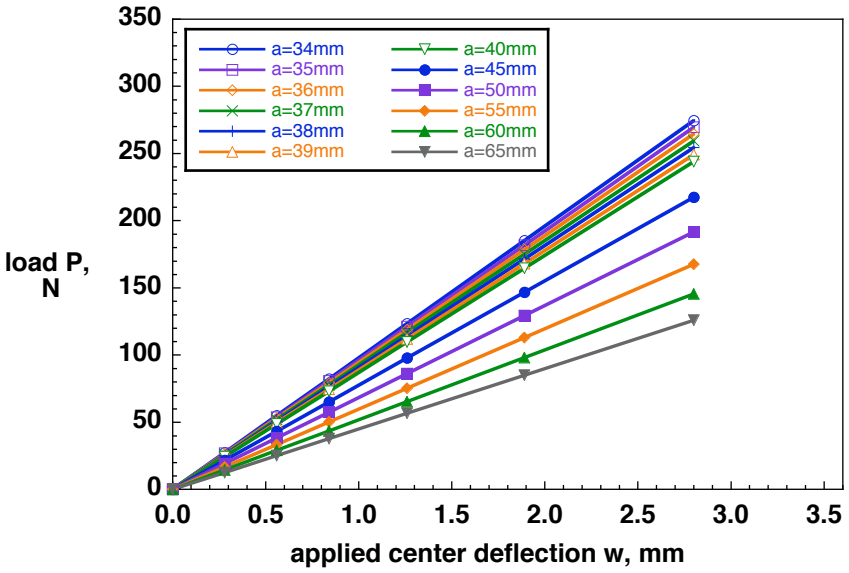
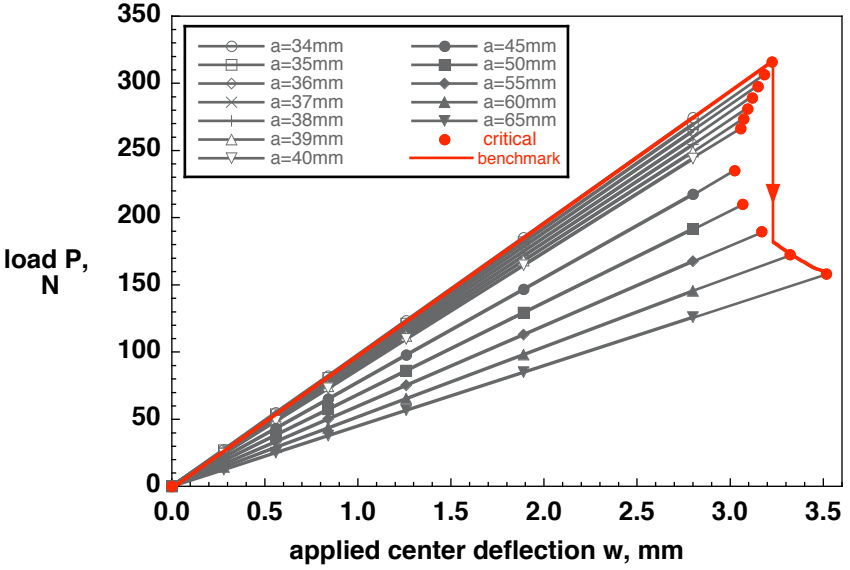
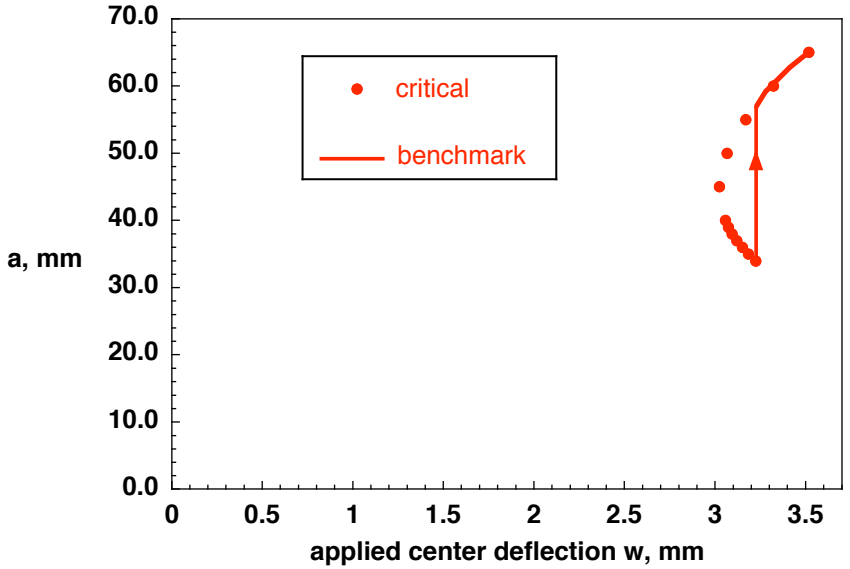
- Failure index and load/displacement for different a





- Benchmark





DELAMINATION PROPAGATION IN SLB SPECIMEN

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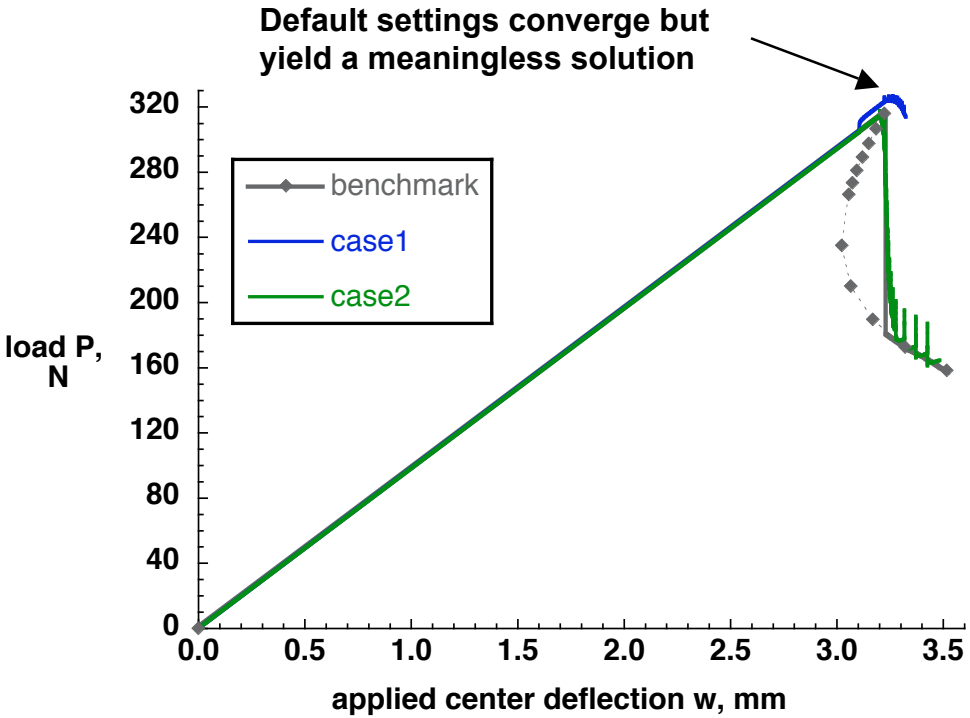
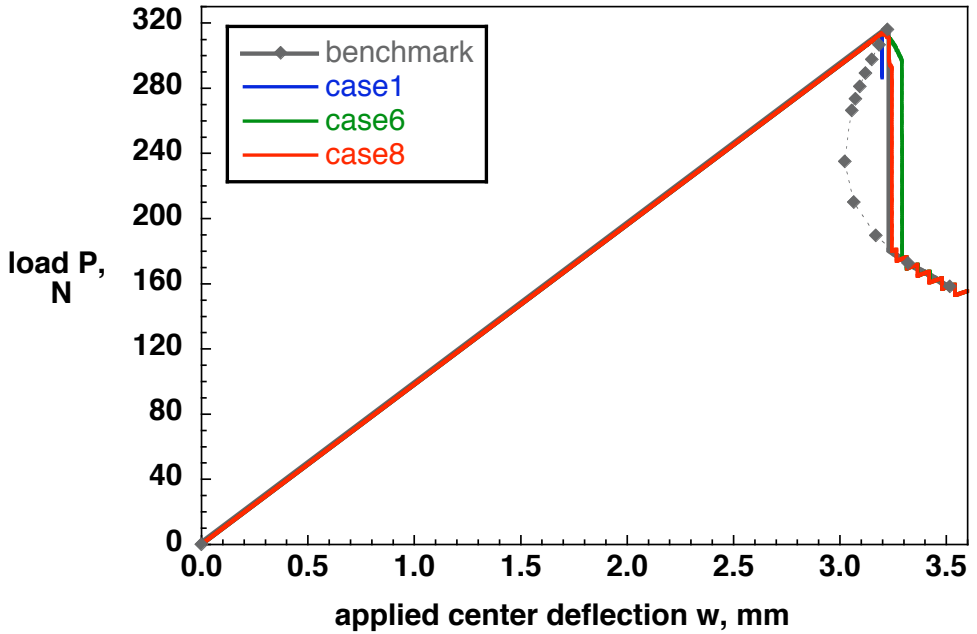
- **Global Stabilization**

case	*1*	*2*
input	E-5	E-6
relTol	0.2	0.2

- **Contact Stabilization**

case	*1*	*6*	*8*
input	E-6	E-3	E-4
relTol	0.2	0.5	0.5





DELAMINATION PROPAGATION IN SLB SPECIMEN

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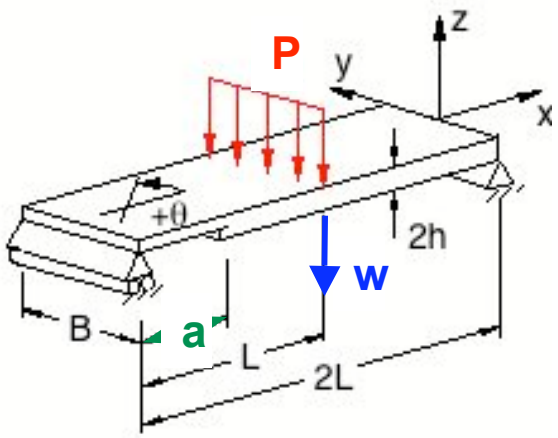
- **Viscous Regularization**

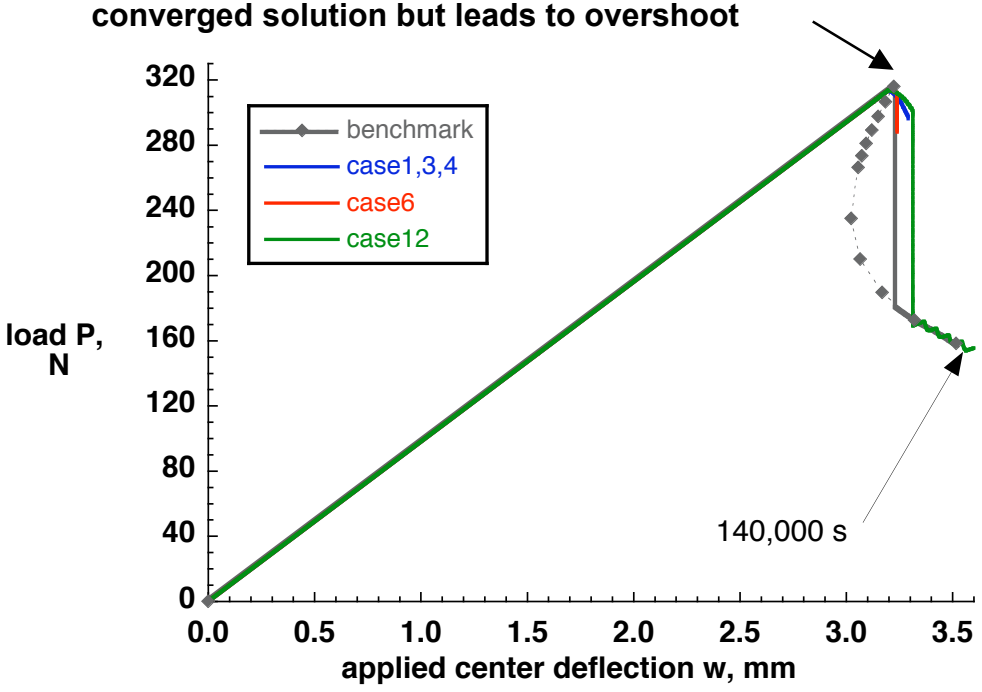
case	1	3	4	6	12
damv	E-5	E-4	E-6	E-2	0.1
relTol	0.5	0.5	0.5	0.5	0.9

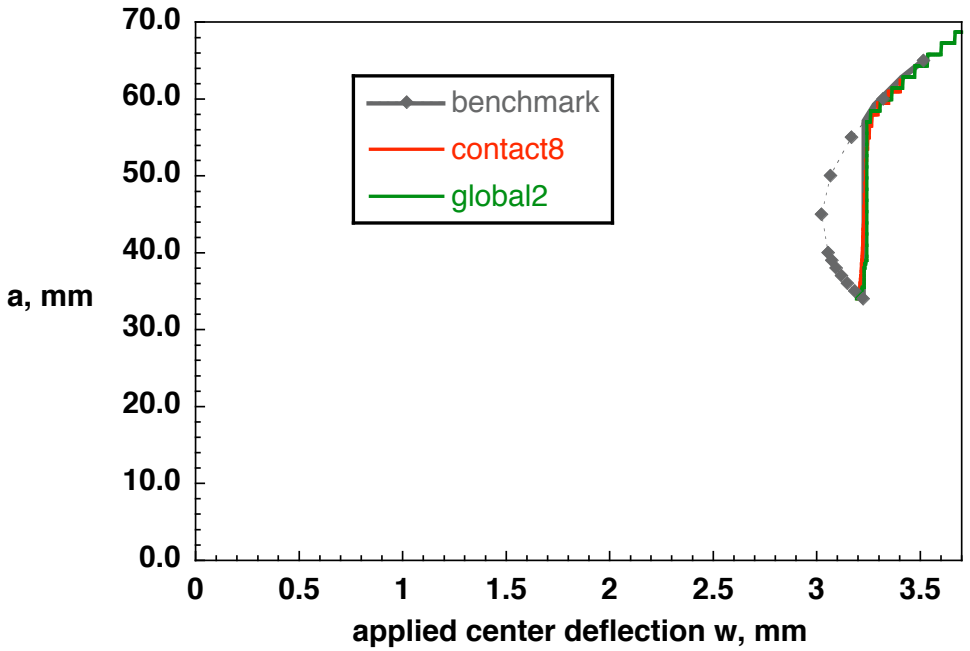
- **Crack length plot**



case	8	2
value	E-6	E-6
relTol	0.2	0.2

Increased release tolerance required to obtain converged solution but leads to overshoot





DELAMINATION PROPAGATION IN SLB SPECIMEN - Shape of developing delamination front

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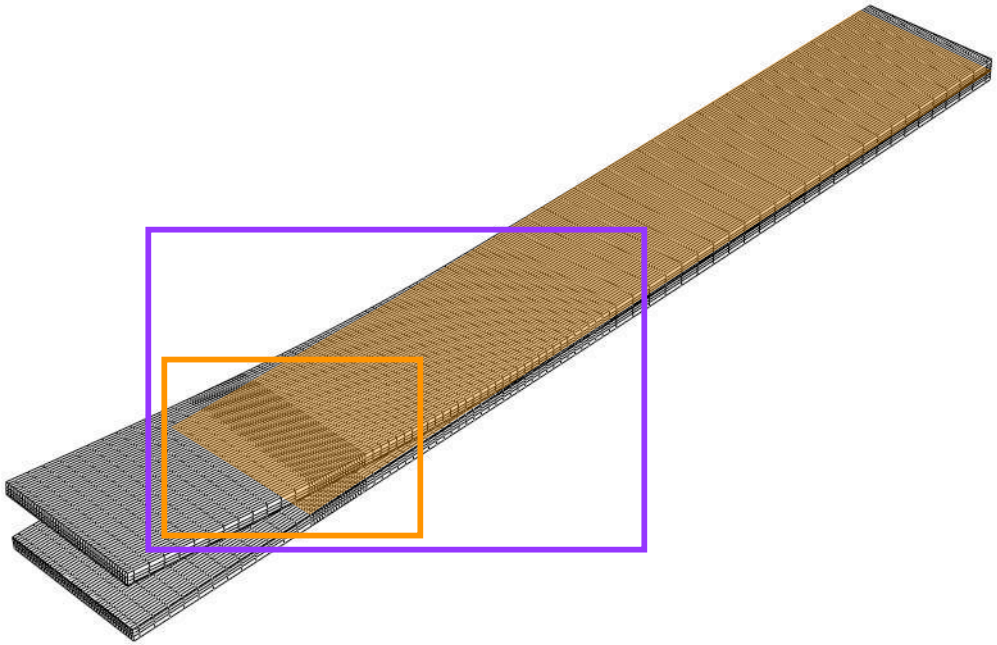
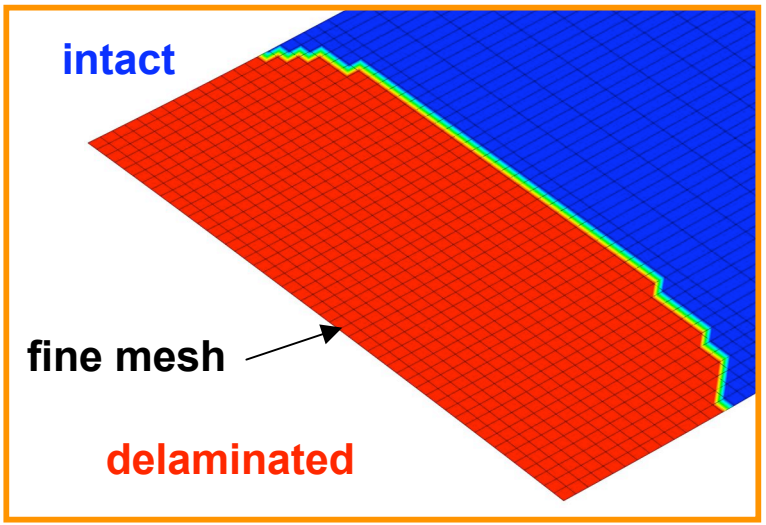
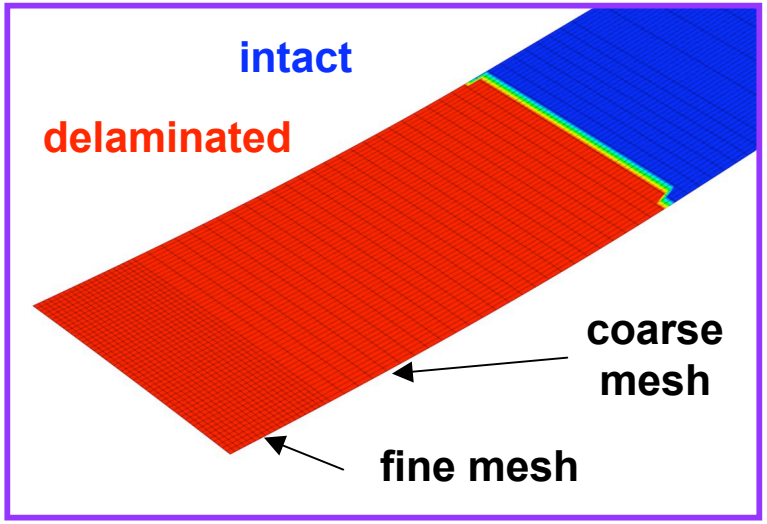
- Deformed model and contact surface



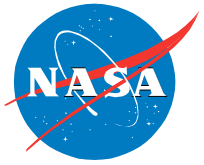
- Bond state after 76 increments



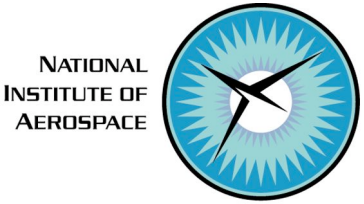
- Bond state after 1000 increments



- Accurately computing the delamination front shape requires fine meshes



CONCLUDING REMARKS



- Mixed-mode energy release rates computed from VCCT for ABAQUS® were in good agreement with results from a post-processing routine
- After testing the automated propagation capability in VCCT for ABAQUS® it is concluded that
  - Selecting the appropriate input parameters to obtain good results requires an iterative procedure
  - Results may converge but yield a meaningless solution
  - The default settings for global stabilization yielded unsatisfactory results
  - Best results were obtained when contact stabilization and viscous regularization were used
  - Accurately computing the delamination front shape requires fine meshes
  - Additional assessment of the propagation capabilities in more complex specimens and on a structural level is required