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BENCHMARKING OF DELAMINATION PROPAGATION AND FATIGUE GROWTH PREDICTION CAPABILITIES: STATUS AND REMAINING CHALLENGES

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NASA Langley Research Center**

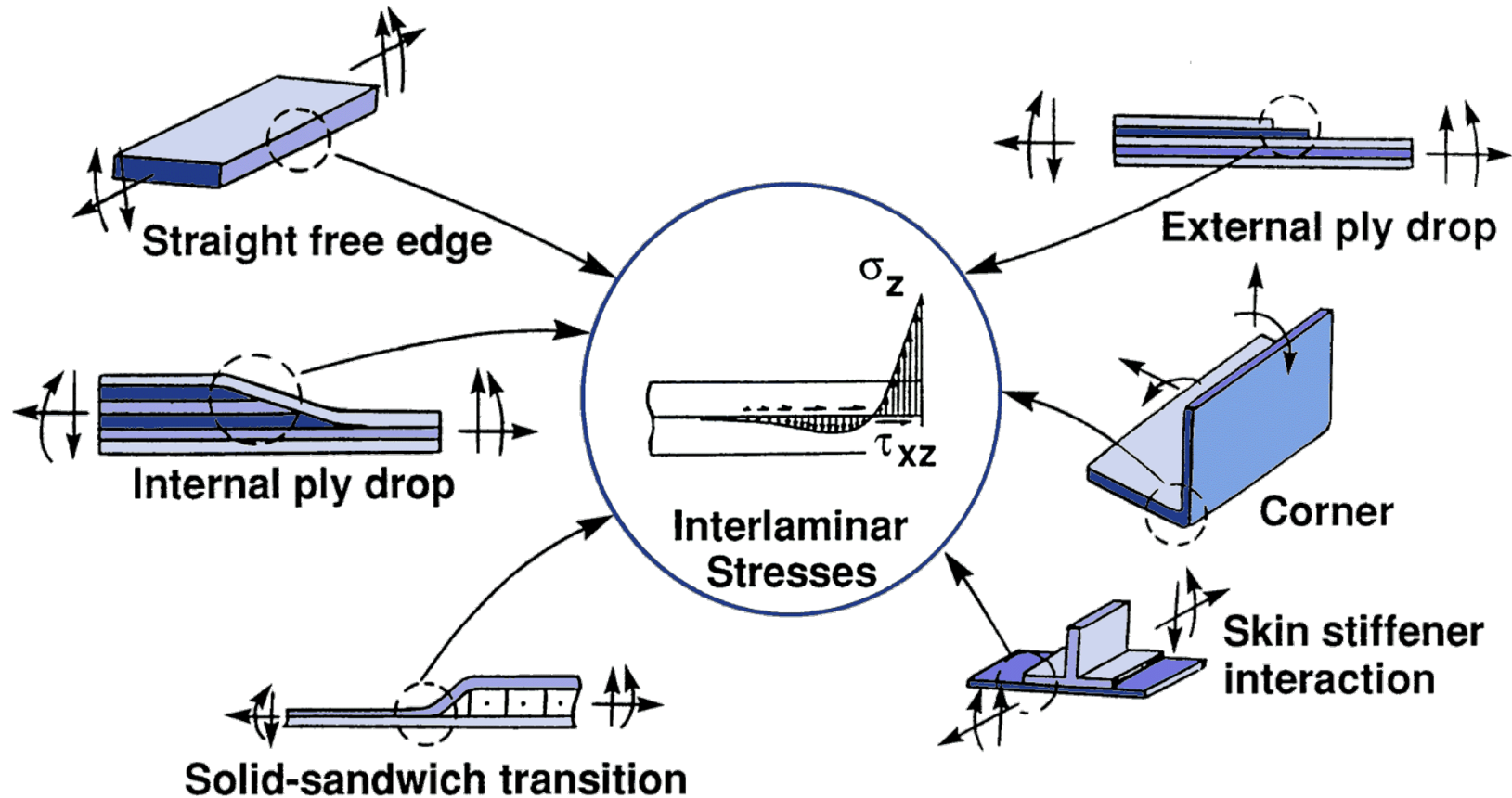
SIMULIA FCRT meeting, Providence, RI, May 14, 2012

OUTLINE



- **Background**
- **Analysis Benchmarking**
 - **Why is benchmarking important?**
 - **Benchmark example for delamination propagation prediction under mode II quasi-static loading based on the End-Notched Flexure Specimen (ENF)**
 - **Benchmark example for delamination onset and growth prediction under mode II cyclic loading**
 - **Discussion of problems encountered**
- **Status Summary**
- **Remaining Challenges**

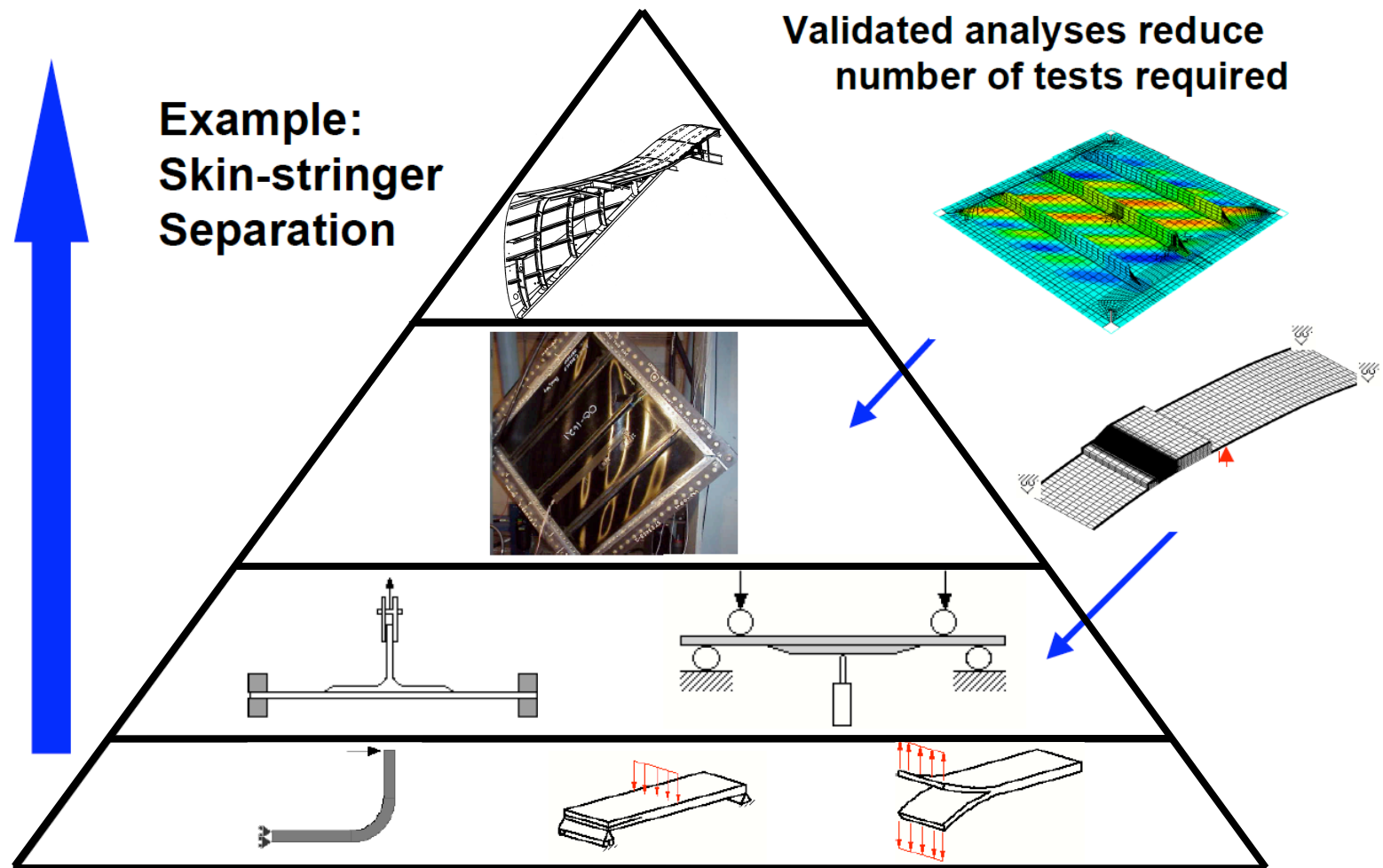
BACKGROUND: Delamination Sources at Geometric and Material Discontinuities



BACKGROUND

Building Block Approach for Design and Certification

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WHY BENCHMARKING ?



Analysis Capabilities Today

- Boeing's VCCT element (commercialized first as VCCT for ABAQUS®, now available in Abaqus/Standard® 6.8, 6.9, 6.10, 6.11)
- 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

Therefore

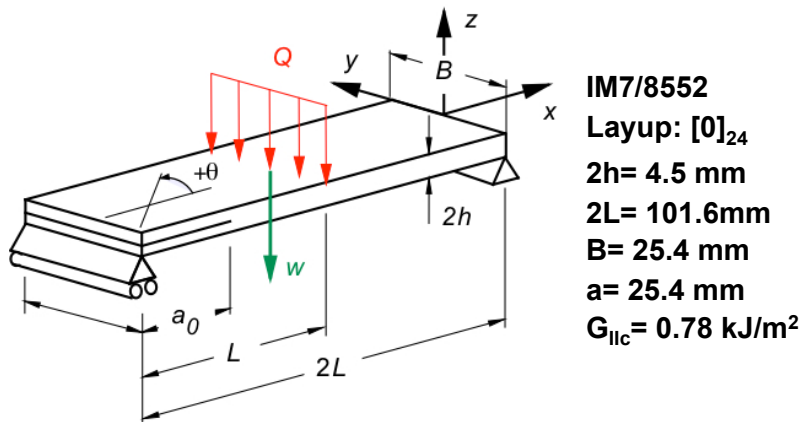
- Benchmarking is required to gain confidence in the software tools used
- Benchmarking highlights the issues associated with the input of a code
- Benchmark cases have to be simple and independent of software used
- Once the parameters have been identified, they may be used as starting point to model large scale finite element models of subcomponent test specimens for methodology validation

BENCHMARK PROBLEM: End-Notched Flexure (ENF) Specimen

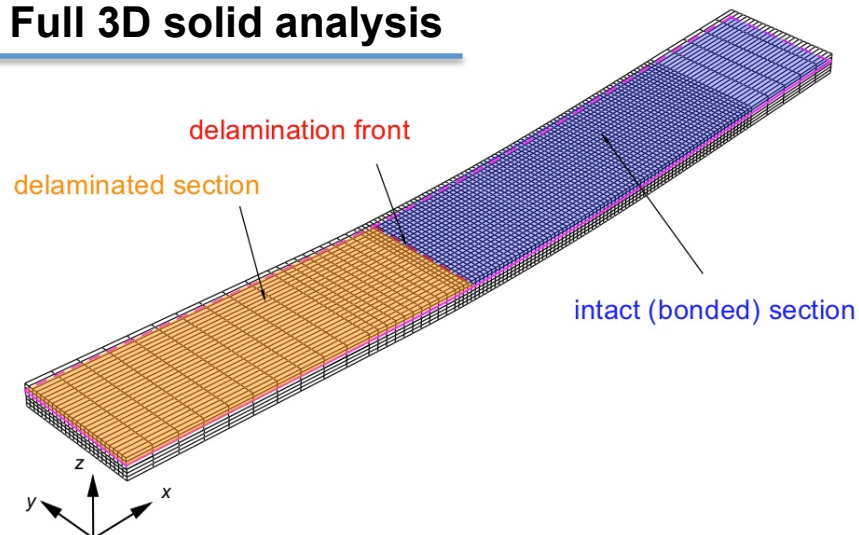
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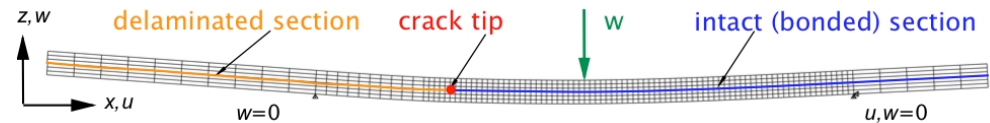
ENF specimen dimensions*



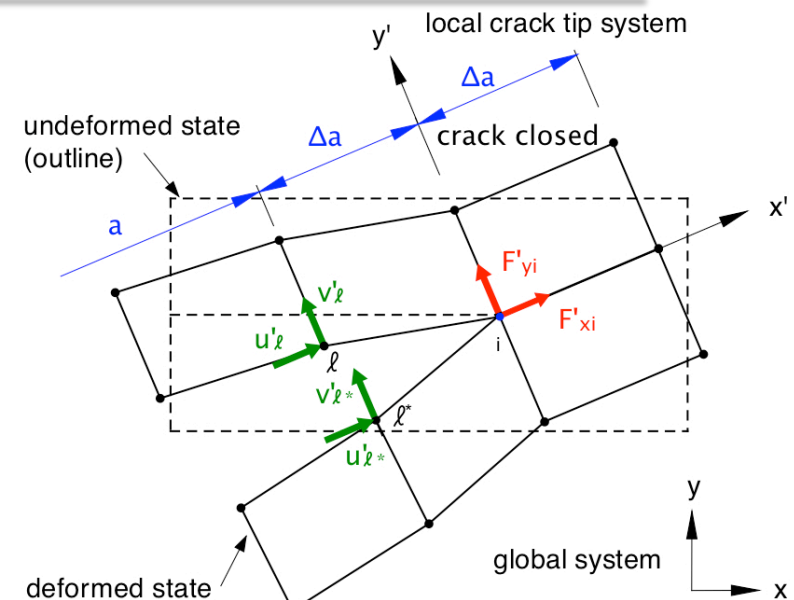
Full 3D solid analysis



2D plane strain and plane stress analysis



Virtual Crack Closure Technique (VCCT)**



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

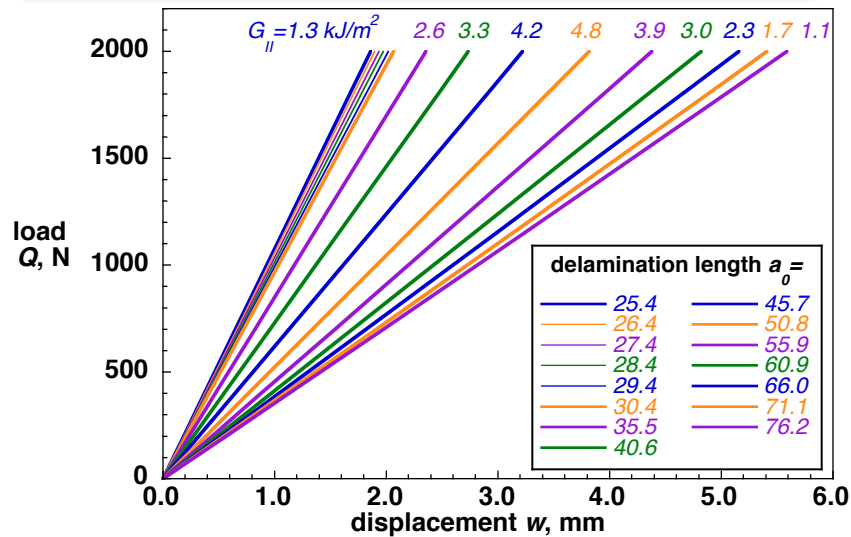
*O'Brien, Johnston, Toland, NASA/TM-2010-216838, 2010.

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

MANUAL BENCHMARK SOLUTION: FE Simulation of ENF Specimen Using 2D models



Load/displacement plots for different delamination lengths a ($Q=2000$ N)

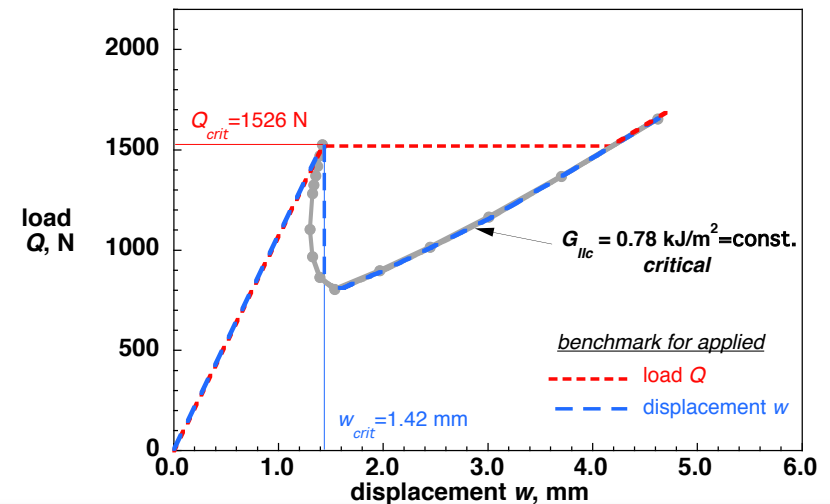
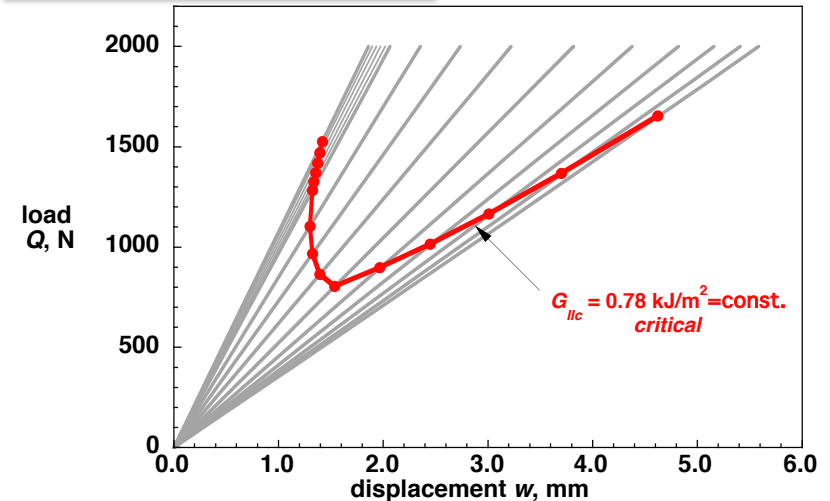


Mathematical relationship between load and energy release rate

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

$$\Rightarrow P_{crit} = Q \sqrt{\frac{G_c}{G_T}}, \quad w_{crit} = w \sqrt{\frac{G_c}{G_T}}$$

Benchmark cases



DEMONSTRATION FOR ABAQUS/STANDARD: Applied Displacement w , 2D Planar FE Models

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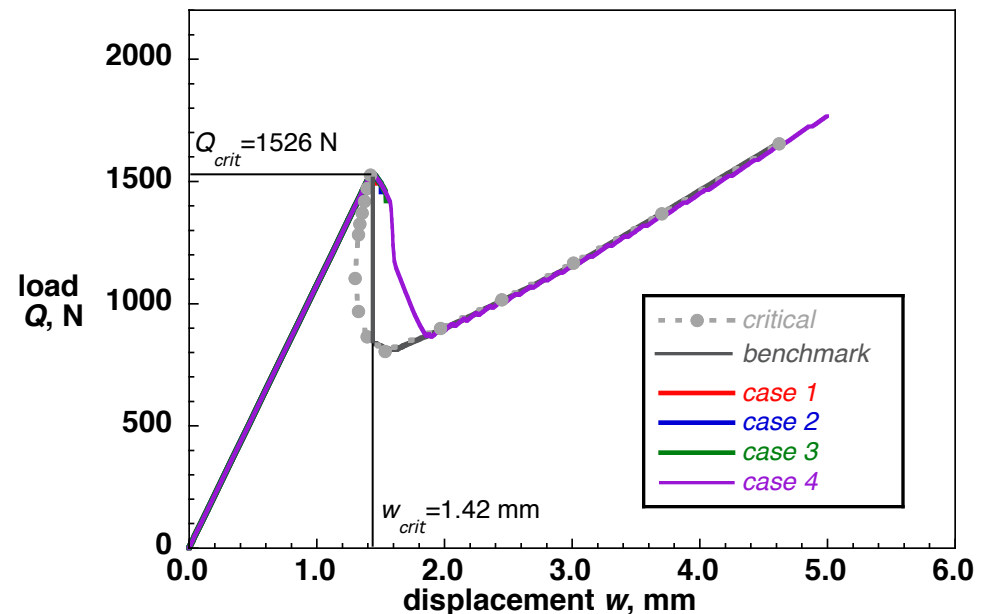


Assessment based on the comparison of benchmark and automated propagation

- Input data for delamination failure criterion was kept constant for all analyses performed
- Initial and maximum increment size were selected at $0.001 \times$ final load
- To overcome convergence problems, four parameters may be adjusted
 - Release tolerance ($relTol$)
 - Contact stabilization (cs)
 - Viscous regularization ($damv$)
 - Global stabilization (gs) - not used due to unreliable results found in previous study*

Release tolerance only

case	1	2	3	4
relTol	0.2	0.3	0.4	0.5



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

DEMONSTRATION FOR ABAQUS/STANDARD®:

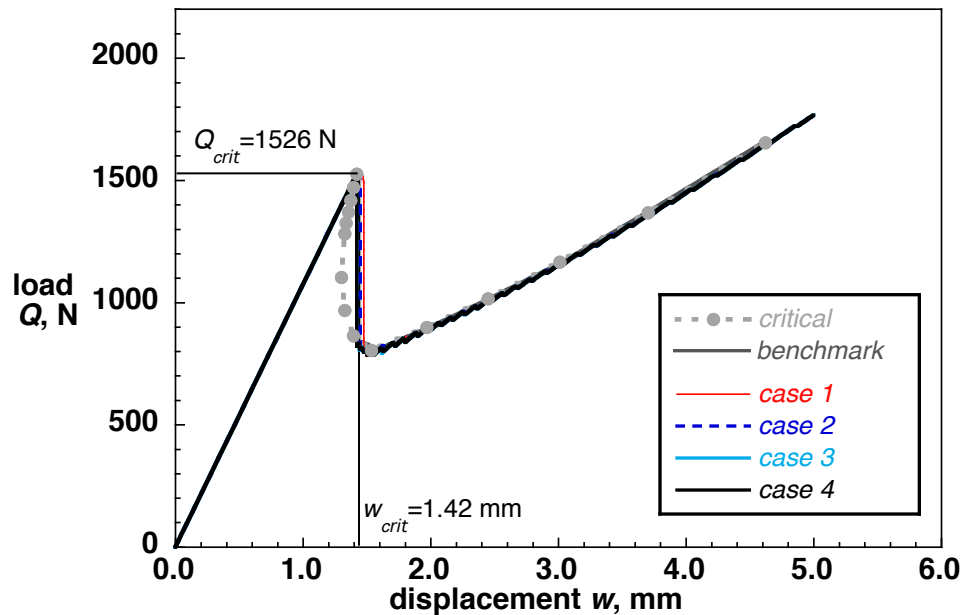
2D Planar FE Models (CPE4I), Contact Stabilization

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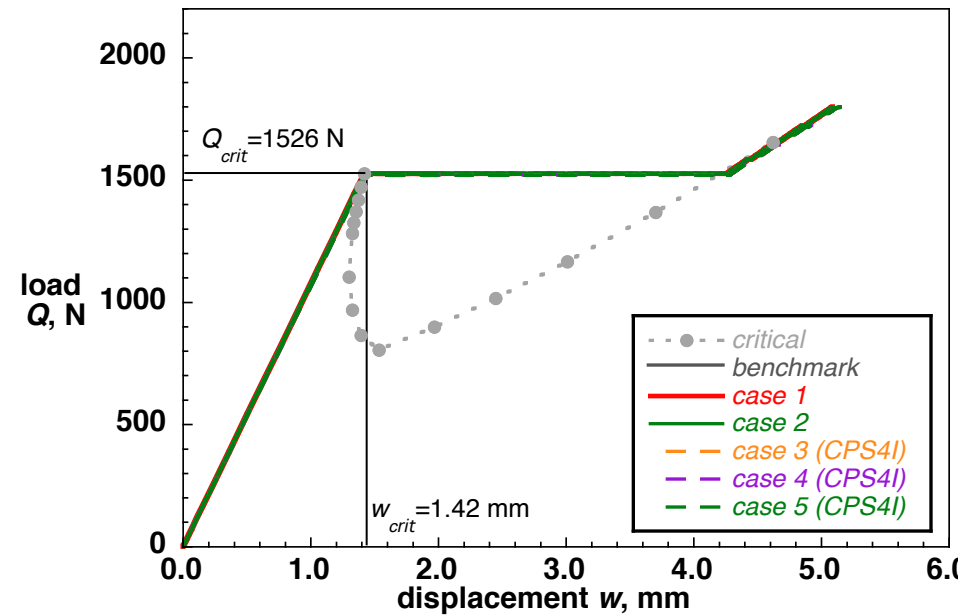
Applied displacement w

case	1	2	3	4
cs	E-6	E-6	E-4	E-6
relTol	0.2	0.1	0.01	0.01



Applied load Q

case	1	2	3	4	5
cs	E-4	E-6	E-6	E-6	E-6
relTol	0.01	0.01	0.2	0.1	0.01



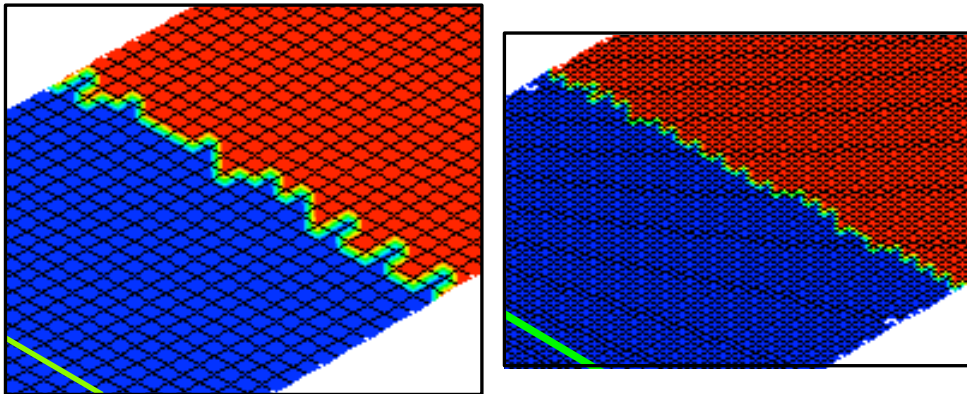
DEMONSTRATION FOR ABAQUS/STANDARD®:

Delamination front shape obtained from 3D solid models

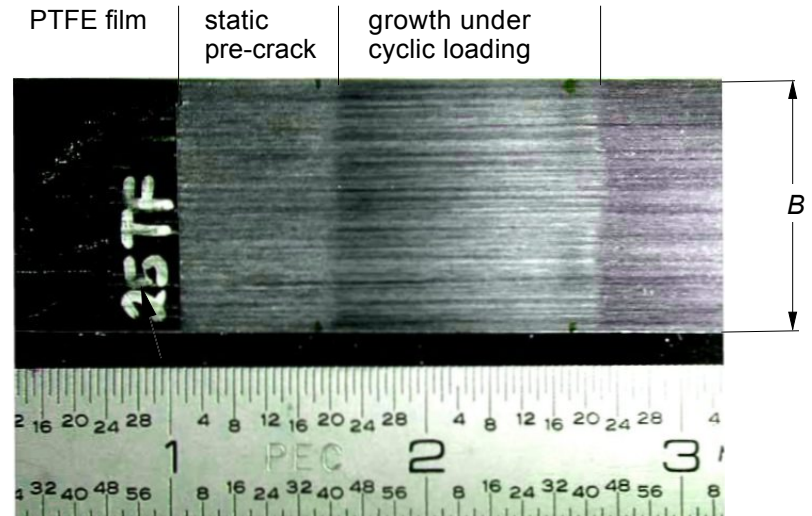
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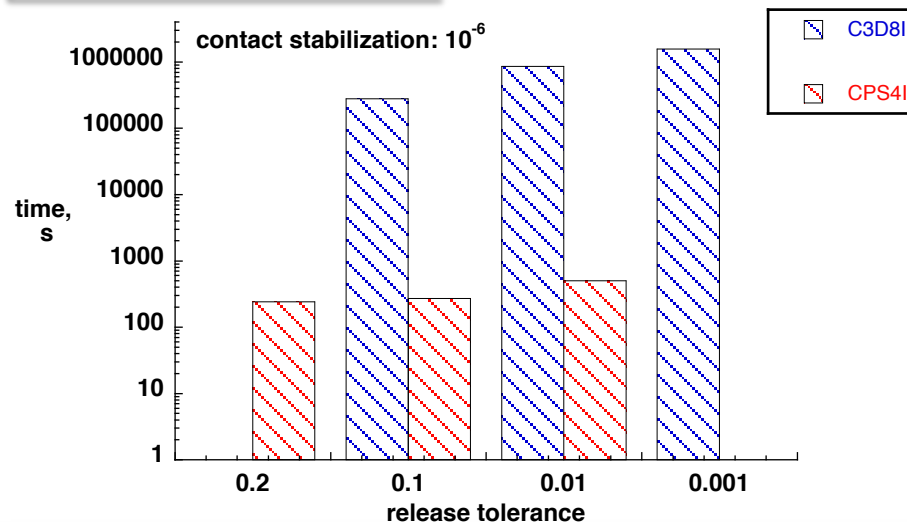
Fronts obtained from coarse and fine mesh



Experimentally observed fronts



Analysis time



Observations

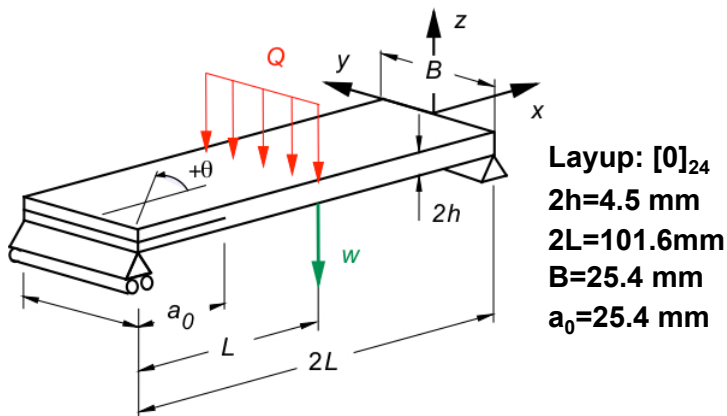
- Study required to find appropriate combination of input values
- Fine meshes yield expected front shape
- Long analysis time for solid models
- Published as NASA/CR-2011-217305

MANUAL FATIGUE BENCHMARK SOLUTION: ENF Specimen Fatigue Loading

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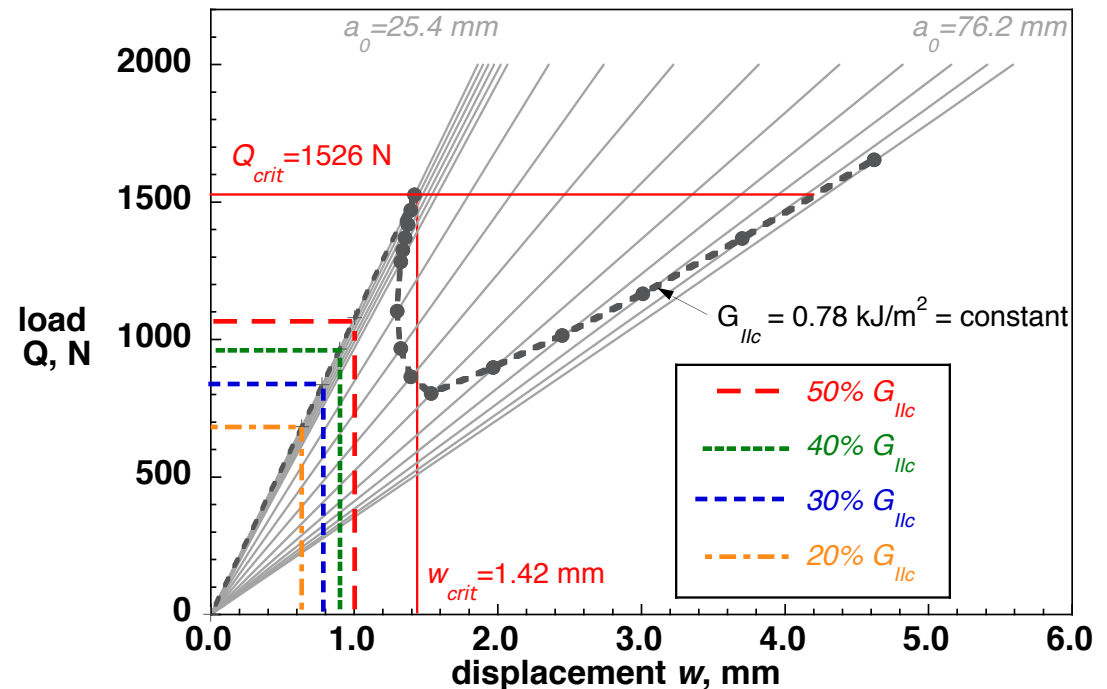


ENF specimen dimensions*



- Based on related testing*
 - Frequency 5Hz
 - Load ratio $R=0.1$
 - Fatigue loading at 50%, 40%, 30% 20% G_{IIc}

Fatigue loading at 50%, 40%, 30%, 20% G_{IIc}



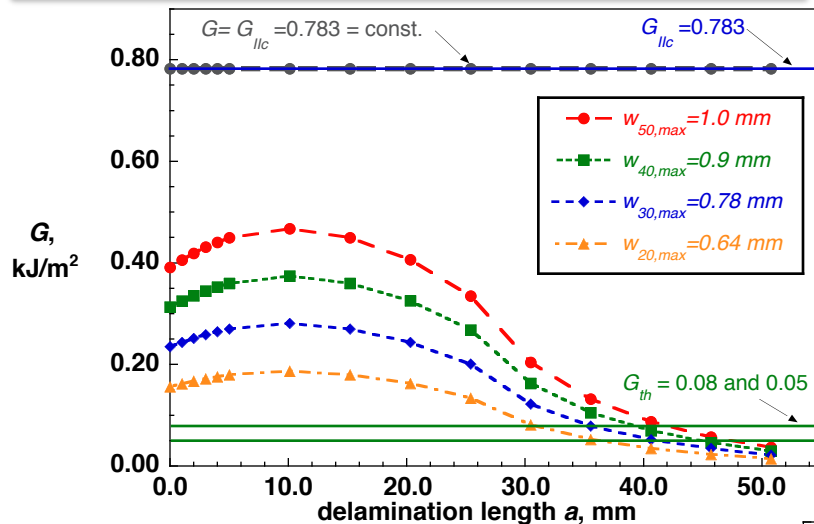
*O'Brien, Johnston, Toland, NASA/TM-2010-216838, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION: Creating Benchmark for Applied Displacement w

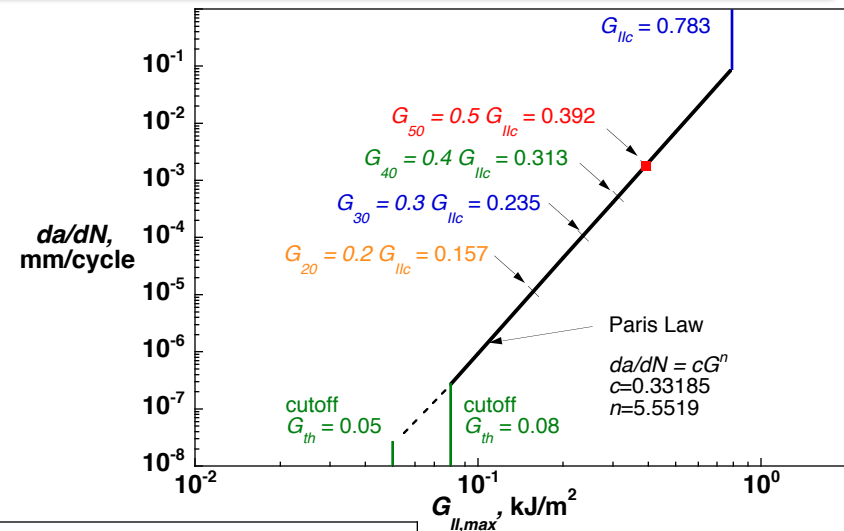
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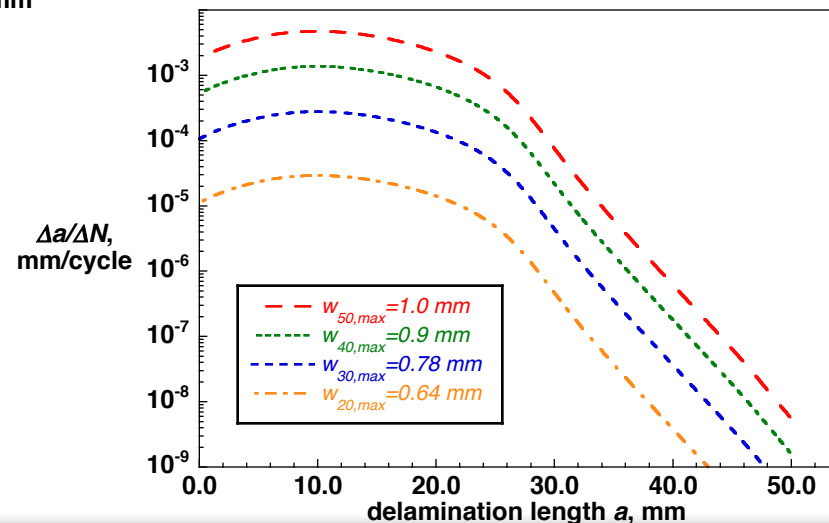
Decrease of G_I with increasing length a



Delamination growth (Paris Law)*



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



- $a = a_0 + \sum \Delta a$
- $N_G = \sum N_i$

*O'Brien, Johnston, Toland,
NASA/TM-2010-216838, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION: Creating Benchmark for Applied Displacement w - cont.

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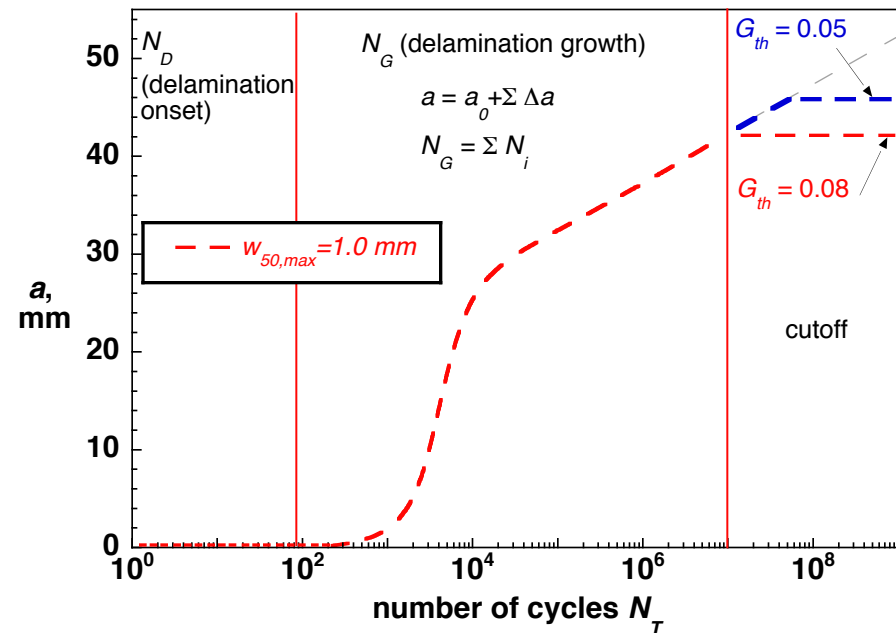
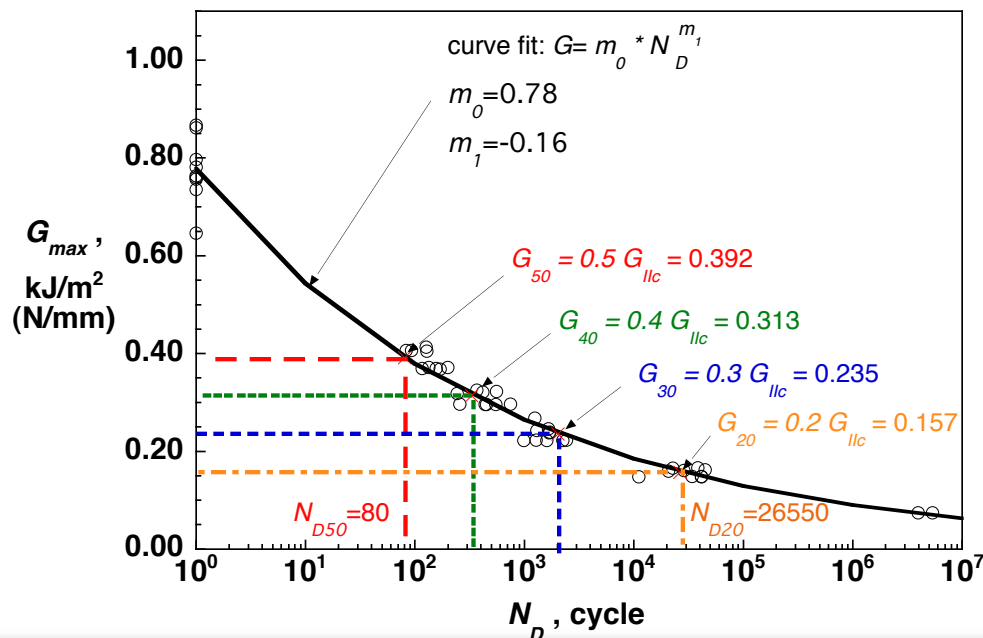
Delamination growth N_G

- $a = a_0 + \sum \Delta a$
- $N_G = \sum N_i$

Benchmark: Cycles to onset and growth

$$N_T = N_D + N_G$$

Cycles to delamination onset N_D^*



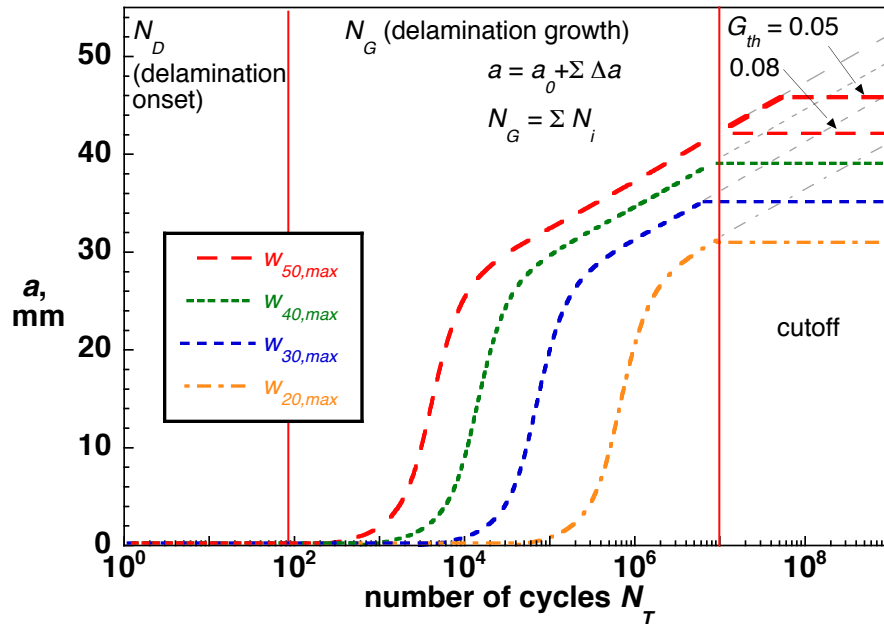
*O'Brien, Johnston, Toland, NASA/TM-2010-216838, 2010.

MANUAL FATIGUE BENCHMARK SOLUTION: Resulting Benchmark Cases

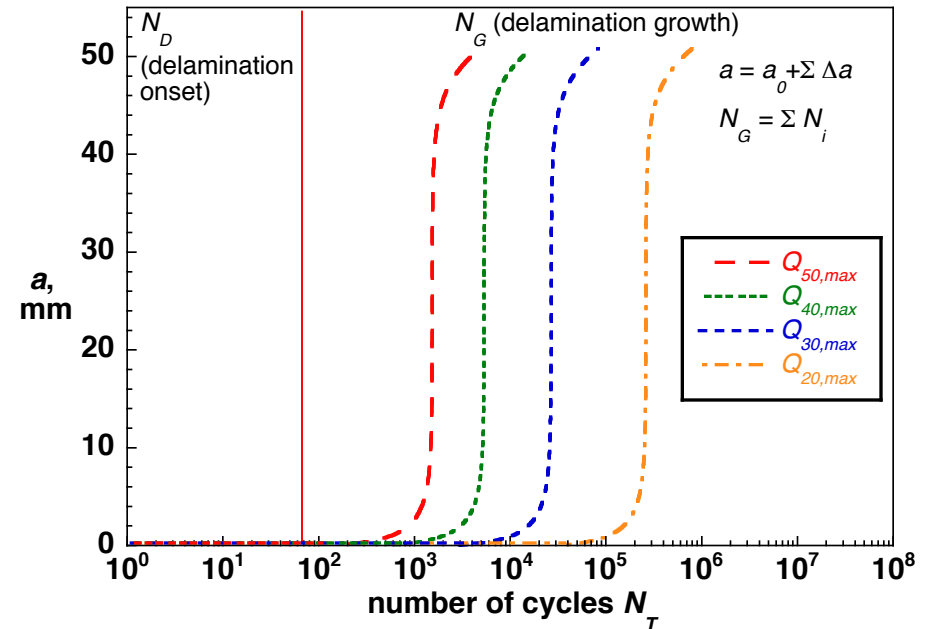
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Benchmark cases for applied displacement w



Benchmark cases for applied load Q



Benchmarking procedure

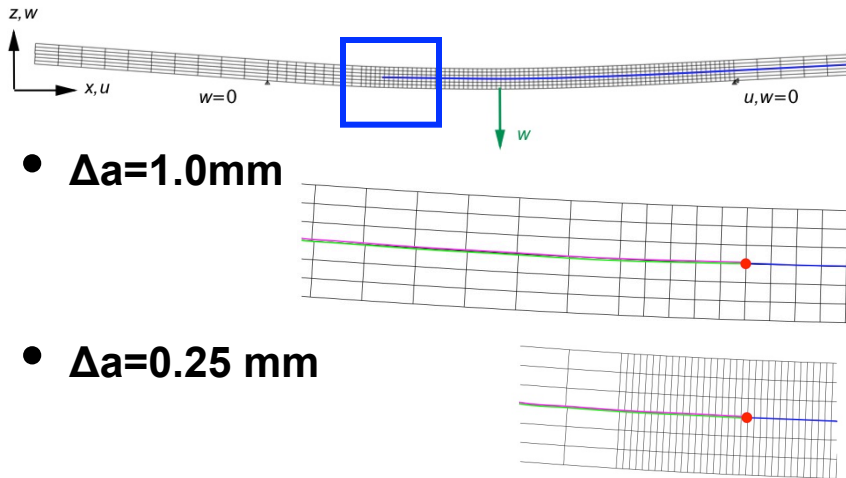
- Keep input parameters for fracture criterion and loading constant
- Study influence of mesh size
- Study influence of start time t_0
- Study influence of number of terms in Fourier Series used to approximate load

DEMONSTRATION OF FATIGUE BENCHMARK EXAMPLE FOR ABAQUS® - Results for w_{50}

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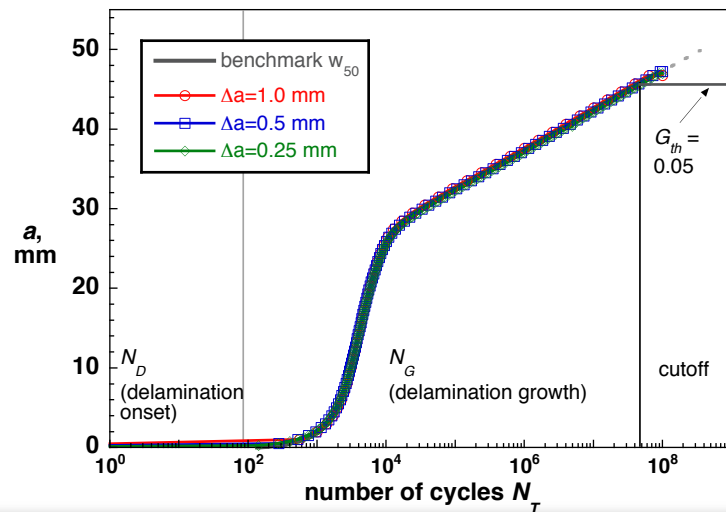


Influence of mesh refinement

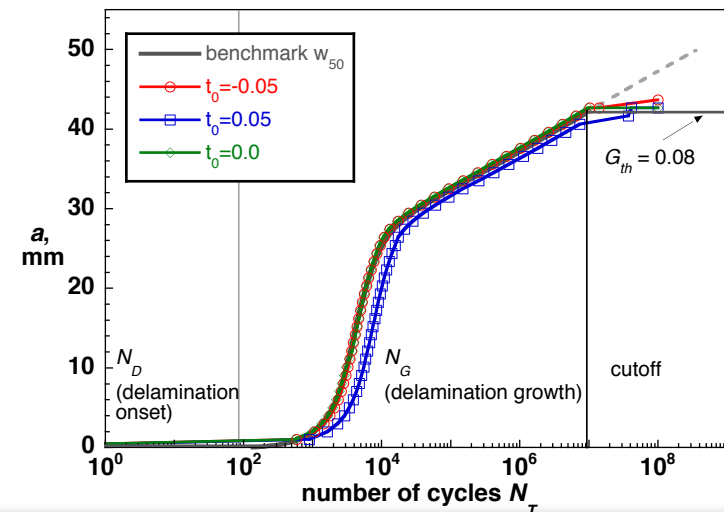
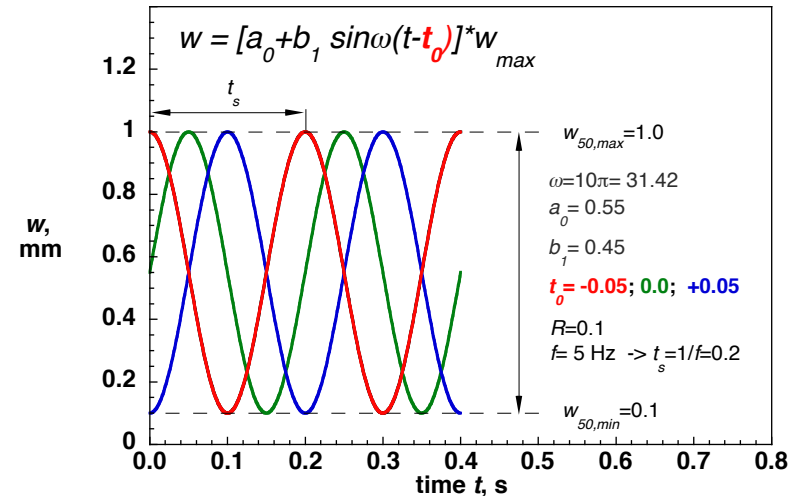


• $\Delta a = 1.0 \text{ mm}$

• $\Delta a = 0.25 \text{ mm}$



Influence of start time t_0



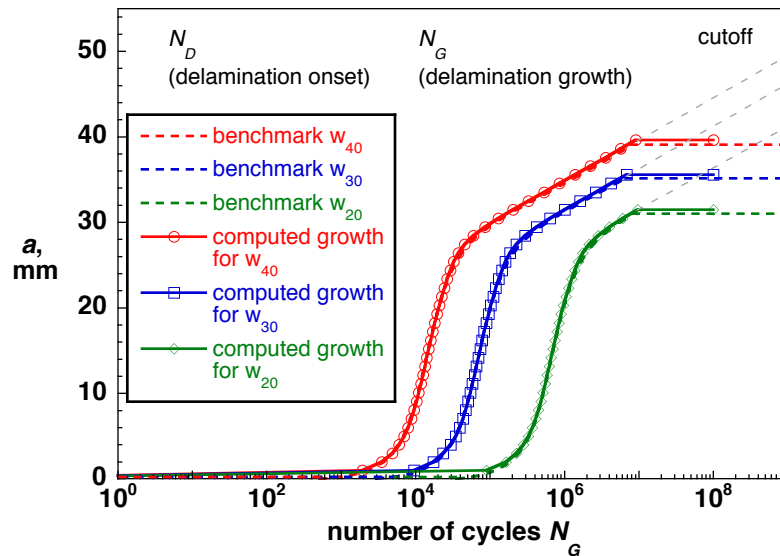
DEMONSTRATION OF FATIGUE EXAMPLE

Results obtained from 2D planar models

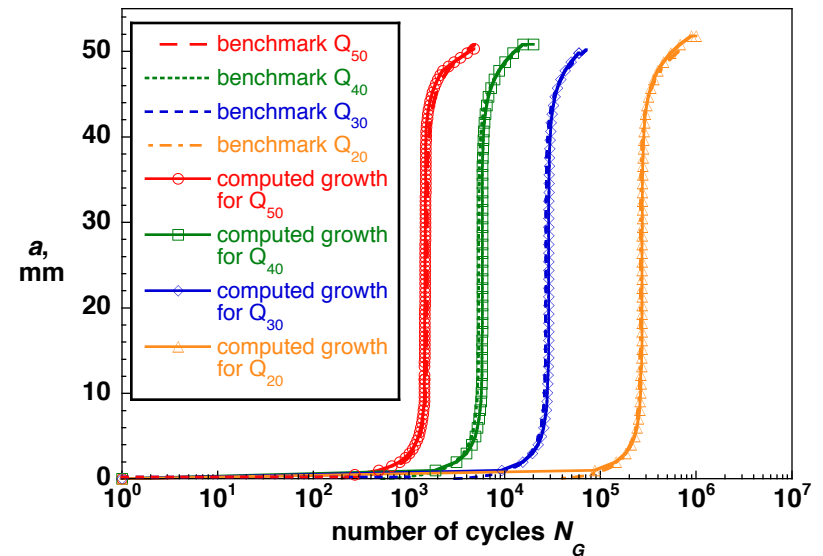
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Applied displacements w_{40} , w_{30} , w_{20}



Applied loads Q_{50} , Q_{40} , Q_{30} , Q_{20}



Assessment

- Stabilization or viscous damping not required
- Release tolerance has no effect
- New input parameters become important:
 - Start time t_0
 - Number of terms in Fourier series

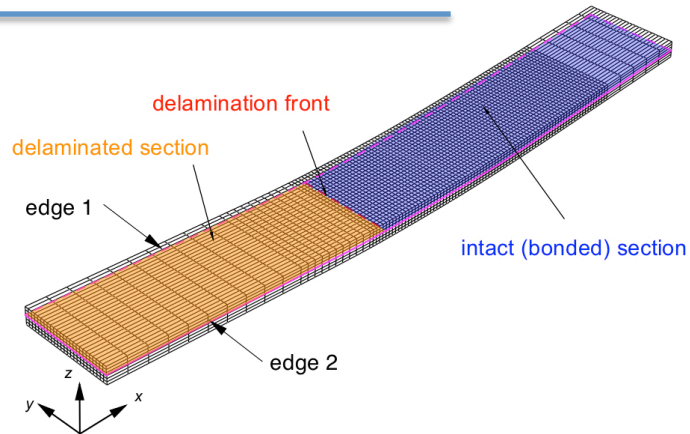
DEMONSTRATION OF FATIGUE EXAMPLE

Results obtained from 3D solid models

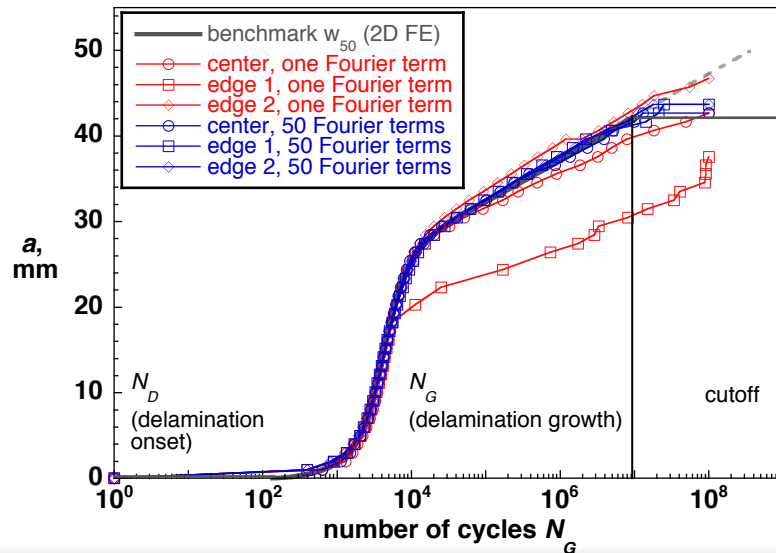
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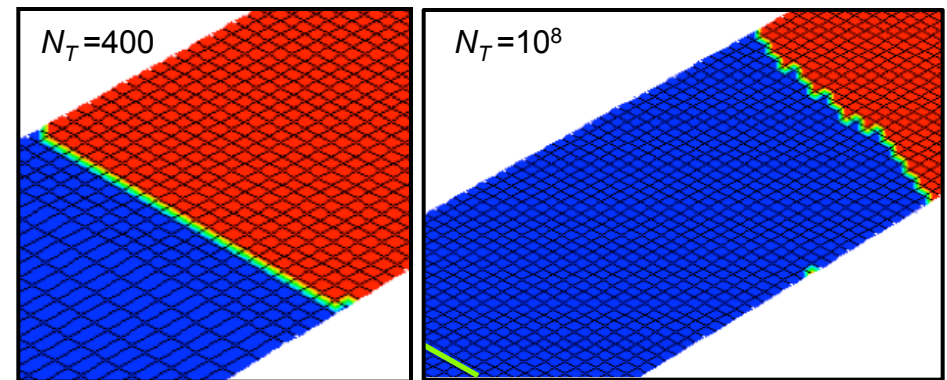
Solid 3D FE model $\Delta a = 1.0$ mm



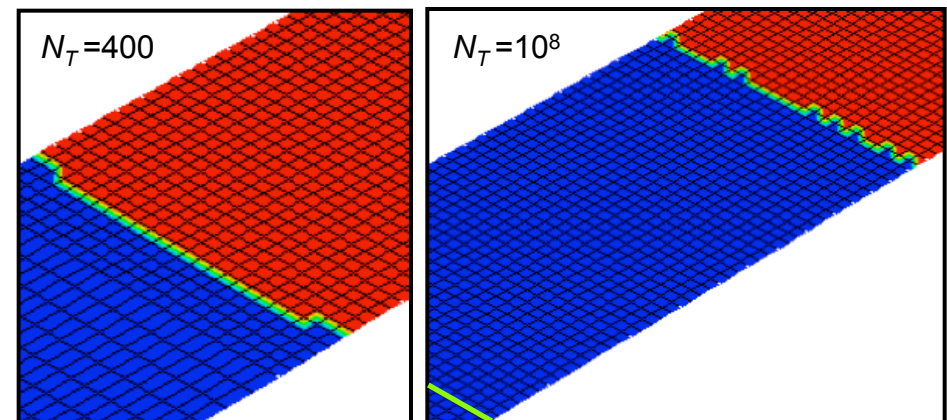
Applied displacements w_{50}



Fronts from analysis with one Fourier term



Fronts from analysis with 50 Fourier terms



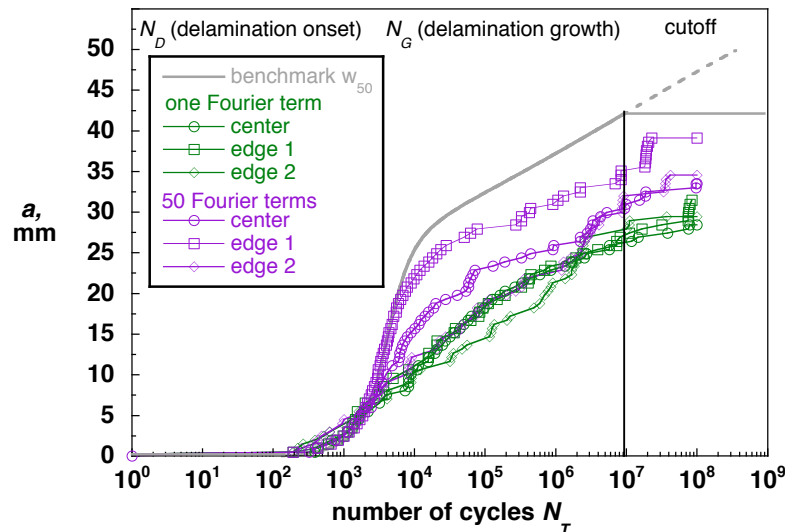
DEMONSTRATION OF FATIGUE EXAMPLE

Results obtained from 3D solid models - continued

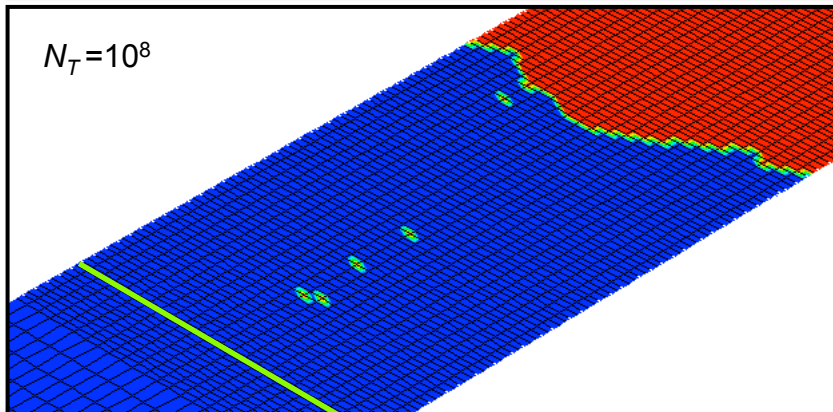
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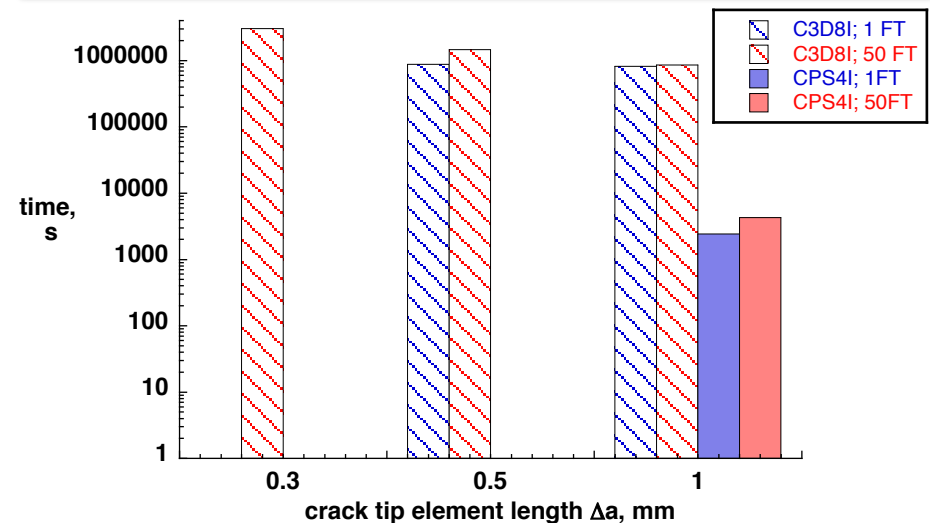
Results from solid 3D FE model $\Delta a = 0.5$ mm



Fronts from analysis with 50 Fourier terms



Analysis time



Observations

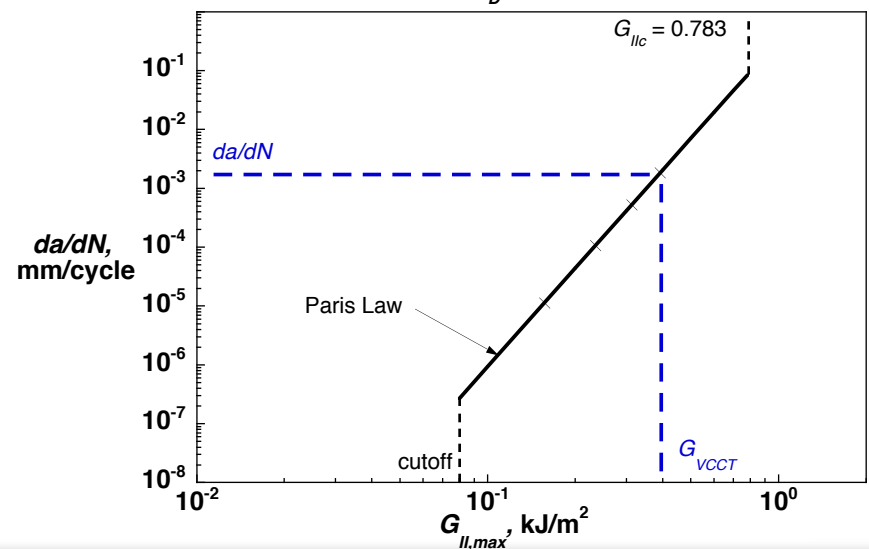
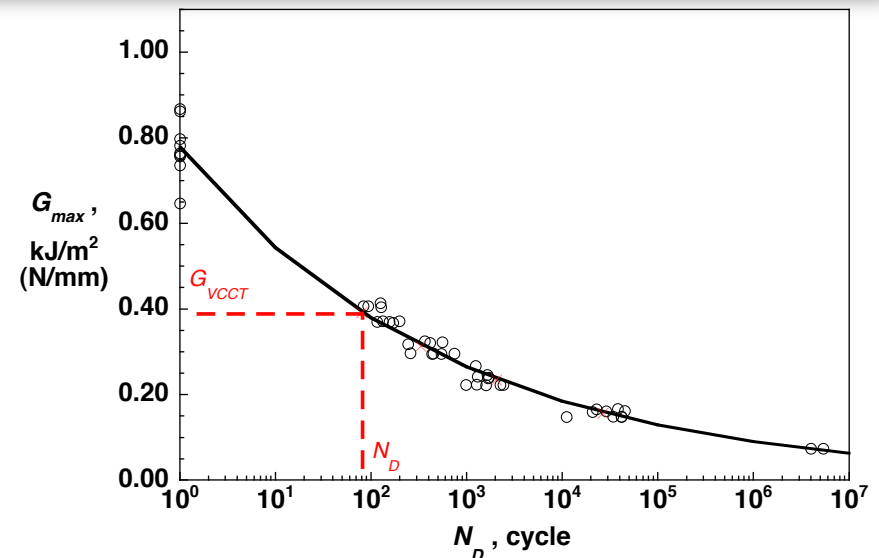
- Long analysis time observed for solid models (days, weeks)
- Refined mesh yielded less accurate results and delamination front shapes
- Effect of number of terms in Fourier series on results needs to be studied further

FATIGUE DELAMINATION GROWTH

Suggestion for faster analysis



- Observed limitations of direct cyclic analysis
 - Assumes geometrically linear behavior
 - Fixed contact conditions
 - Long analysis time
- Suggestion to provide option for user to turn off the direct cyclic analysis
 - Compute G_{VCCT} for the original front and determine N_D from onset curve
 - Compute $G_{i,VCCT}$
 - Determine da/dN from Paris Law
 - Determine advance Δa_i for given number of cycles N_i
 - Advance front $a = a_0 + \sum \Delta a_i$
 - Determine $N_G = \sum N_i$
 - Determine $N_T = N_D + N_G$



STATUS SUMMARY



- **Analysis capabilities for automated delamination propagation under quasi-static loading and delamination growth under cyclic loading have become widely available**
- **Therefore, a benchmarking approach for the assessment of automated analysis was developed and demonstrated successfully for Abaqus/Standard®**
- **Benchmarking highlights the issues associated with input parameters required in commercial finite element codes**
- **Results from propagation and growth analyses were in general in good agreement with the benchmark, however, selecting the appropriate input parameters was not straight forward**
- **Identified input parameters will be used on large scale finite element models of subcomponent test specimens for methodology validation**

REMAINING CHALLENGES



- **Abaqus/Standard® specific observations**
 - **Selecting the appropriate input parameters requires an iterative approach**
 - **Computation time even for a simple specimen using 3D models is very long**
 - **The input for the direct cyclic analysis procedure appeared complicated**
 - **The direct cyclic analysis may not be necessary and the user should be able to turn it off and still be able to perform growth analysis**
- **Future applications require**
 - **Input of mixed-mode failure criterion for onset and growth**
 - **Geometrically nonlinear analysis for growth under cyclic loading**
 - **No limitations on contact conditions for growth under cyclic loading**
 - **Analysis of complex failure mechanism such as interaction of delamination propagation and matrix cracking and branching**

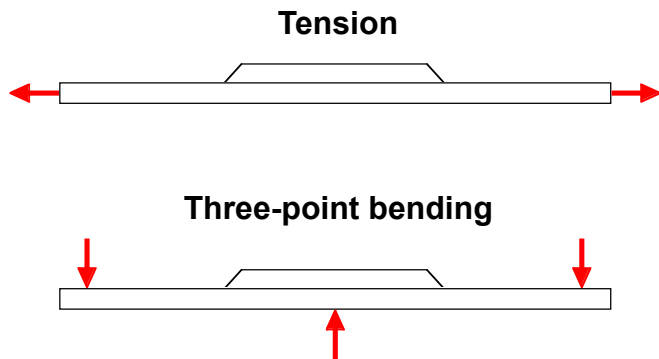
REMAINING CHALLENGES

Complex Failure Mechanism

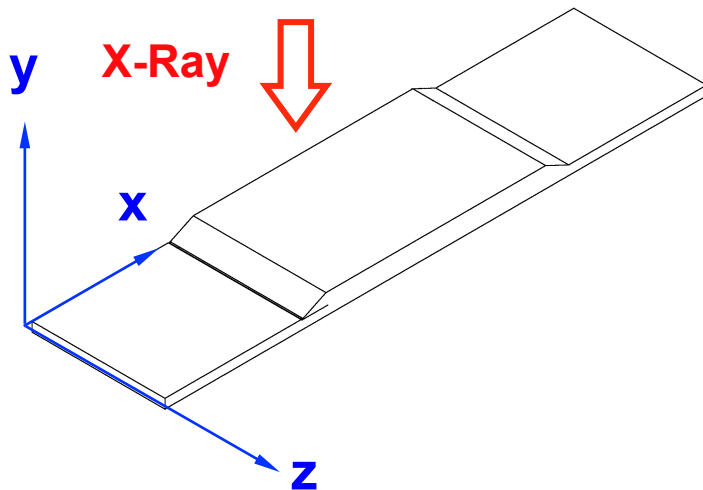
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Example skin/stiffener specimen



X-Ray of delaminated specimen



*Paris, Cvitkovich, Krueger, NASA/TM-2008-215308, 2008.

flange edge

delamination

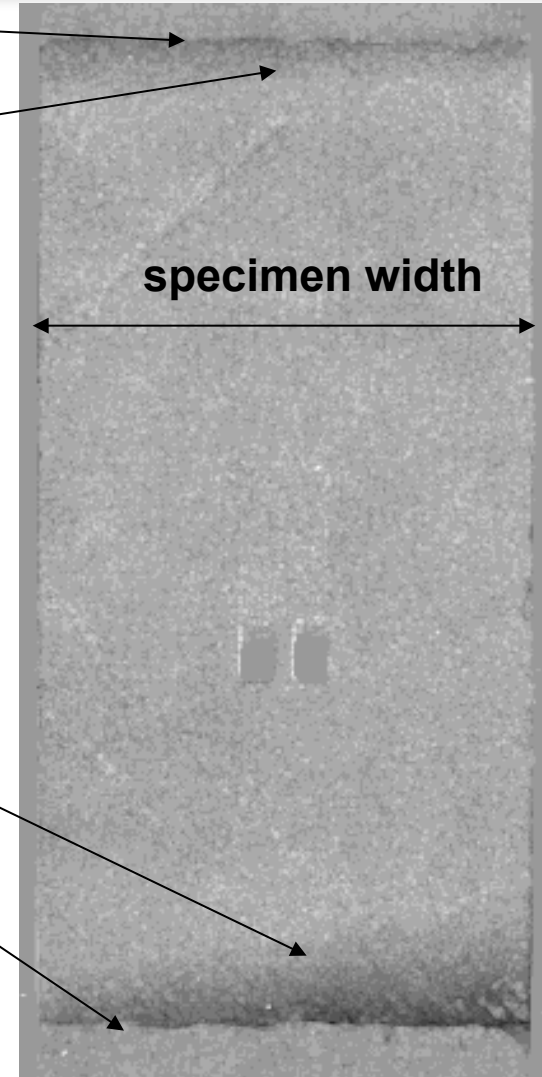
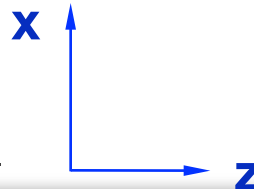
specimen width

flange

730 cycles

delamination

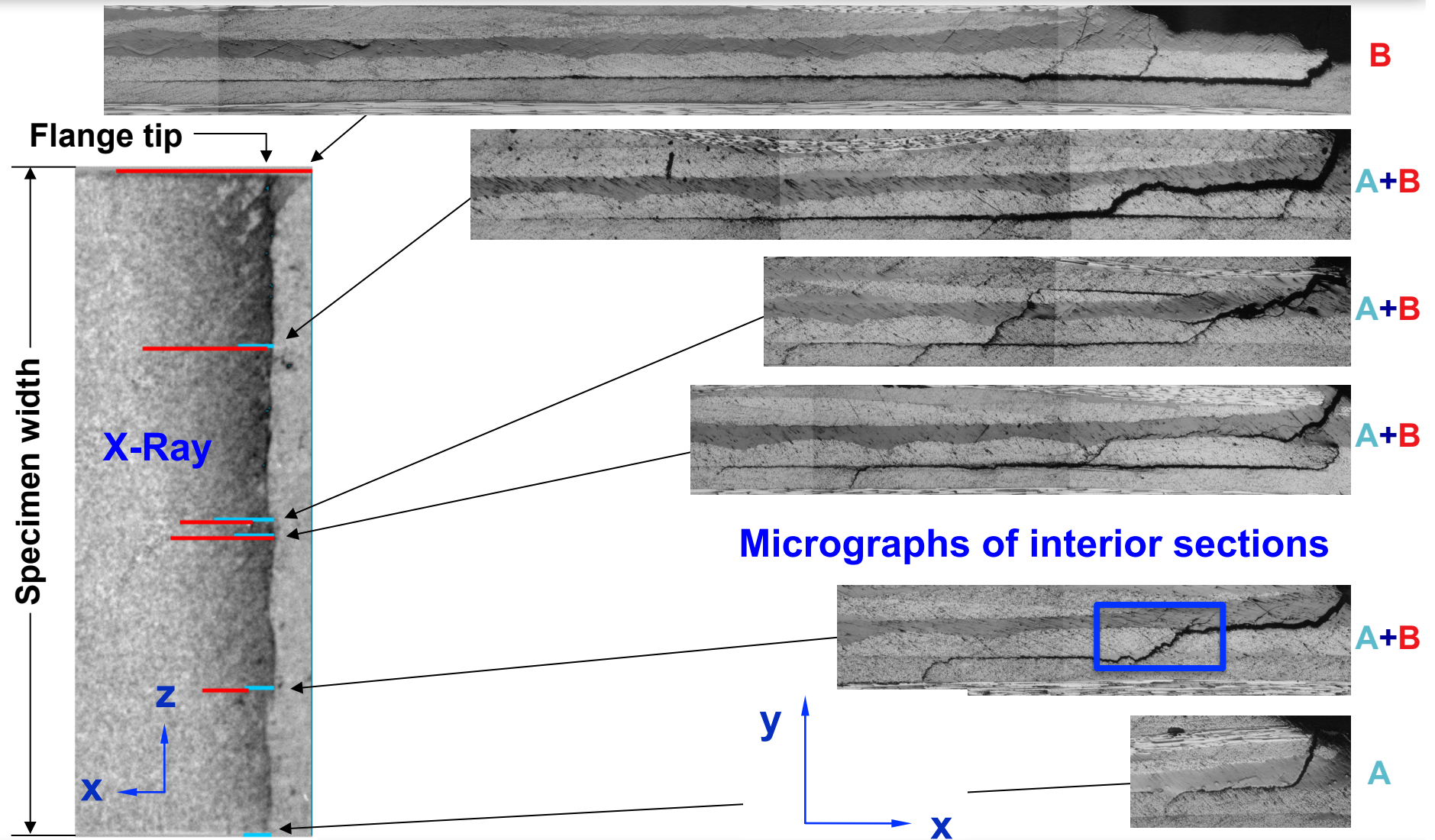
flange edge



REMAINING CHALLENGES

Delamination and Matrix Crack Interaction

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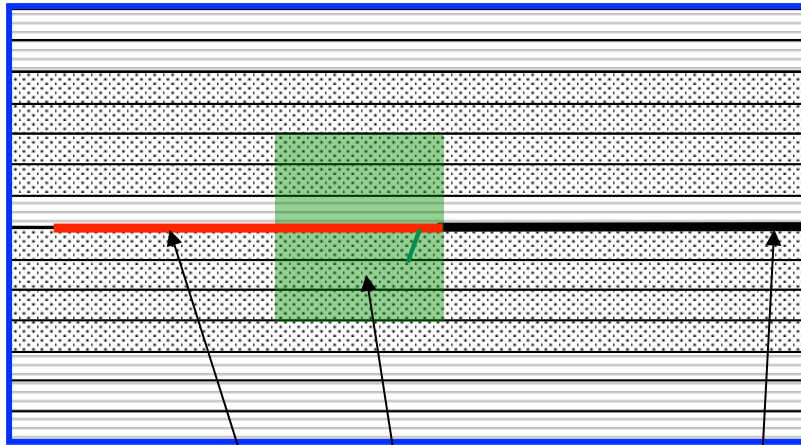


REMAINING CHALLENGES

Modeling approach to study interaction



Damage initiation as first matrix crack

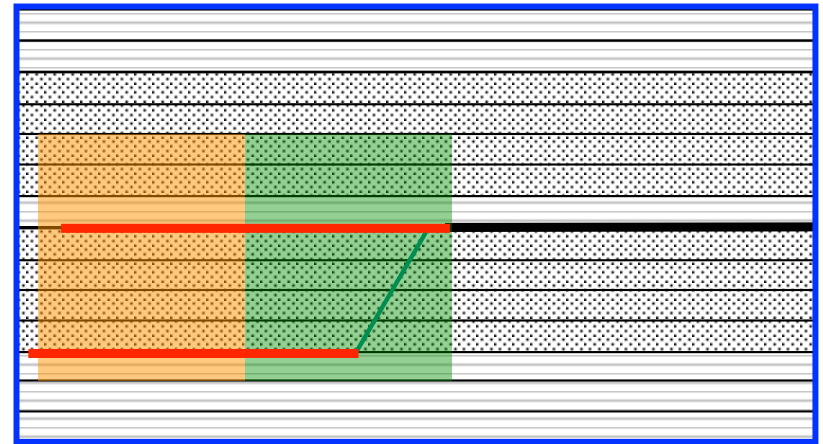


VCCT at ply interface to
monitor delamination onset

original delamination

zone enhanced for XFEM
to monitor matrix crack
onset

New delamination onset from matrix crack



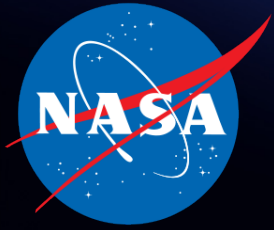
Observations

- **Quasi-static**
 - Limited to 1 crack per enriched zone
 - Convergence issues for large number of enriched zones
 - Other user defined criteria for initiation required
- **Fatigue**
 - Limitations similar to VCCT for delamination growth



REFERENCES

- E. F. Rybicki and M. F. Kanninen, "A Finite Element Calculation of Stress Intensity Factors by a Modified Crack Closure Integral," *Eng. Fracture Mech.*, Vol. 9, pp. 931-938, 1977.
- R. Krueger, "An Approach to Assess Delamination Propagation Simulation Capabilities in Commercial Finite Element Codes," NASA/TM-2008-215123, 2008.
- A. C. Orifici and R. Krueger, "Assessment of Static Delamination Propagation Capabilities in Commercial Finite Element Codes Using Benchmark Analysis," NASA/CR-2010-216709, NIA report no. 2010-03, 2010.
- R. Krueger, "Development of a Benchmark Example for Delamination Fatigue Growth Prediction," NASA/CR-2010-216723, NIA report no. 2010-04, 2010.
- R. Krueger, "Development and Application of Benchmark Examples for Mode II Static Delamination Propagation and Fatigue Growth Predictions," NASA/CR-2011-217194, NIA report no. 2011-02, 2011.
- I. Paris, M. Cvitkovich, R. Krueger, "Characterization of Fatigue Damage for Bonded Composite Skin/Stringer Configurations," NASA/TM-2008-215308, 20008.



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

DEMONSTRATION FOR ABAQUS/STANDARD®:

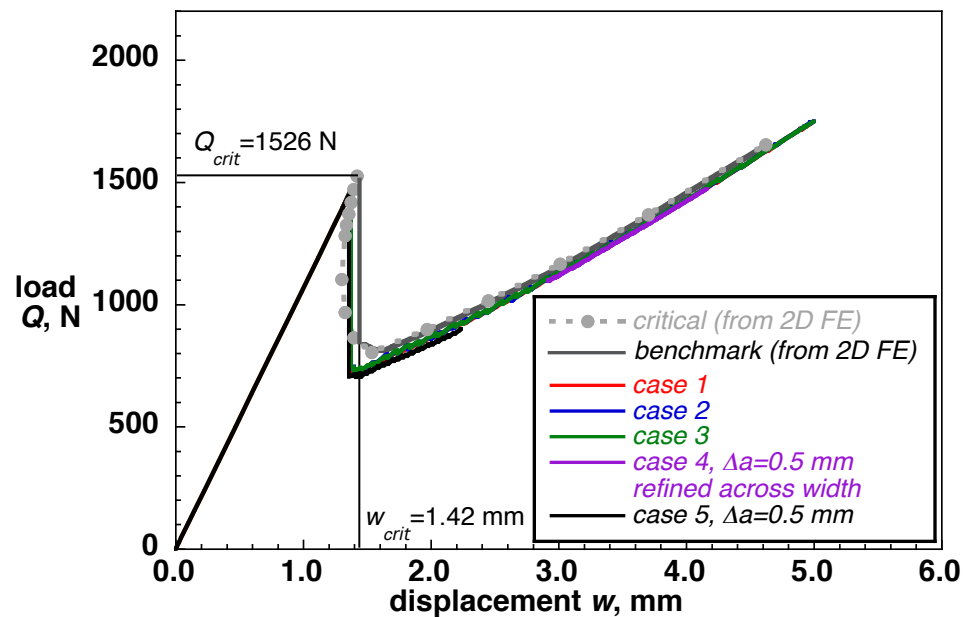
3D Solid FE Models

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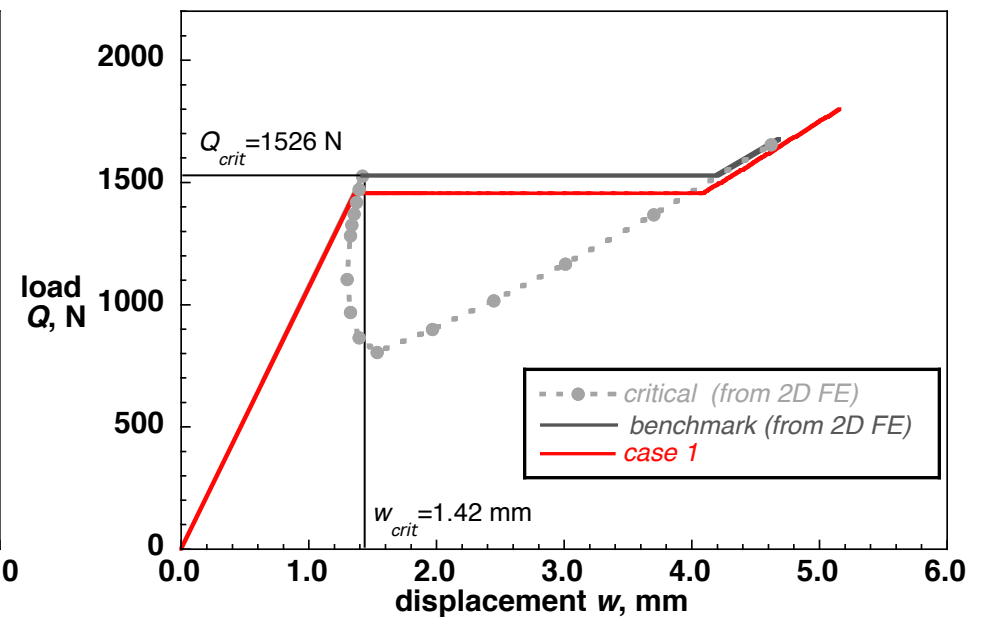
Applied displacement w

case	1	2	3	4	5
cs	E-6	E-6	E-6	E-6	E-6
relTol	0.5	0.2	0.1	0.1	0.1



Applied load Q

case	1
cs	E-6
relTol	0.1

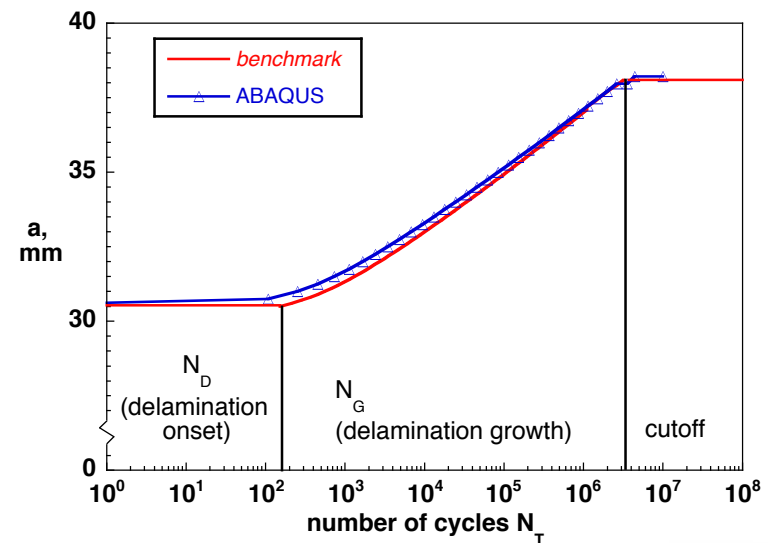
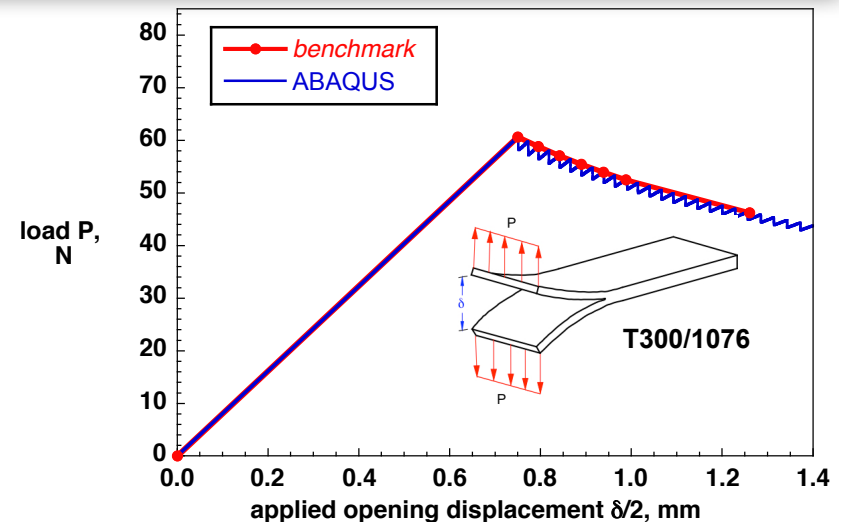


FIRST BENCHMARK PROBLEM: Double Cantilever Beam (DCB) Specimen

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- A static DCB benchmark was created based on a manual delamination propagation analysis
 - Assessment based on the comparison of benchmark and automated delamination propagation
 - Published as NASA/TM 2008-215123 and NASA/CR-2010-216709
- A fatigue DCB benchmark was created based on the previous DCB example
 - Loading and frequency based on proposed ASTM DCB fatigue standard
 - Assessment based on the comparison of benchmark and prediction of delamination onset and growth
 - Published as NASA/CR-2010-216723



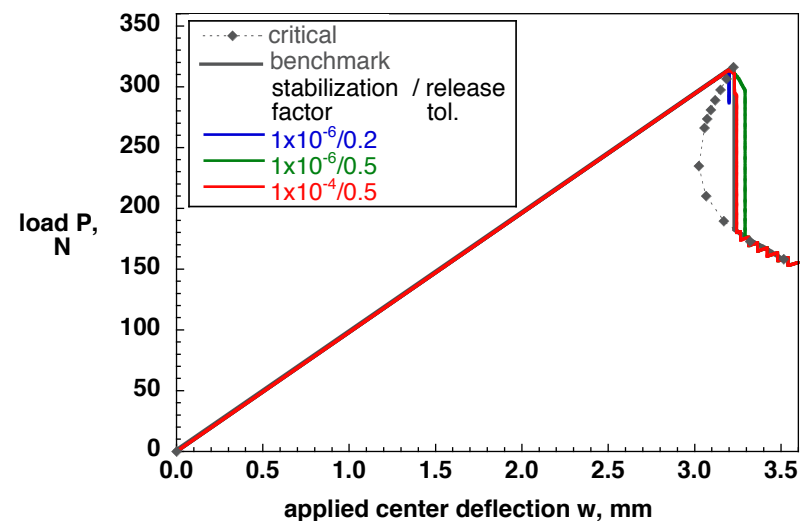
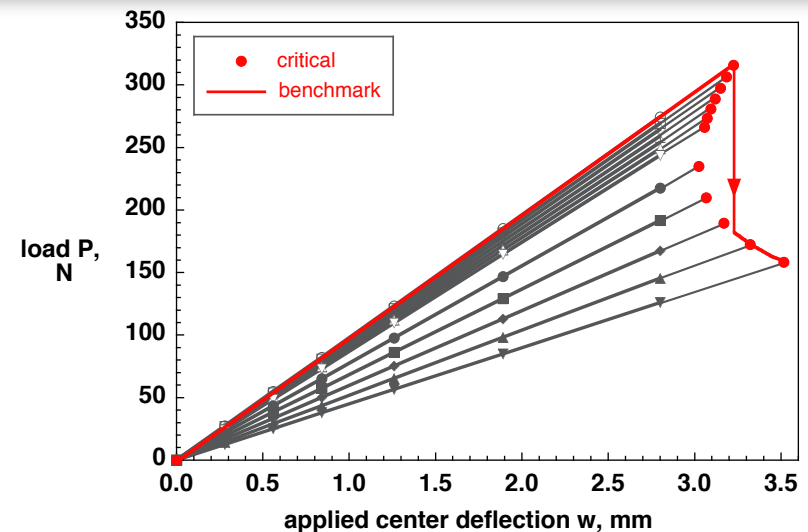
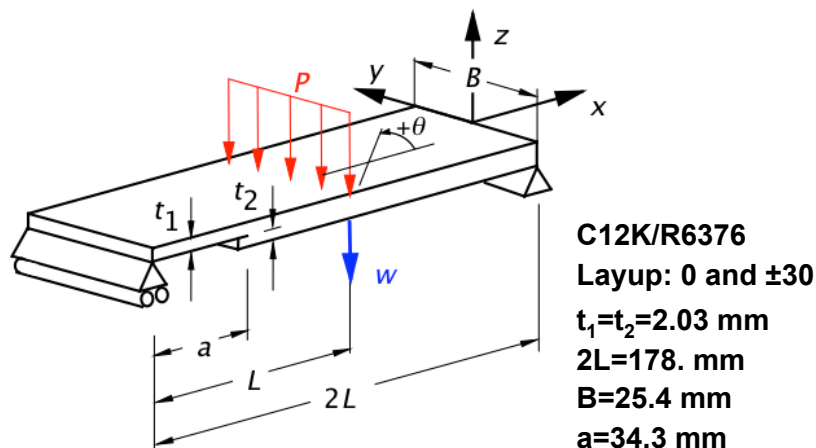
ADDITIONAL BENCHMARK PROBLEMS:

Single Leg Bending (SLB) Specimen

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- A static SLB benchmark was created based on a manual delamination propagation analysis
 - Fixed mixed-mode I/II ratio at about 40% mode II ($G_{II}/G_T \approx 0.4$)
 - Assessment based on the comparison of benchmark and automated delamination propagation
 - Published as NASA/TM 2008-215123



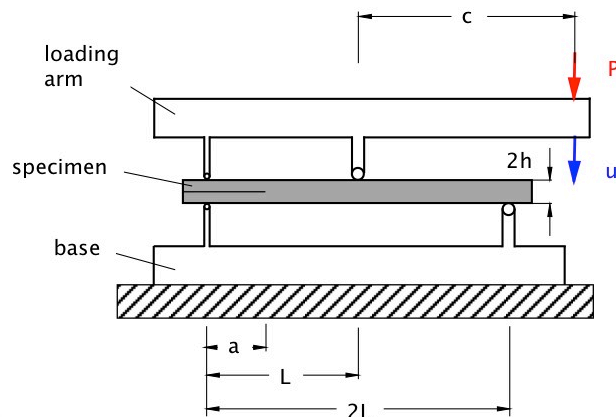
ADDITIONAL BENCHMARK PROBLEMS:

Mixed-Mode Bending (MMB) Specimen



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

- A static MMB benchmark was created based on a manual delamination propagation analysis
 - Three mixed-mode I/II ratio investigated
 - 20% mode II ($G_{II}/G_T \approx 0.2$)
 - 50% mode II ($G_{II}/G_T \approx 0.5$)
 - 80% mode II ($G_{II}/G_T \approx 0.8$)
 - Assessment based on the comparison of benchmark and automated delamination propagation
 - Published as NASA/TM 2012-217562



IM7/8552
Layup: $[0]_{24}$
 $2h=4.5$ mm
 $2L=101.6$ mm
 $B=25.4$ mm
 $a=25.4$ mm

