DEVELOPMENT OF BENCHMARK EXAMPLES FOR DELAMINATION ONSET AND FATIGUE GROWTH PREDICTION

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Imperial College, London, United Kingdom, August 3, 2011

OUTLINE

- Background
- Why is benchmarking important?
- Development of a benchmark example for delamination propagation prediction under static loading
- Demonstration of the benchmark example for ABAQUS® Standard
  - Comparison of predicted propagation with benchmark example
  - Dependency of results on selection of input parameters
  - Discussion of problems encountered
- Application of example to MARC and MSC.NASTRAN
- Example for delamination growth prediction under cyclic loading
- Summary
- Ongoing and future work

BACKGROUND: Delamination Sources at Geometric and Material Discontinuities

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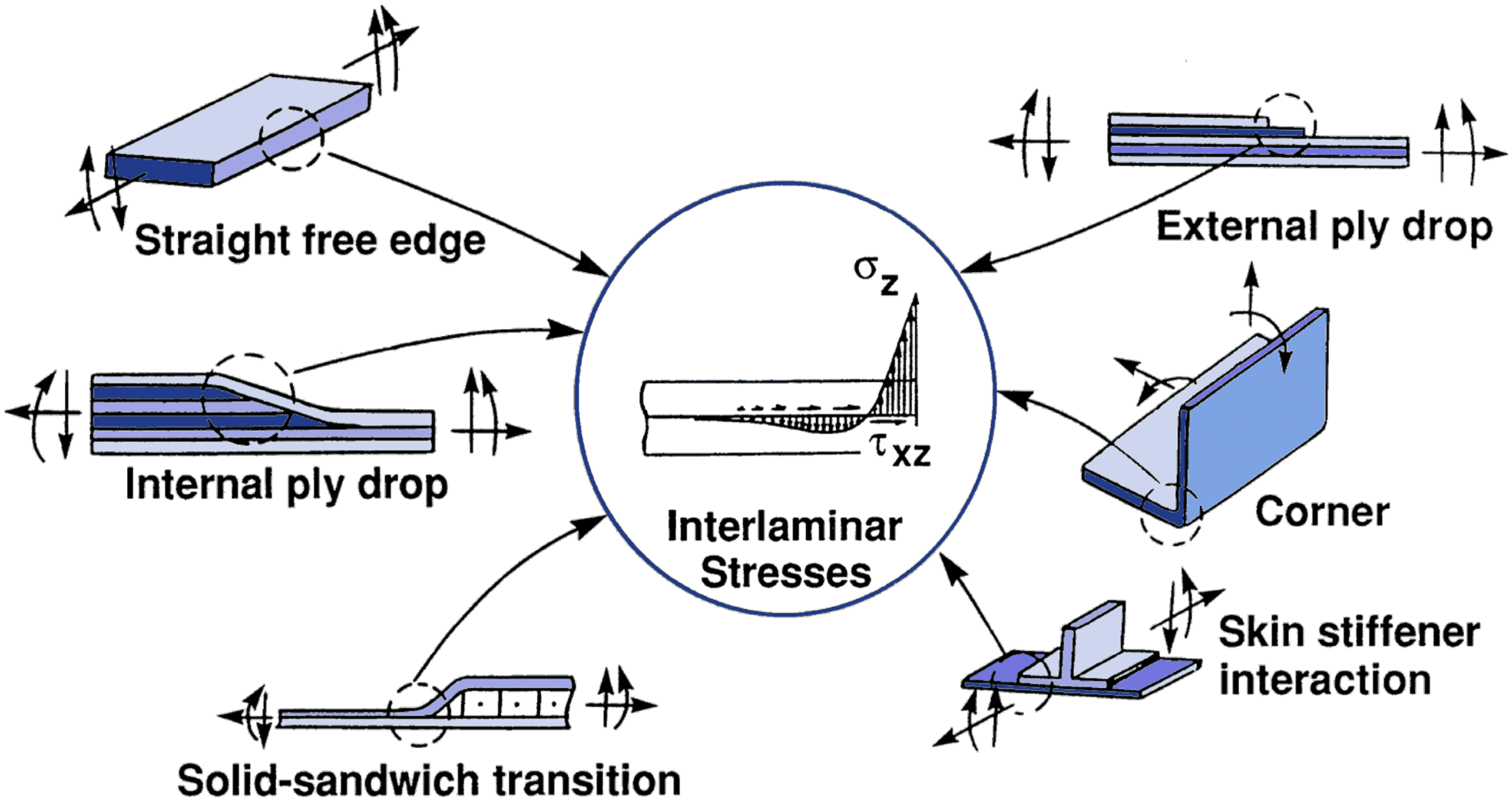
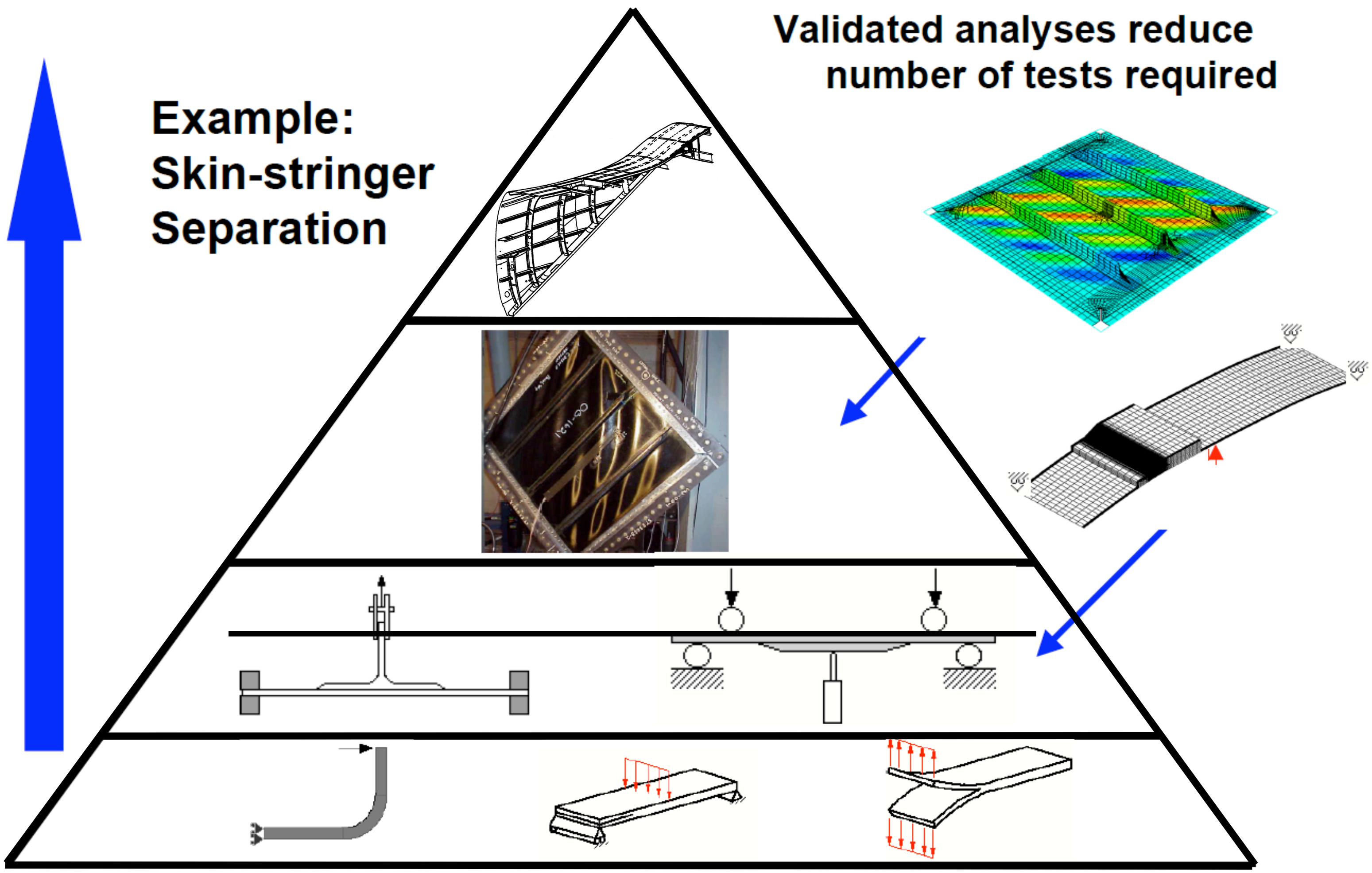


BACKGROUND

Building Block Approach for Design and Certification



WHY BENCHMARKING ?

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 FE-codes or user written post-processing routines
- Crack extension or delamination propagation analyses performed manually which was time consuming

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Today

- Boeing's VCCT element (commercialized first as VCCT for ABAQUS®, now available in ABAQUS® Standard 6.8, 6.9, 6.10)
- MARC™, NASTRAN™ SOL 600 and SOL 400 include VCCT options
- Other codes … (e.g. SAMCEF™, GENOA™, ESRD StressCheck®, ANSYS®)
- Automatic propagation analysis and fatigue crack growth is possible

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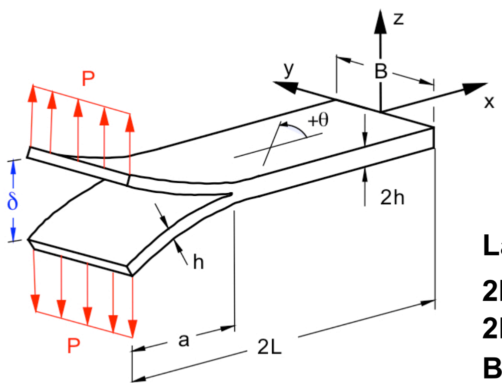
Therefore

- Benchmarking is required to gain confidence in the software tools used
- Benchmarking highlights the issues associated with the input of a particular code
- Once the parameters have been identified, they may be used as starting point to model more complex configurations
- Benchmark cases have to be simple and independent of software used

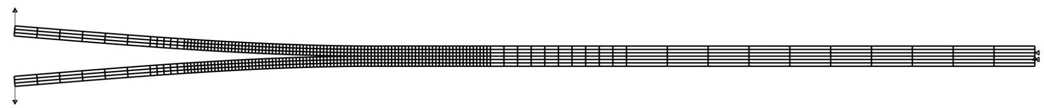
BENCHMARK PROBLEM:
DCB Specimen

DCB specimen

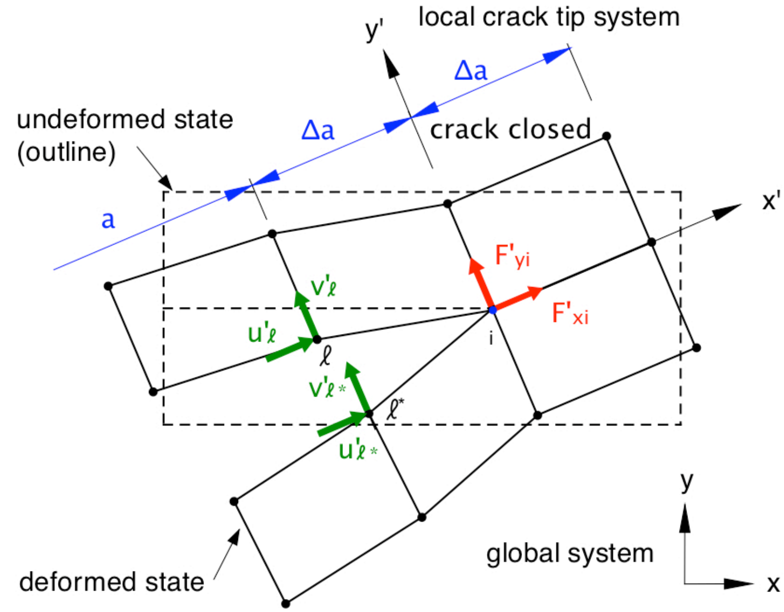


Layup: $[0]_{24}$
2h=3.0 mm
2L=150.0 mm
B=25.0 mm
a=30.5 mm

2D plane strain and plane stress analysis

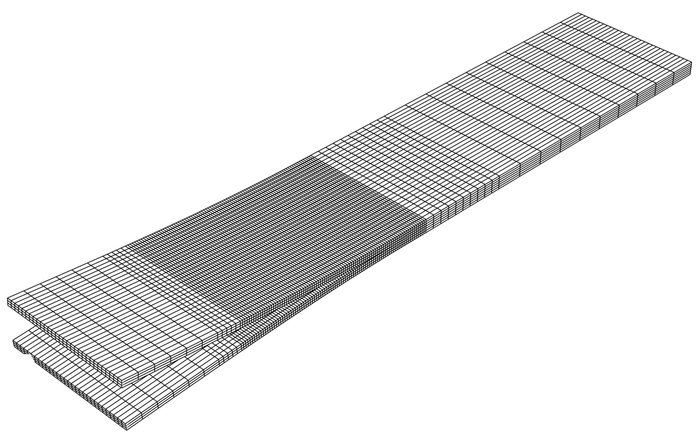


Virtual Crack Closure Technique (VCCT)*



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

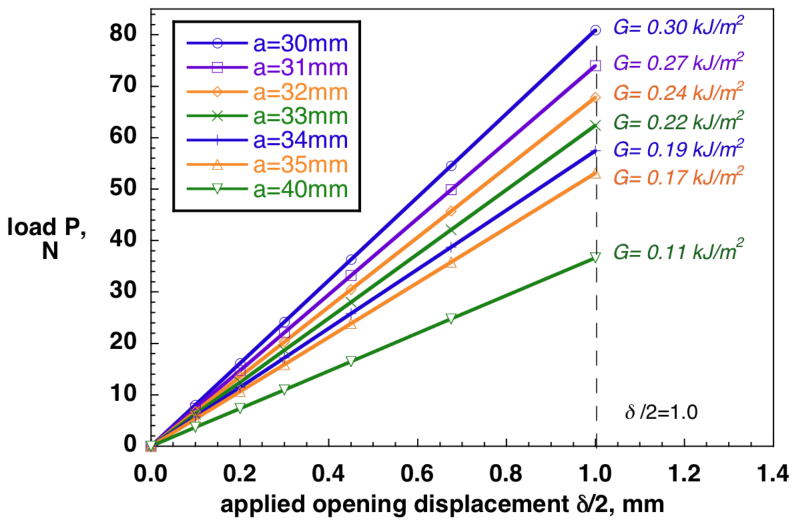
Full 3D solid analysis



*Rybicki and Kanninen, Eng. Fracture Mech., 1977.

MANUAL BENCHMARK SOLUTION:
DCB Specimen*

Load/displacement plots for different delamination lengths a (δ/2=1.0 mm)



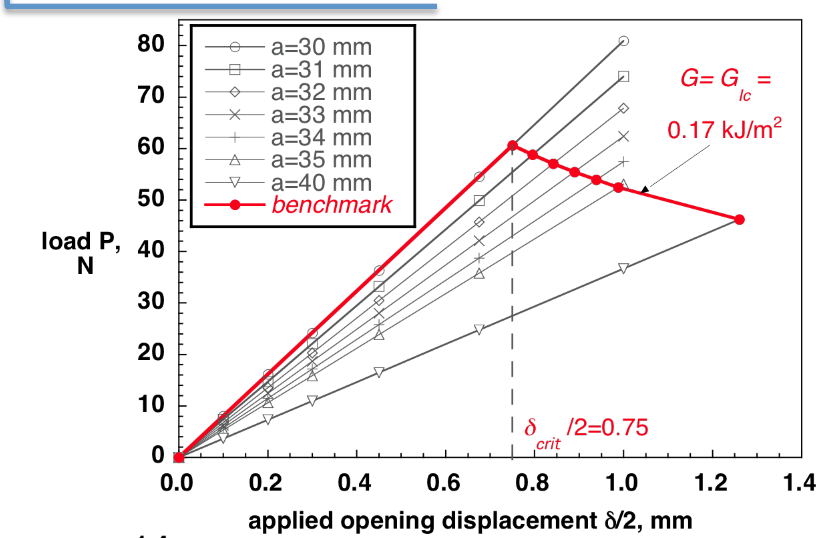
Mathematical relationship between load and energy release rate

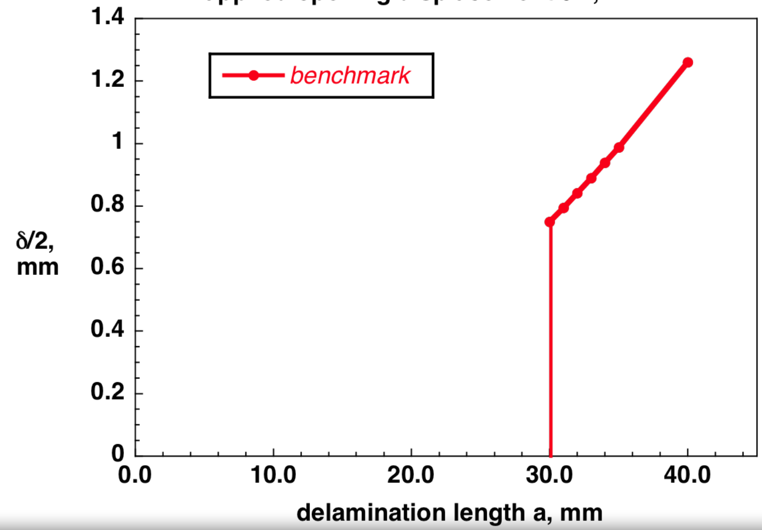
$$G = \frac{P^2}{2} \cdot \frac{\partial C_P}{\partial A} \Rightarrow \frac{G_T}{G_c} = \frac{P^2}{P_{crit}^2}$$

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

*Krueger, NASA/TM-2008-215123, 2008.

Benchmark case





DEMONSTRATION FOR ABAQUS® STANDARD:
DCB Specimen*

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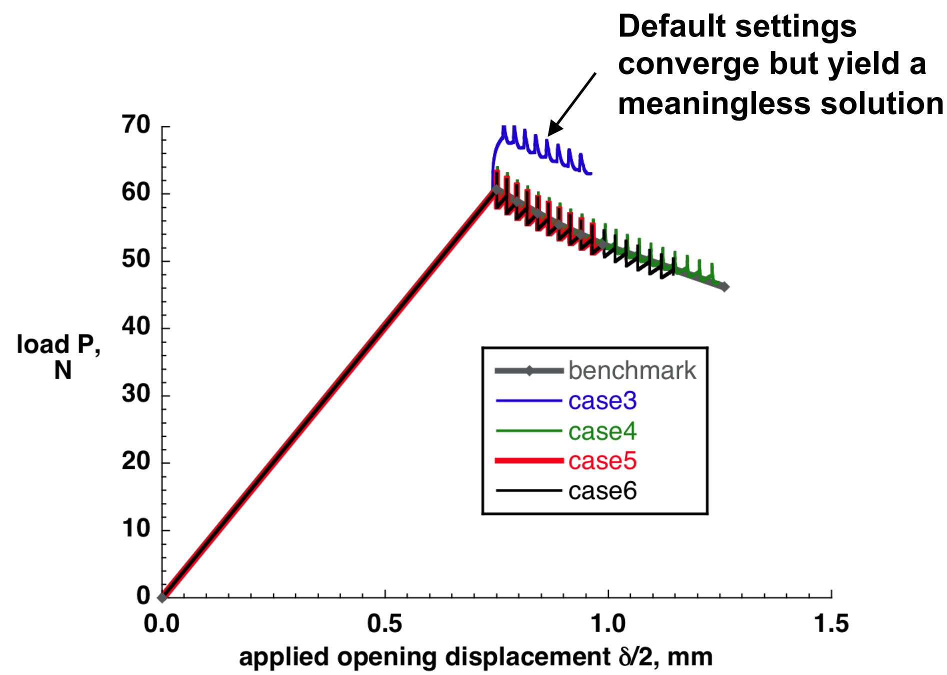
Assessment based on the comparison of benchmark and automated propagation

- **Input data for delamination failure criterion was kept constant for all analyses performed**
- **Initial and maximum increment size were selected at 0.001 *x* final load**
- **To overcome convergence problems, four parameters may be adjusted**
  - *release tolerance (relTol)*
  - *Contact stabilization (cs)*
  - *Global stabilization (gs)*
  - *Viscous regularization (damv)*

Global stabilization

case	*3*	*4*	*5*	*6*	*7*	*8*
gs	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



*Krueger, NASA/TM-2008-215123, 2008.

DEMONSTRATION FOR ABAQUS® STANDARD:
DCB Specimen* - continued

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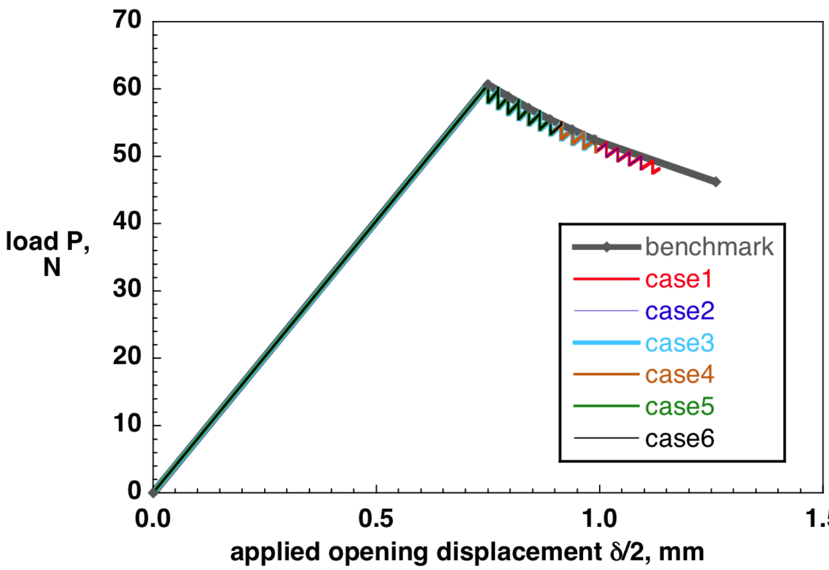
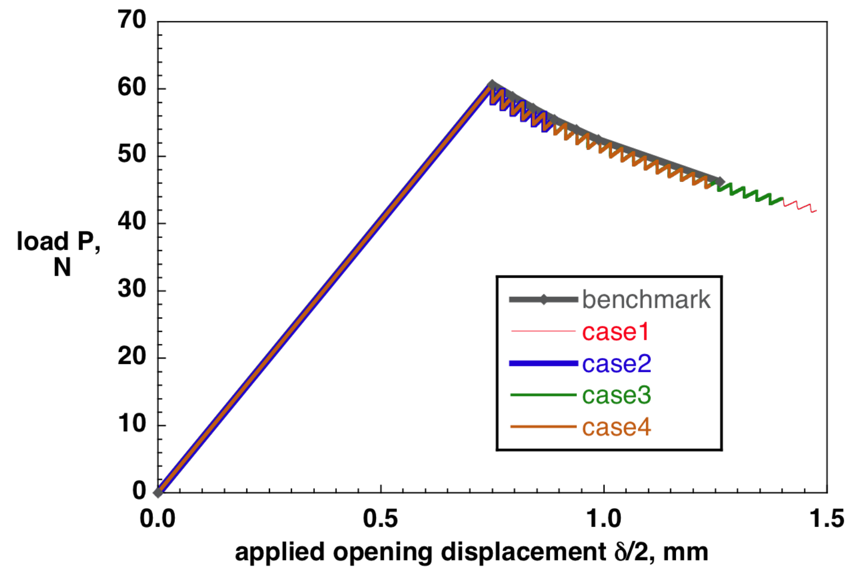
Contact Stabilization

case	1	2	3	4	5	6
cs	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



- Iterative procedure required to find appropriate combination of input values

*Krueger, NASA/TM-2008-215123, 2008.

NAFEMS BENCHMARK CASE OF A DCB SPECIMEN*

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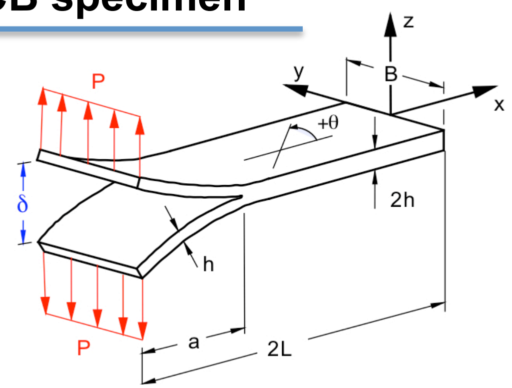
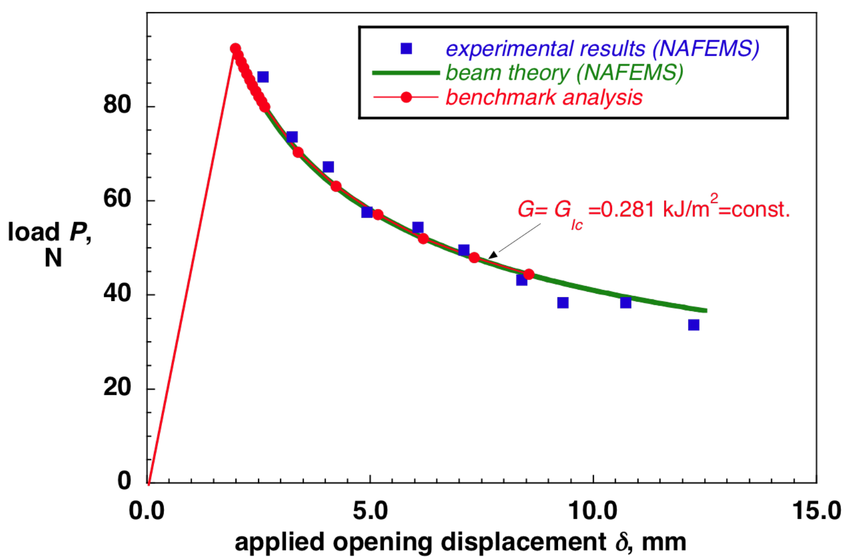
DCB specimen



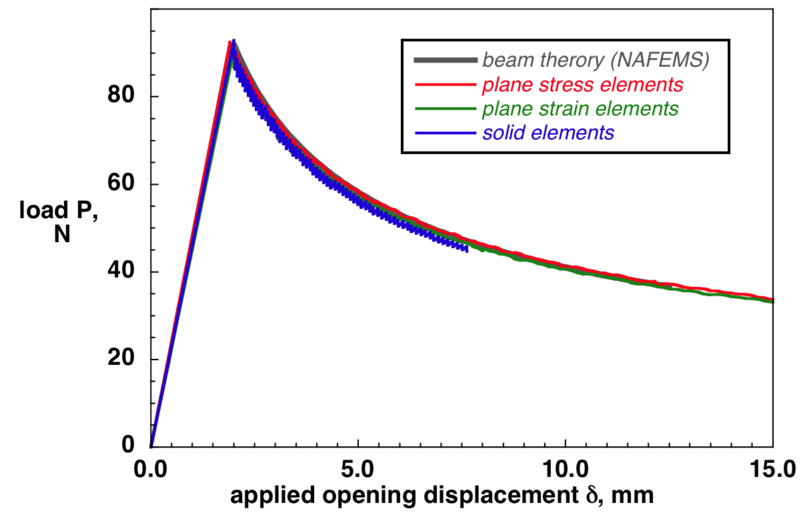
Layup: $[0]_{24}$
2h=3.0 mm
2L=150.0 mm
B=30.0 mm
a=30.0 mm

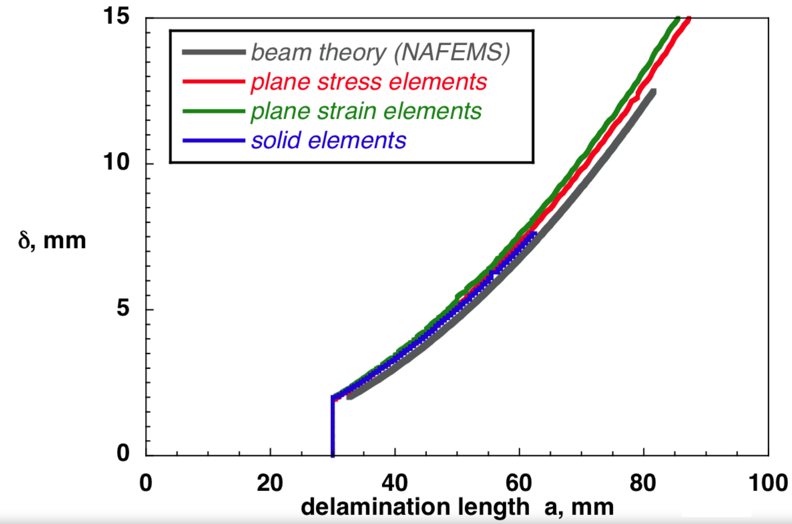
Benchmark case



*G.A.O. Davies, R00084, NAFEMS, 2002.

Assessment





MANUAL BENCHMARK SOLUTION:
Single-Leg Bending (SLB) Specimen*

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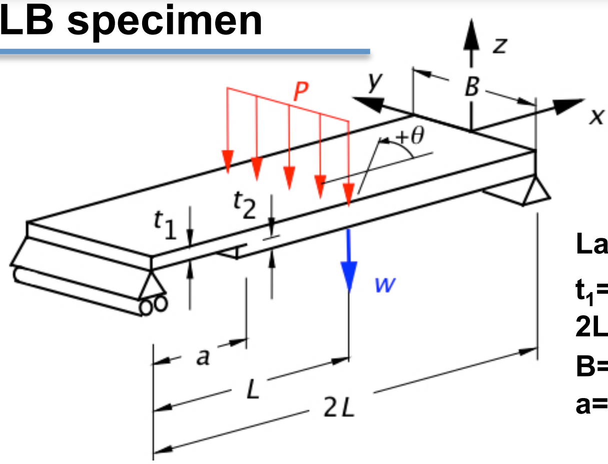
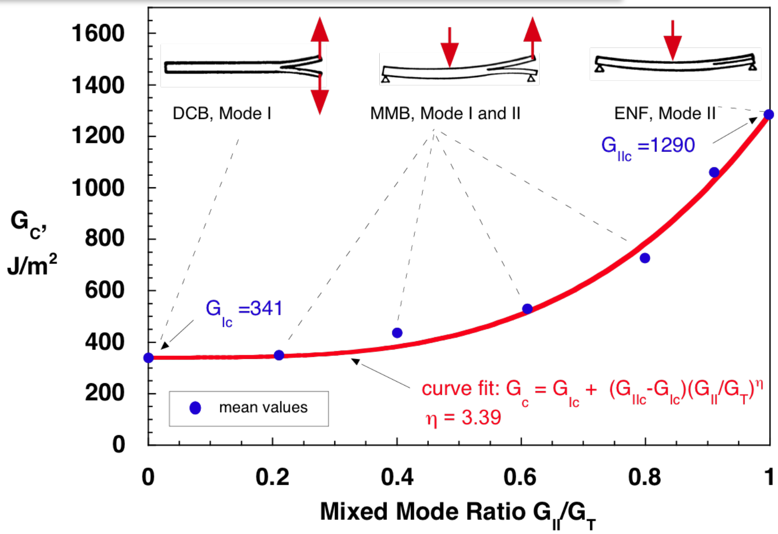
SLB specimen

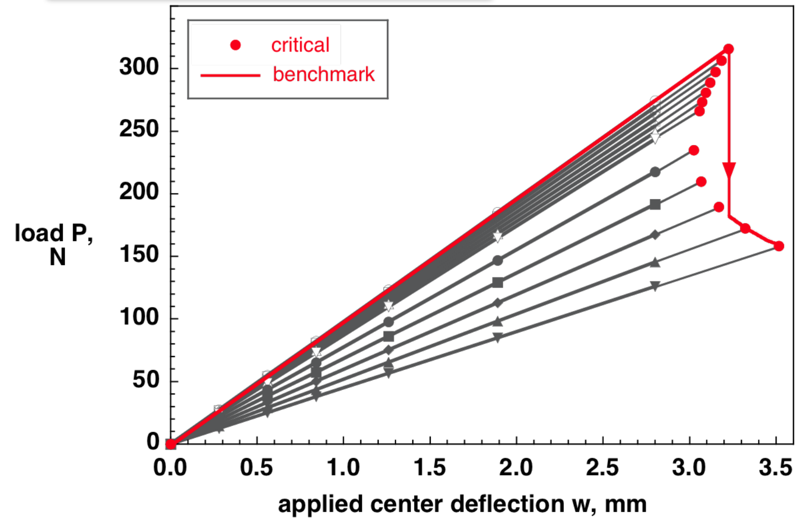


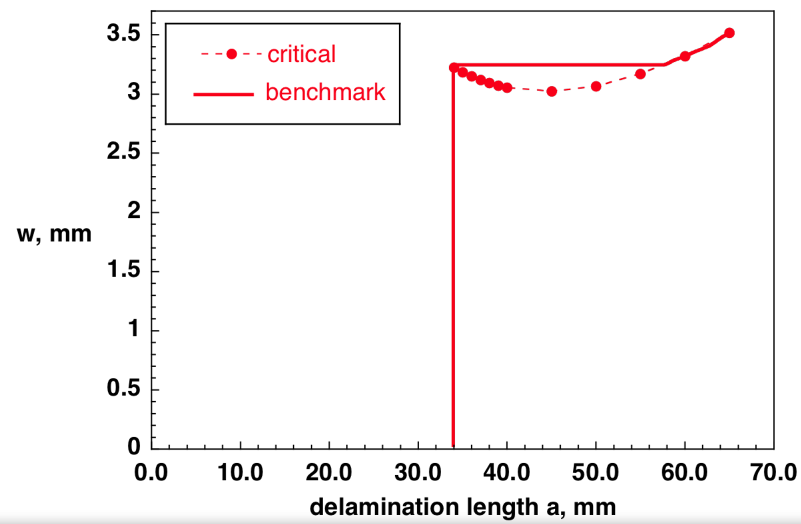
Layup: 0 and ±30
t_1=t_2=2.03 mm
2L=178. mm
B=25.4 mm
a=34.3 mm

Mixed-mode failure criterion



Benchmark case





*Krueger, NASA/TM-2008-215123, 2008.

DEMONSTRATION FOR ABAQUS® STANDARD:
SLB Specimen*

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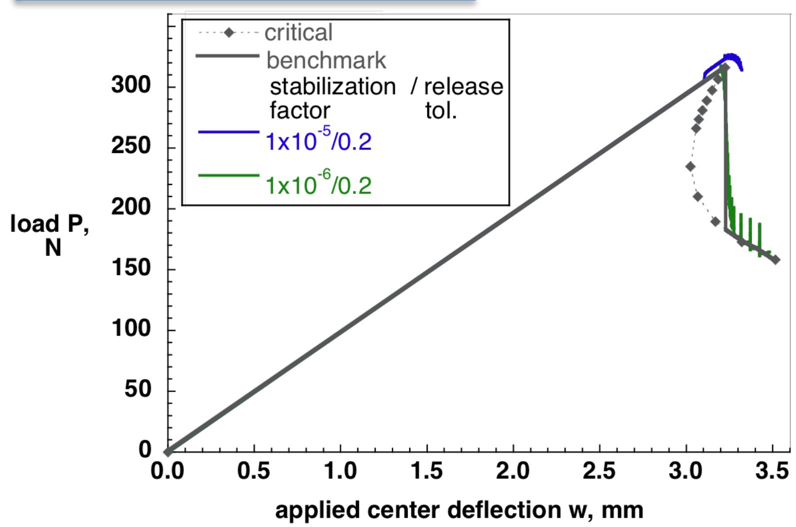
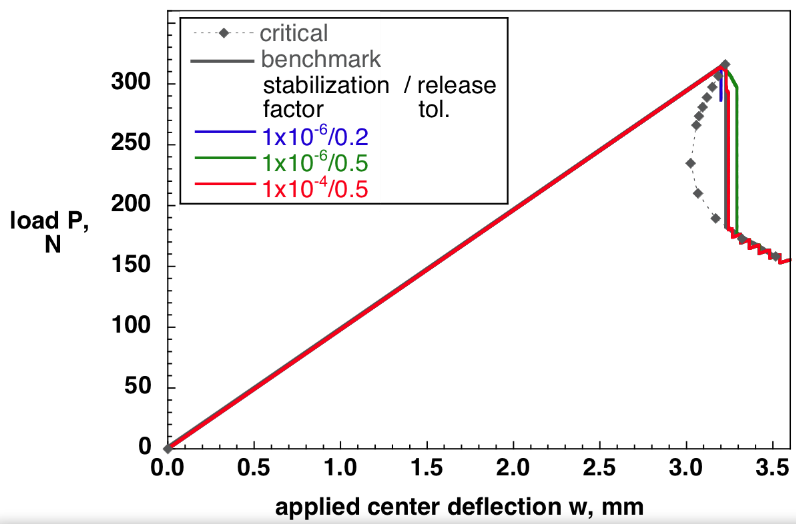
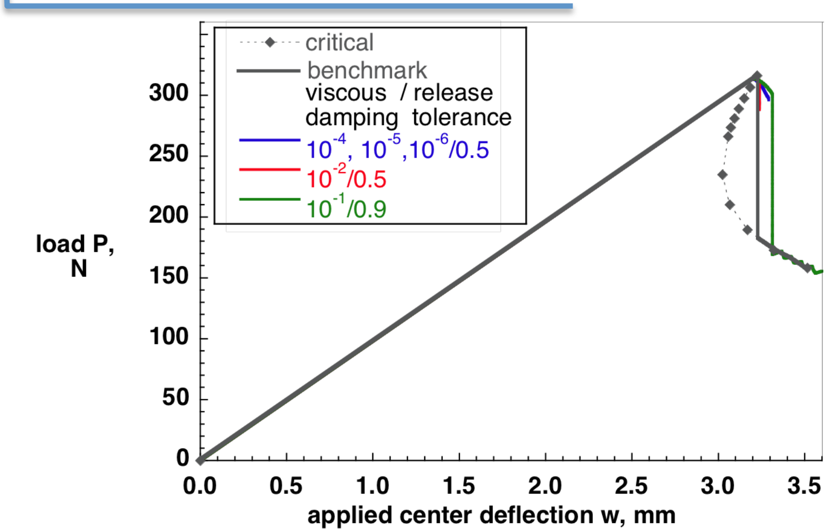
Global and contact stabilization





Viscous Regularization



Assessment

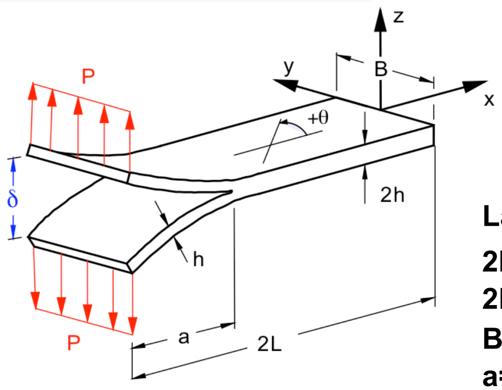
- Results may converge but yield meaningless solution => global stabilization no longer used
- Increased release tolerance suggested in handbook to obtain converged. Solution, however leads to overshoot
- Gradual reduction over several analyses suggested

*Krueger, NASA/TM-2008-215123, 2008.

DEMONSTRATION FOR MARC AND NASTRAN:
DCB Specimen*

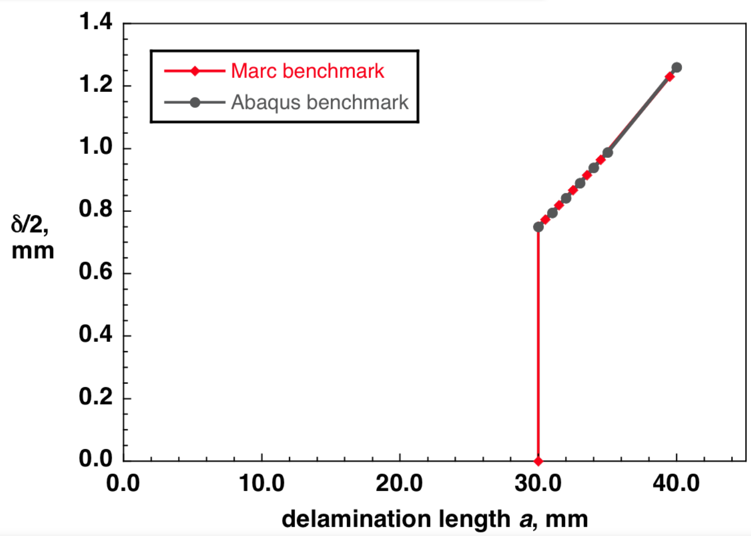
National Institute of Aerospace

DCB specimen

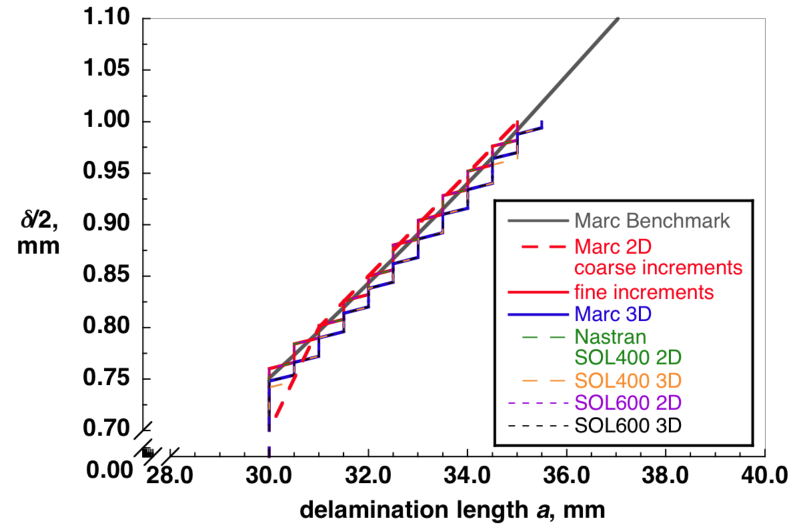


Layup: $[0]_{24}$
2h=3.0 mm
2L=150.0 mm
B=25.0 mm
a=30.5 mm

DCB benchmark case



Automated propagation



Assessment

- Stabilization or viscous damping not required
- Point on delamination onset (peak load, peak displacement) is missed when coarse time increments are used

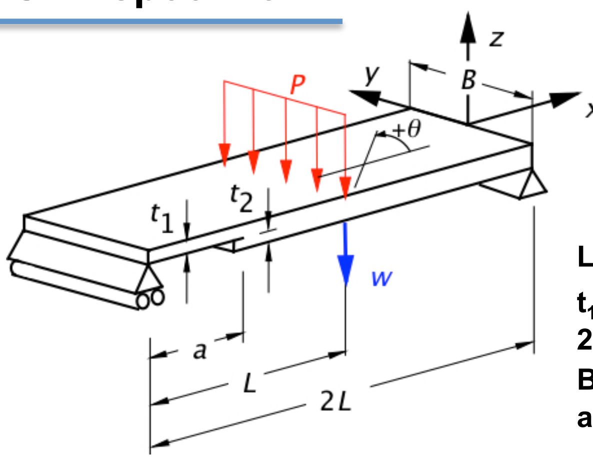
*Orifici and Krueger, NASA/CR-2010-216709, 2010.

DEMONSTRATION FOR MARC AND NASTRAN:

SLB Specimen*

NATIONAL INSTITUTE OF AEROSPACE

SLB specimen



Layup: 0 and ±30

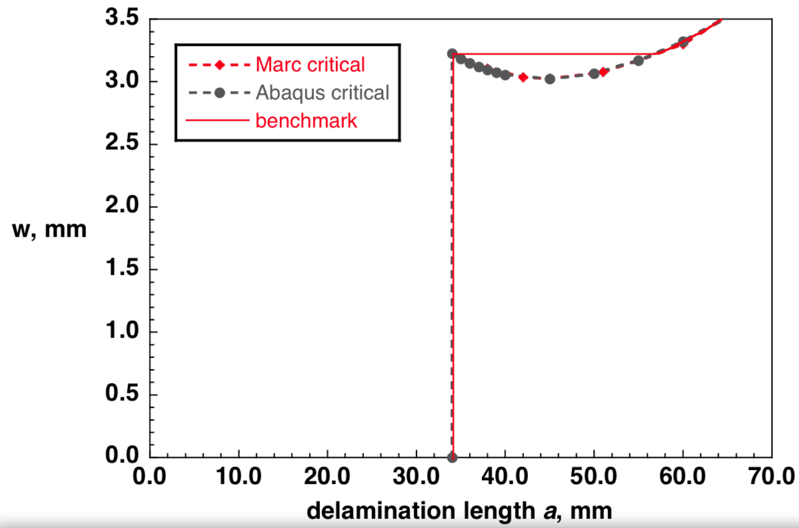
t_1=t_2=2.03 mm

2L=178. mm

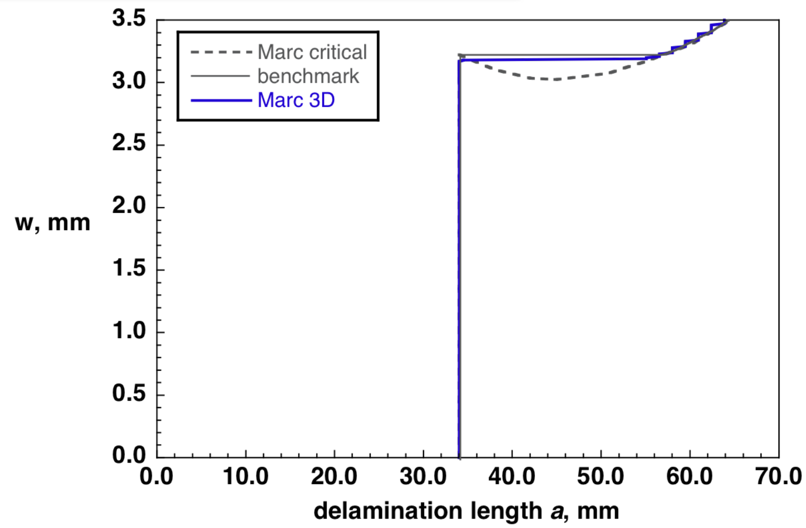
B=25.4 mm

a=34.3 mm

SLB benchmark case



Automated propagation



Assessment

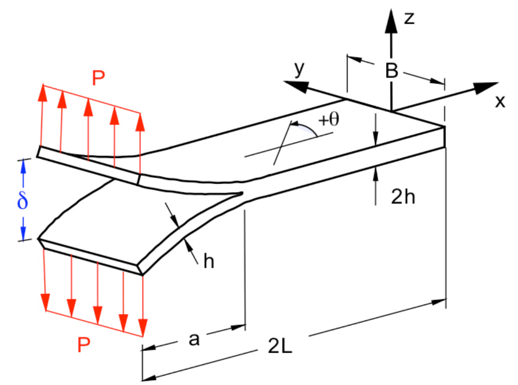
- Stabilization or viscous damping not required
- Analyses require fewer iterations and run efficiently

*Orifici and Krueger, NASA/CR-2010-216709, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION:
DCB Specimen*

National Institute of Aerospace

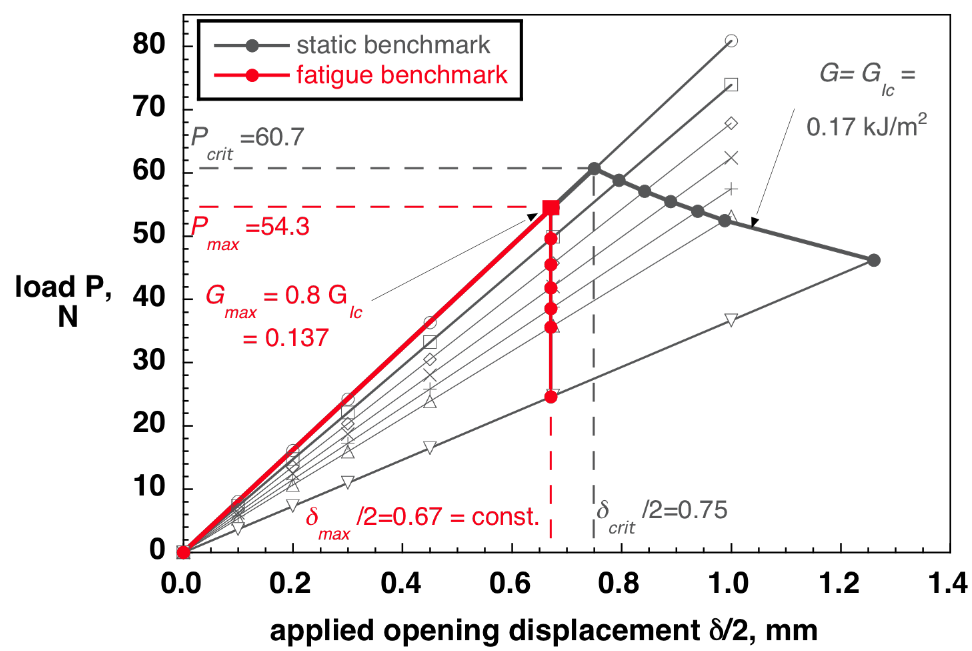
DCB specimen



layup: $[0]_{24}$
2h=3.0 mm
2L=150.0 mm
B=25.0 mm
a=30.5 mm

- **Based on proposed ASTM standard**
  - Frequency 10Hz
  - Load ratio R=0.1
  - Fatigue loading at 80% G_{IC} => $\delta/2_{max}$=0.67 mm

Fatigue loading at 80% G_{IC} ($\delta/2_{max}$=0.67 mm)



*Krueger, NASA/CR-2010-216723, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION:
DCB Specimen* - continued

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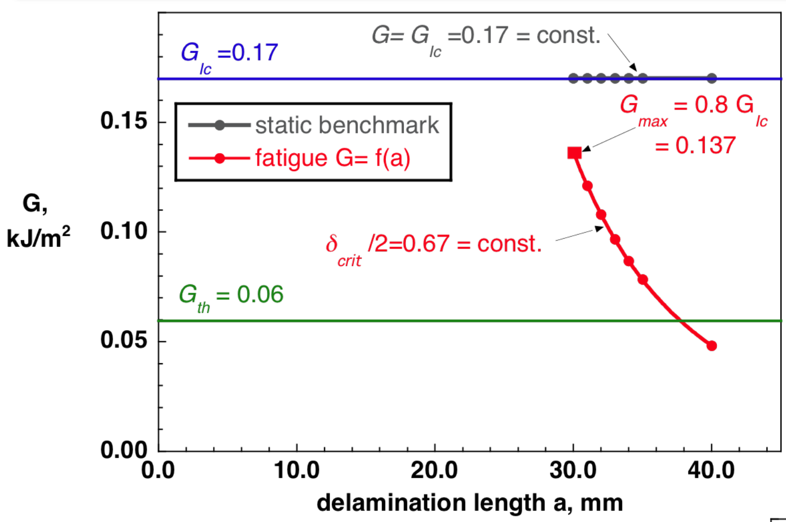
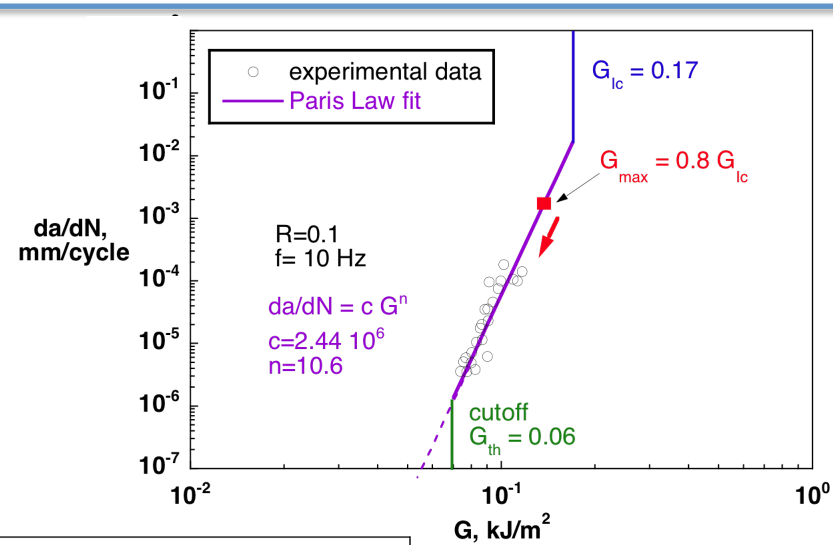
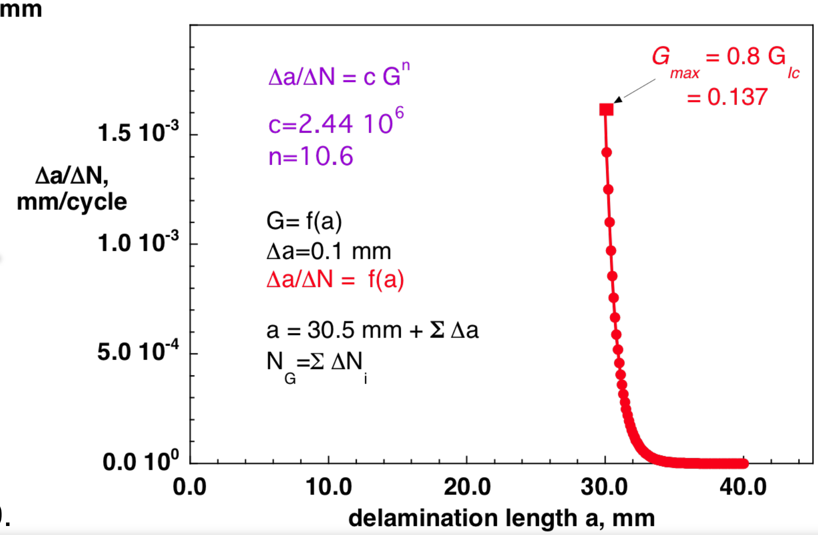
Decrease of G_I with increasing length a



Delamination growth (Paris Law)



Calculated delamination growth rate $\Delta a/\Delta N$



*Krueger, NASA/CR-2010-216723, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION:
DCB Specimen* - concluded

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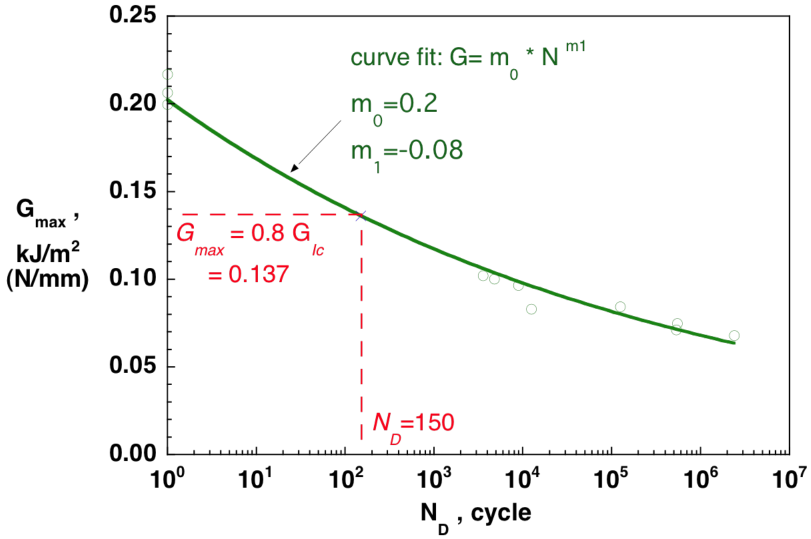
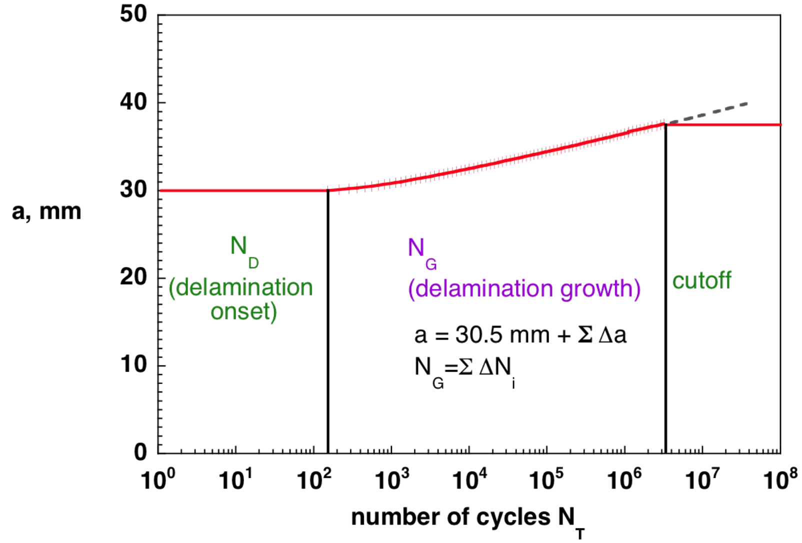
Cycles to delamination onset N_D



Benchmark: Cycles to onset and growth N_T



Benchmarking procedure

- Keep input parameters for fracture criterion and loading constant
- Study influence of input parameters
- Study influence of element type and mesh size
- Adjust solution controls to reduce computation time

*Krueger, NASA/CR-2010-216723, 2010.

DEMONSTRATION OF FATIGUE BENCHMARK EXAMPLE FOR ABAQUS®*

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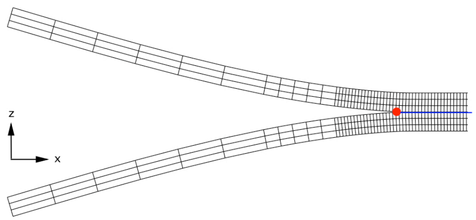
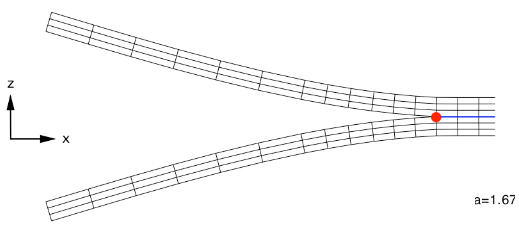
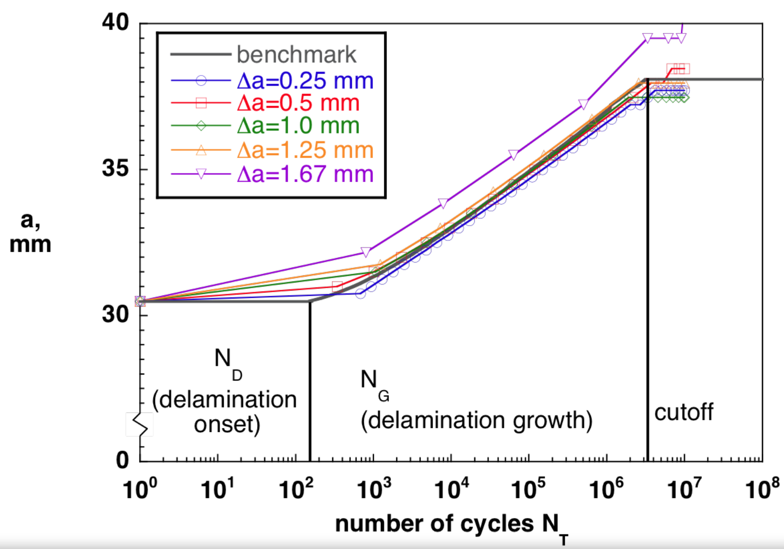
Influence of mesh refinement

- **Δa=0.25 mm**

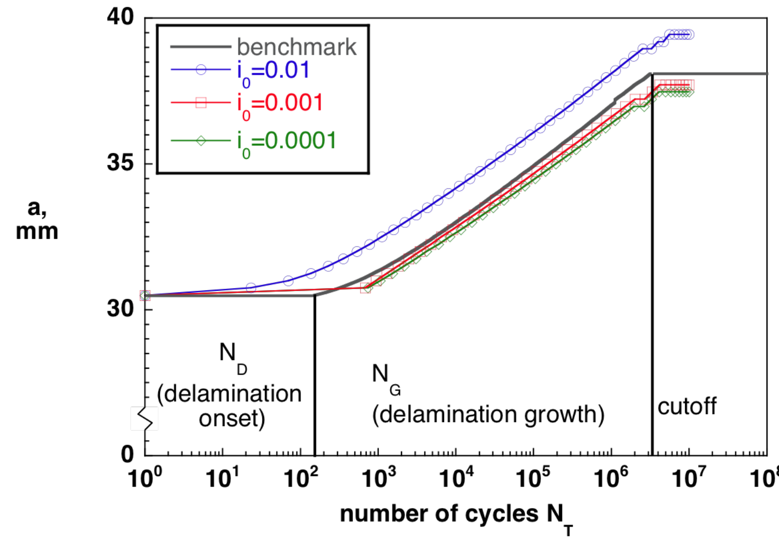


- **Δa=1.67 mm**





Influence of initial time increment i_0



Assessment

- **Stabilization or viscous damping not required**
- **Release tolerance has no effect**
- **New input parameters become important:**
  - **Initial time increment i_0**
  - **Parameters for Fourier series**

*Krueger, NASA/CR-2010-216723, 2010.

SUMMARY AND OUTLOOK

- A benchmarking approach for the assessment of automated delamination propagation analysis was developed
- Benchmark examples for delamination propagation under static loading and delamination growth under cyclic loading were created
- The approach was demonstrated successfully for ABAQUS, Marc and MSC.NASTRAN
- Benchmarking highlights the issues associated with the input parameters of different codes
- Additional benchmark examples based on the mode II End-Notched Flexure (ENF) specimen have been created

SUMMARY AND OUTLOOK - CONTINUED

- Further benchmark examples based on the mixed-mode I/II Mixed-Mode Bending (MMB) specimen are being created
- ASTM interested in standard document for benchmarking (ASTM work item WK30580)
- Benchmark input parameters will be used on large scale finite element models of subcomponent test specimens for methodology validation

ACKNOWLEDGEMENTS

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The analyses were performed at the Durability, Damage Tolerance and Reliability Branch - NASA Langley Research Center, Hampton, Virginia, USA.

THANK YOU!

QUESTIONS?

BACKUP SLIDES

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BENCHMARK PROBLEM:
Mode II End-Notched Flexure (ENF) Specimen*

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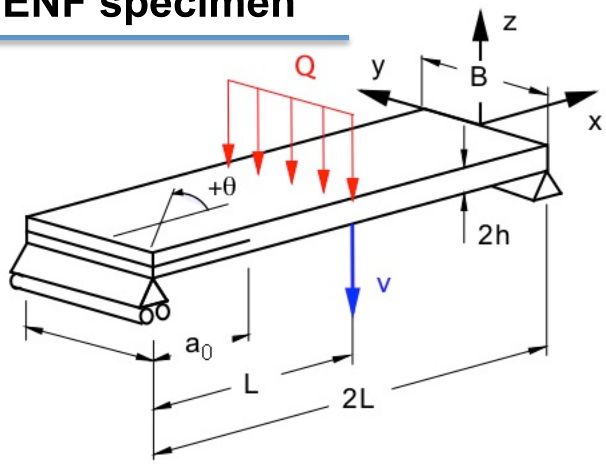
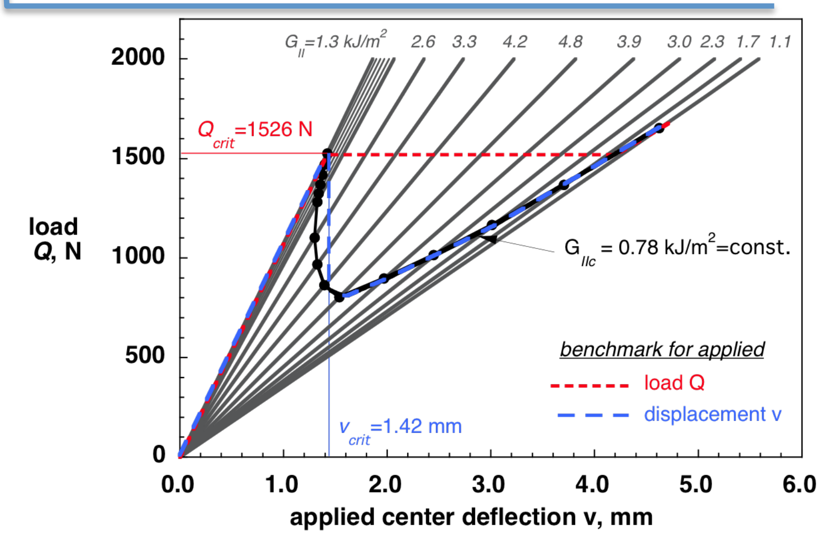
ENF specimen



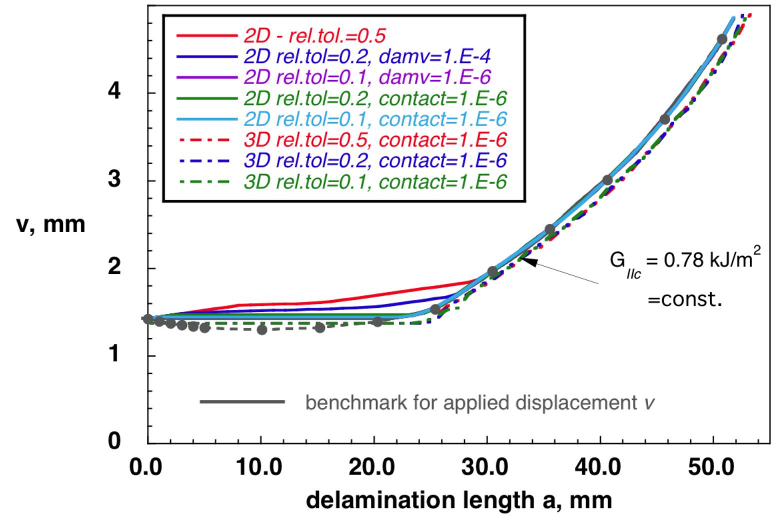
Layup: $[0]_{24}$
2h=4.5 mm
2L=85.4mm
B=25.4 mm
a=25.4 mm

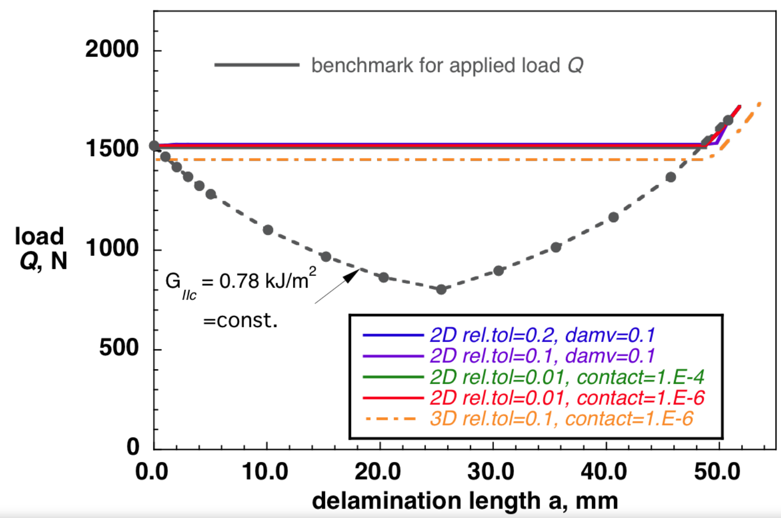
Static benchmark case



*Krueger, AHS 67th Annual Forum, 2011.

Assessment





BENCHMARK PROBLEM:
Mixed-Mode I/II Mixed-Mode Bending (MMB) Specimen

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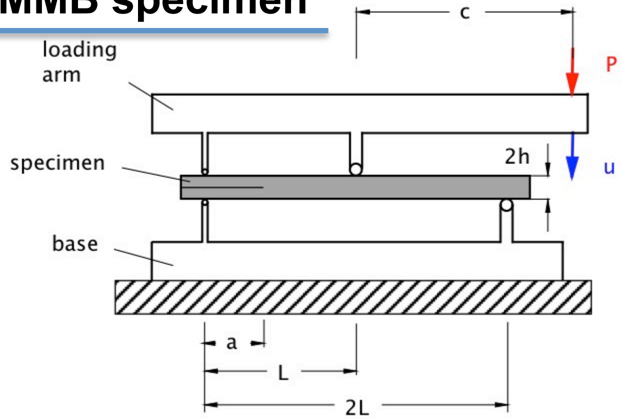
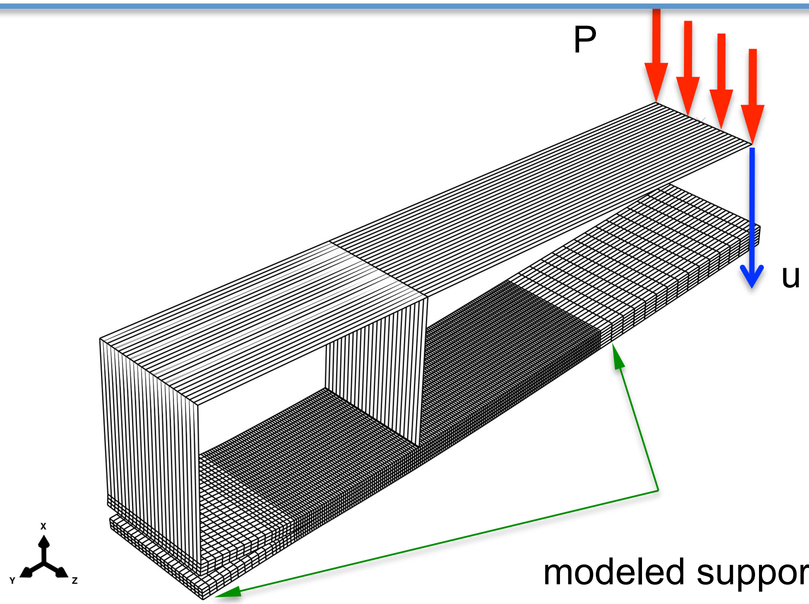
MMB specimen



Layup: $[0]_{24}$
2h=4.5 mm
2L=101.6 mm
B=25.4 mm
a=25.4 mm

Model of an MMB specimen with G_{II}/G_T=0.2



Benchmark case for G_{II}/G_T=0.2 and 0.8