



DEVELOPMENT OF A BENCHMARK EXAMPLE FOR DELAMINATION FATIGUE GROWTH PREDICTION

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OUTLINE

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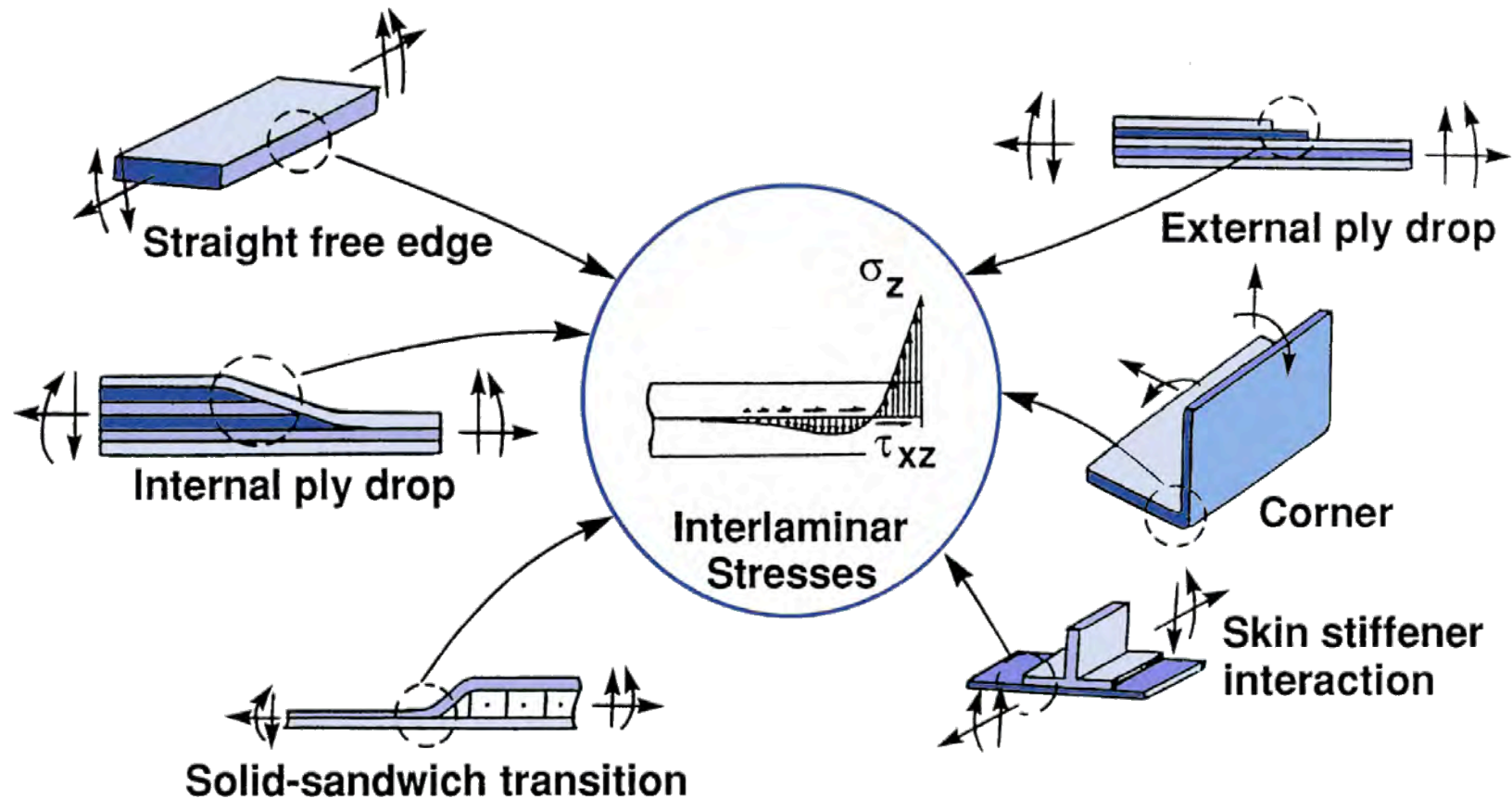


- **Motivation: Delamination in composite materials**
- **Development of a benchmark example for delamination growth prediction under cyclic loading**
 - **Creation of a benchmark example based on a Double Cantilever Beam (DCB) specimen**
 - **Calculation of number of cycles to delamination onset**
 - **Calculation of number of cycles during stable delamination growth**
- **Demonstration of the benchmark example for ABAQUS® Standard**
 - **Verification of correct input parameters**
 - **Comparison of predicted growth with benchmark example**
 - **Dependency of results on selection of input parameters**
 - **Discussion of problems encountered**
- **Concluding remarks**
 - **Planned applications**
 - **Wishlist**



DELAMINATION SOURCES AT GEOMETRIC AND MATERIAL DISCONTINUITIES

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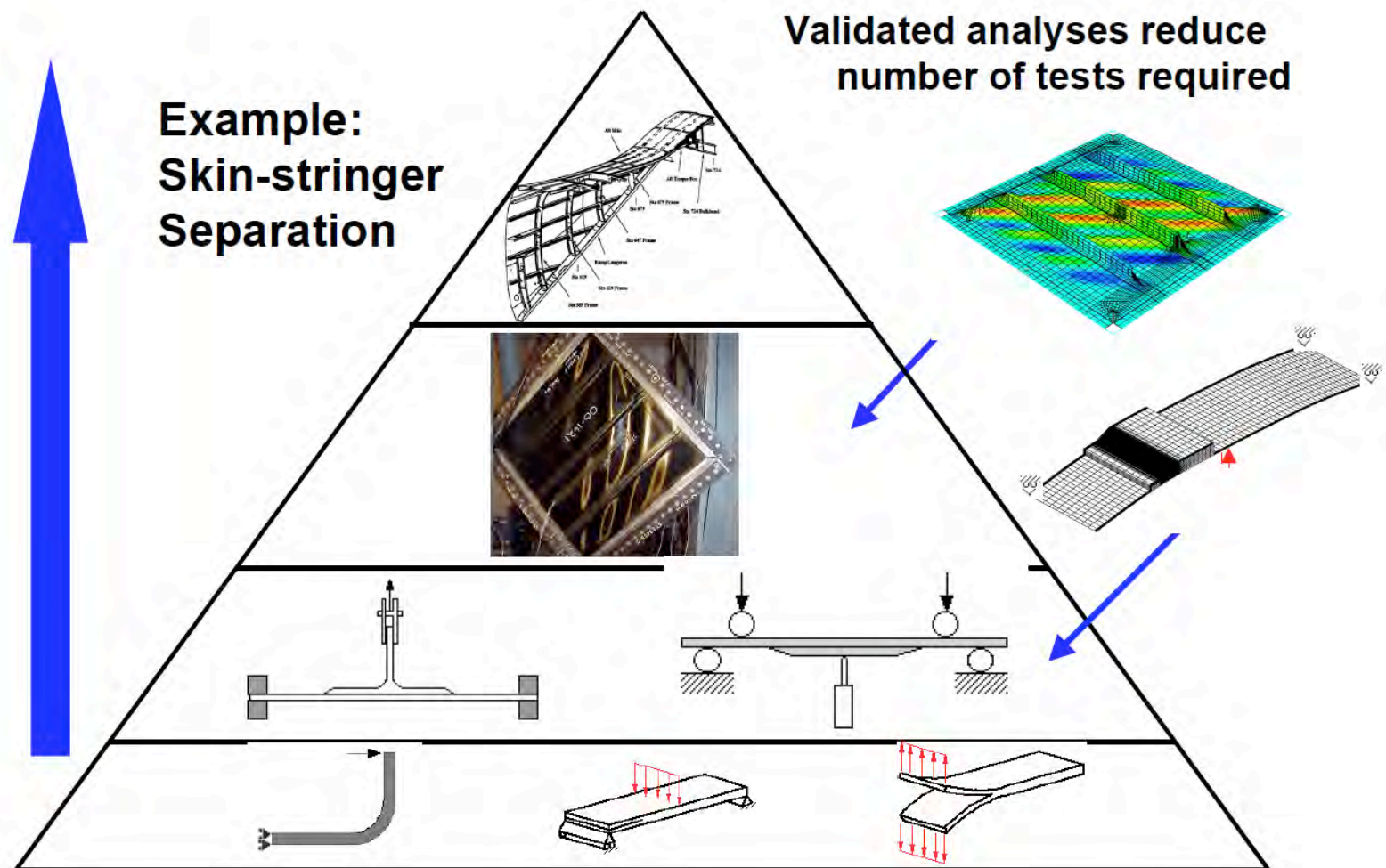


BACKGROUND

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- Building Block Approach for Composite Design and Certification





WHY BENCHMARKING?

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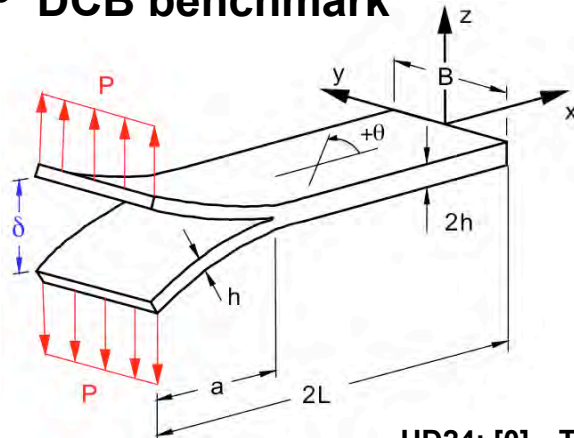
- **Benchmarking is required to gain confidence in the software tools used**
- **Benchmark cases have to be simple**
 - Simple geometry and loading: e.g. Double Cantilever Beam (DCB) specimen
 - Independent of analysis software used
- **A static DCB benchmark was created based on a manual delamination propagation analysis**
 - Assessment based on the comparison of benchmark and automated delamination propagation
 - Presented at FCRT meeting 2007, published as NASA/TM 2008-215123
- **A fatigue 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



BENCHMARK PROBLEM: DCB SPECIMEN



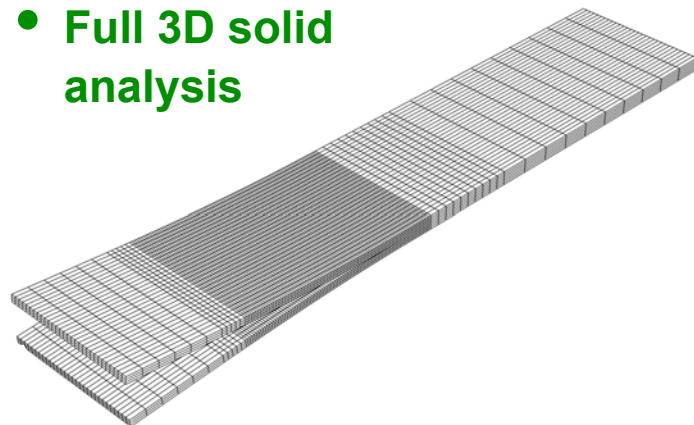
- DCB benchmark



$f=10 \text{ Hz}$
 $R=0.1$
 $G_{lmax}=0.8 G_{lc}$
 based on proposed ASTM
 DCB fatigue standard

UD24: $[0]_{24}$ T300/914C
 $2h=3.0 \text{ mm}$
 $2L=150.0 \text{ mm}$
 $B=25.0 \text{ mm}$
 $a=30.5 \text{ mm}$

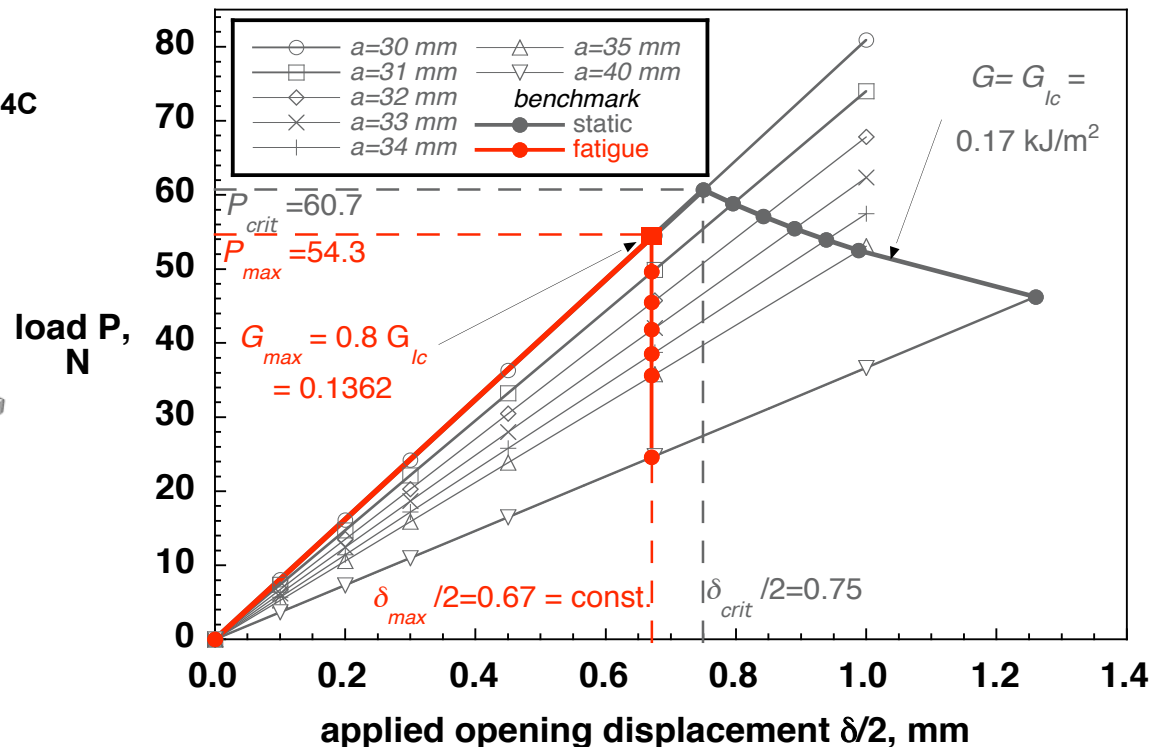
- Full 3D solid analysis



- 2D plane strain and plane stress analysis



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

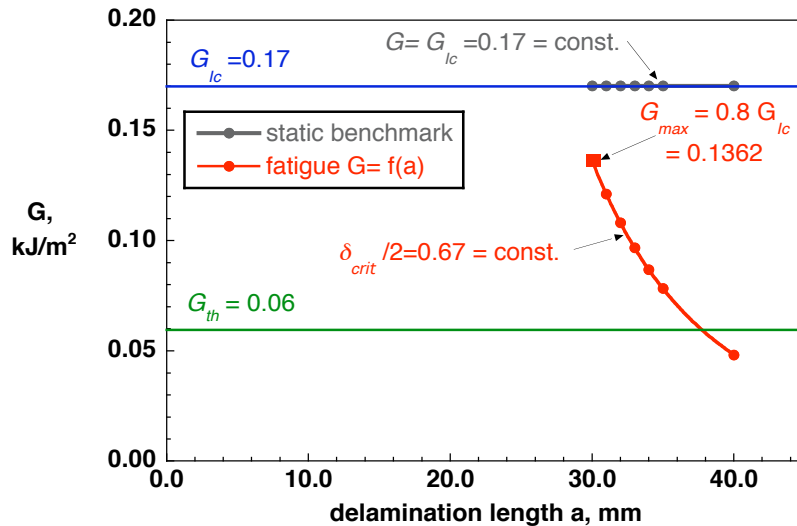




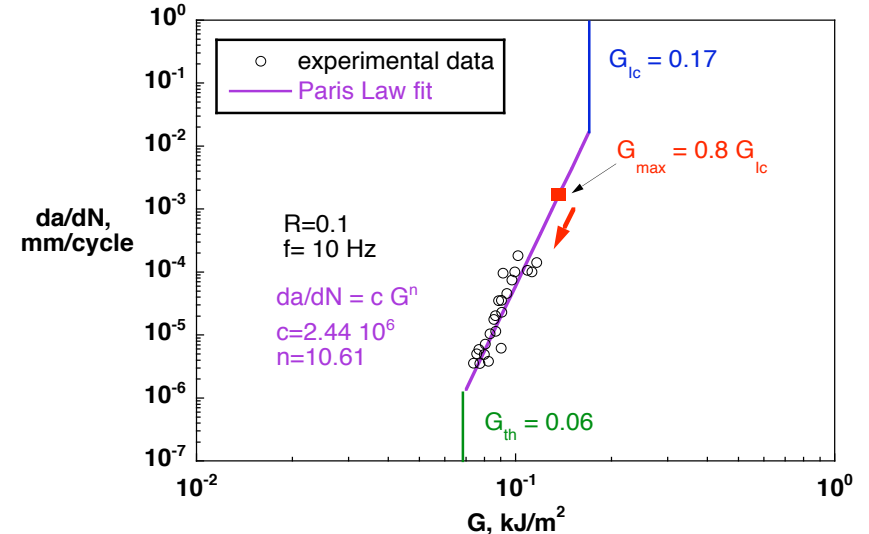
CREATING A BENCHMARK SOLUTION FOR A DCB SPECIMEN



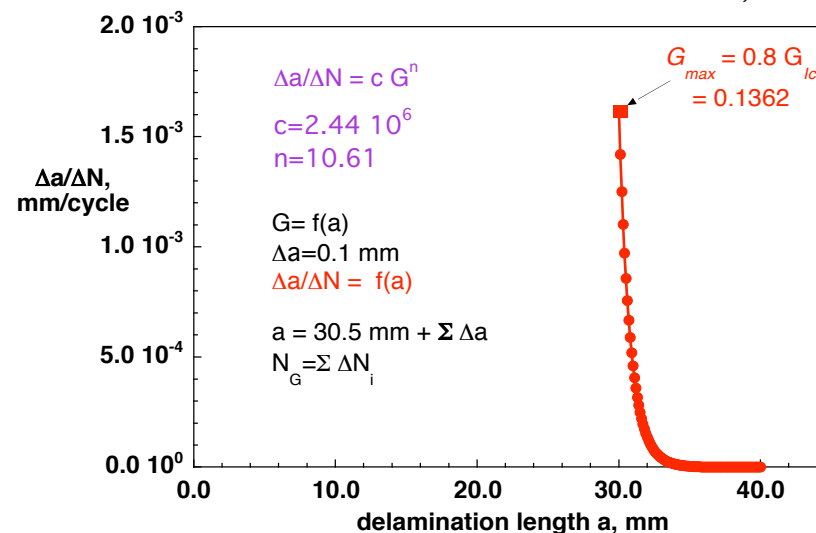
- Decrease of G_I with increasing length a



- Delamination growth (Paris Law)



- Calculated delamination growth rate $\Delta a/\Delta N$ and cycles to growth N_G



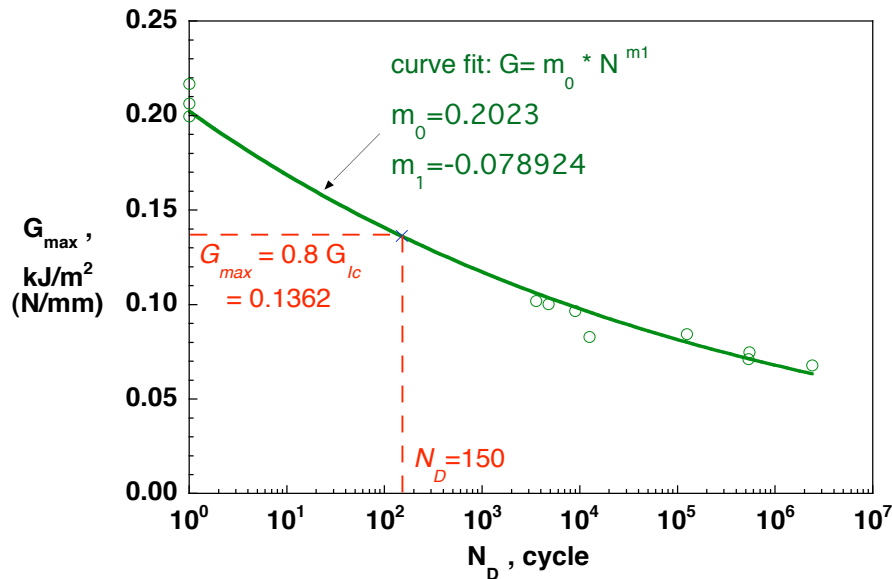


CREATING A BENCHMARK SOLUTION FOR A DCB SPECIMEN (continued)

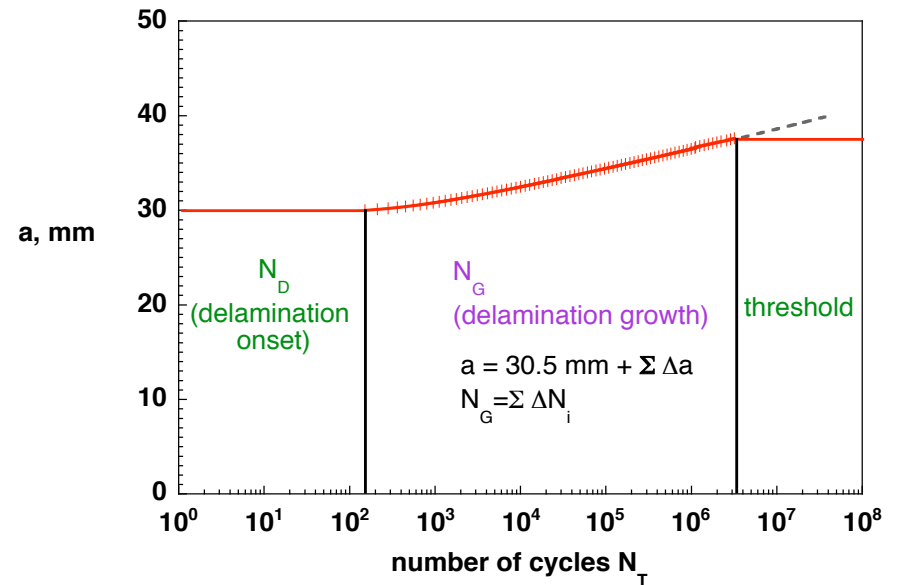
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- Cycles to delamination onset N_D



- Cycles to onset and growth N_T



- Benchmarking procedure

- Keep input parameters for fracture criterion and loading constant
- Study influence of input parameters such as
 - Fourier series approximation
 - Initial time increment
 - Cycle definition as sine or cosine wave
 - Solution controls
- Study influence of element type and mesh size



ABAQUS® STANDARD FRACTURE INPUT

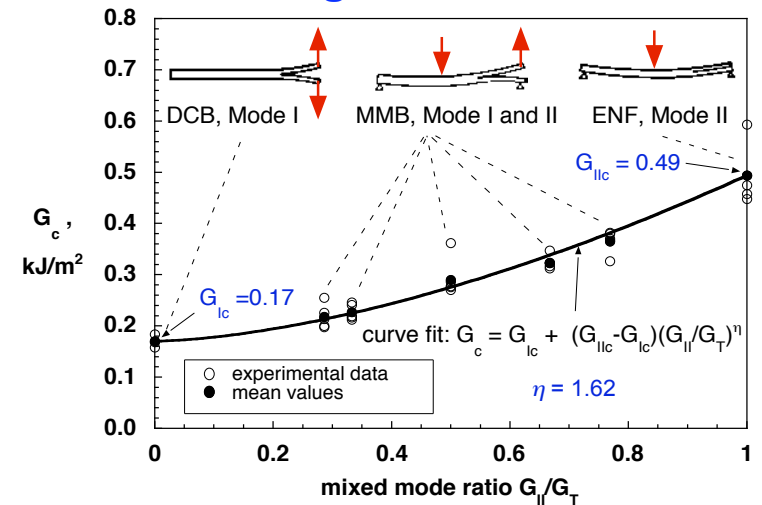


• Keyword

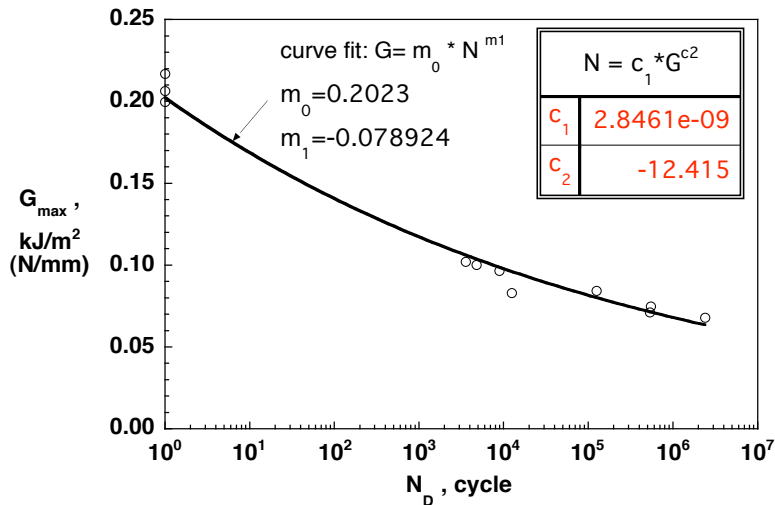
***FRACTURE CRITERION, TYPE=fatigue, MIXED
MODE BEHAVIOR=BK, TOLERANCE=<tol>
<c1>,<c2>,<c3>,<c4>,<r1>,<r2>,<G_{lc}>,<G_{IIc}>,
<G_{IIIc}>,<eta>**

- Mixed-mode fracture toughness required
- Limited to single set of onset and growth data

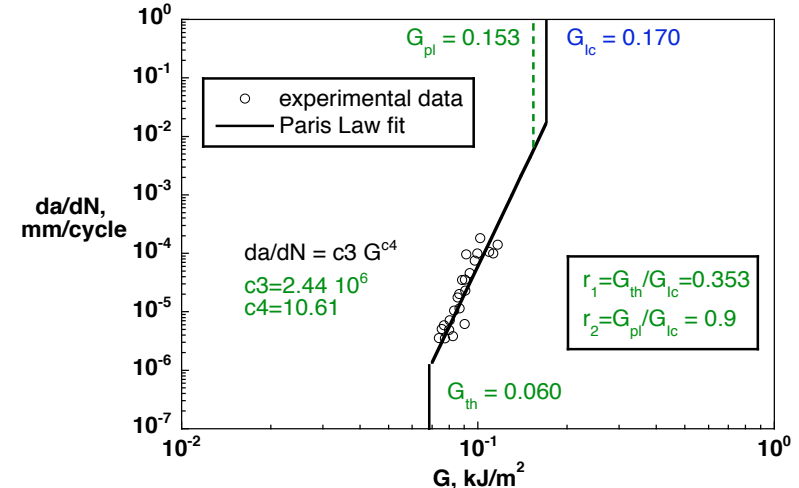
• Fracture toughness data <G_{lc}>,...



• Onset data: <c1>,<c2>



• Growth data: <c3>,<c4>,<r1>,<r2>





ABAQUS® STANDARD LOAD INPUT

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• Keyword

```
*AMPLITUDE, NAME=test, DEFINITION=PERIODIC
1,  $\omega$ ,  $t_0$ ,  $A_0$ 
 $A_1$ ,  $B_1$ 
```

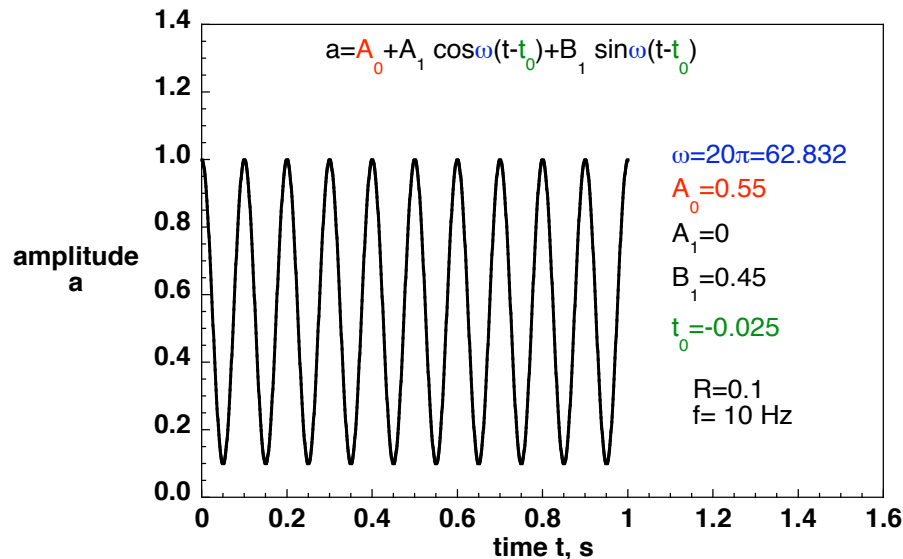
$$\text{amplitude} = [A_0 + A_1 \cos \omega(t - t_0) + B_1 \sin \omega(t - t_0)]$$

• Keyword

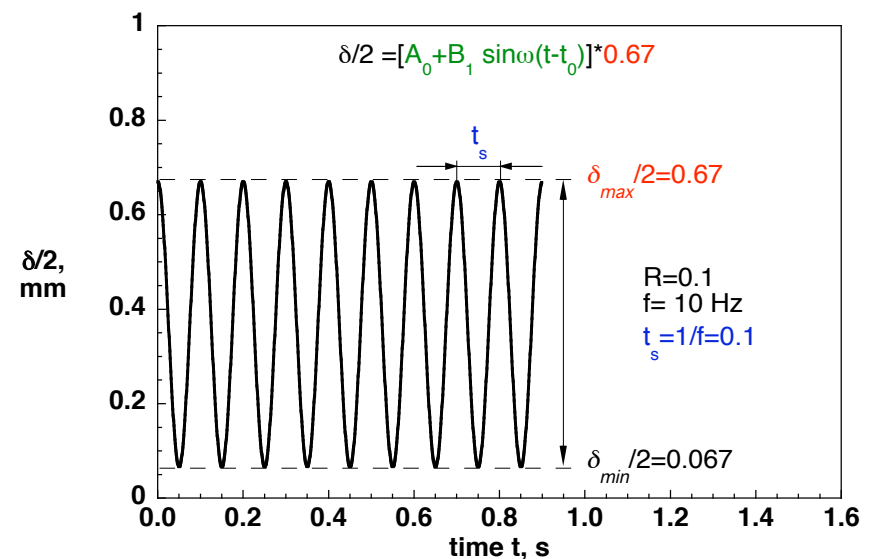
```
*DIRECT CYCLIC, fatigue
 $i_0$ ,  $t_s$ ,  $n_i$ ,  $n_{\max}$ ,  $\Delta n$ , 200
,, 10000000,,
*BOUNDARY, AMPLITUDE=test
LFRONT, 1, 1,  $\delta_{\max}$ 
LFRONTM, 1, 1,  $-\delta_{\max}$ 
```

$$\delta/2 = \text{amplitude} * \delta_{\max}$$

• Amplitude data



• Direct cyclic data

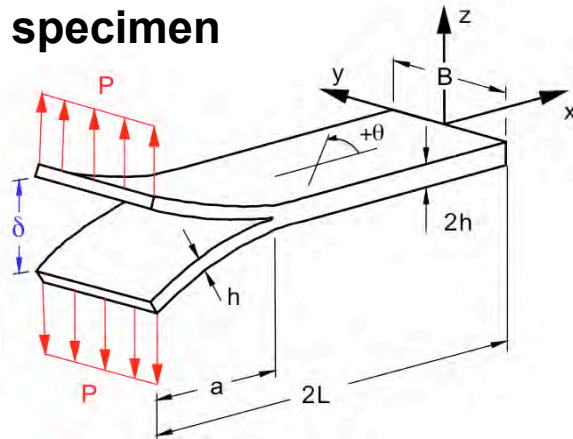




COMPUTED DELAMINATION ONSET AND GROWTH FOR DCB SPECIMEN



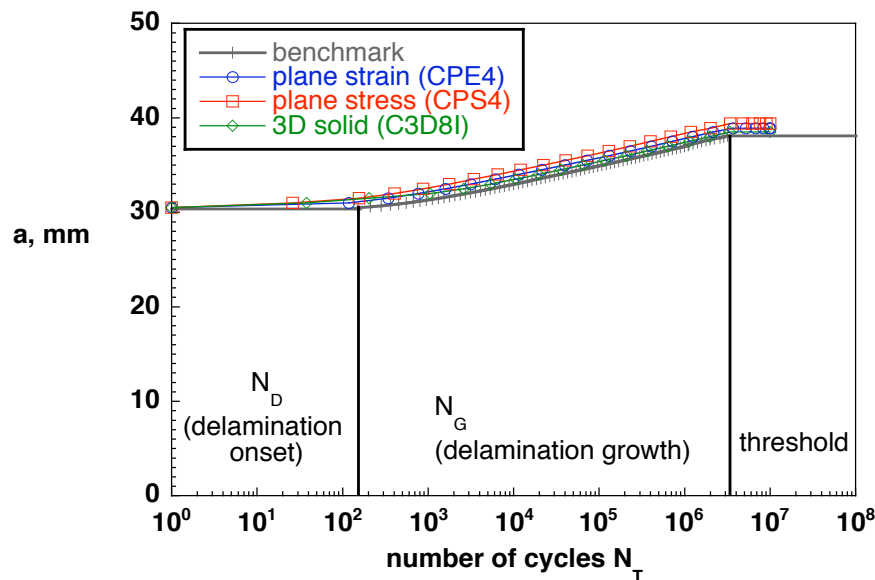
• DCB specimen



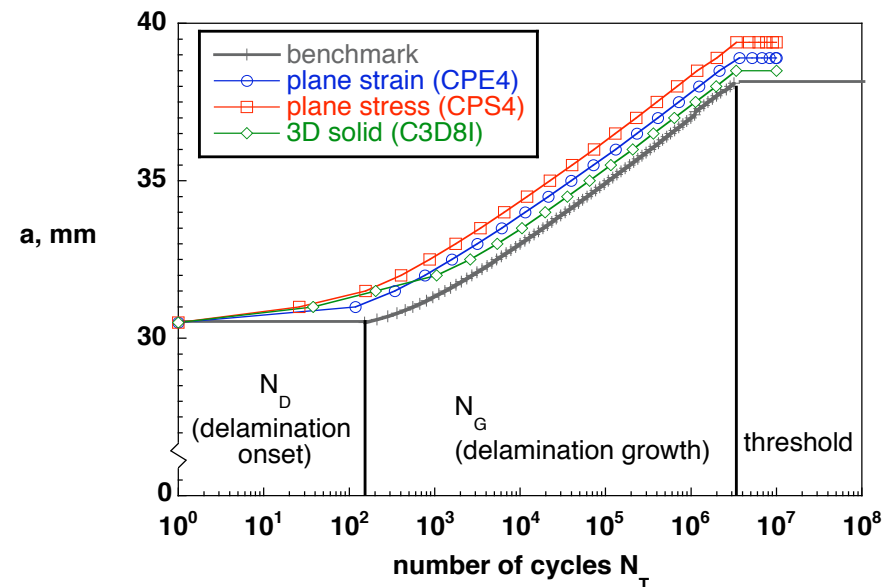
• Initial input parameters

```
*AMPLITUDE,NAME=test,DEFINITION=PERIODIC
1,62.832,0.,0.55
0,0.45
*DIRECT CYCLIC, fatigue
0.001,0.1,,,11,11,5,200
,,1000000,,
```

• Initial results



• Modified scale





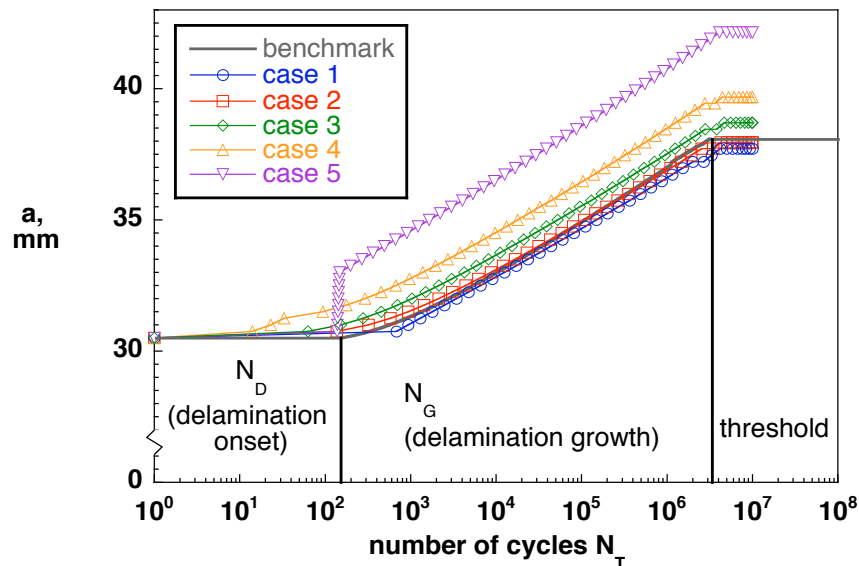
INFLUENCE OF INPUT PARAMETERS ON COMPUTED RESULTS



• Fourier series

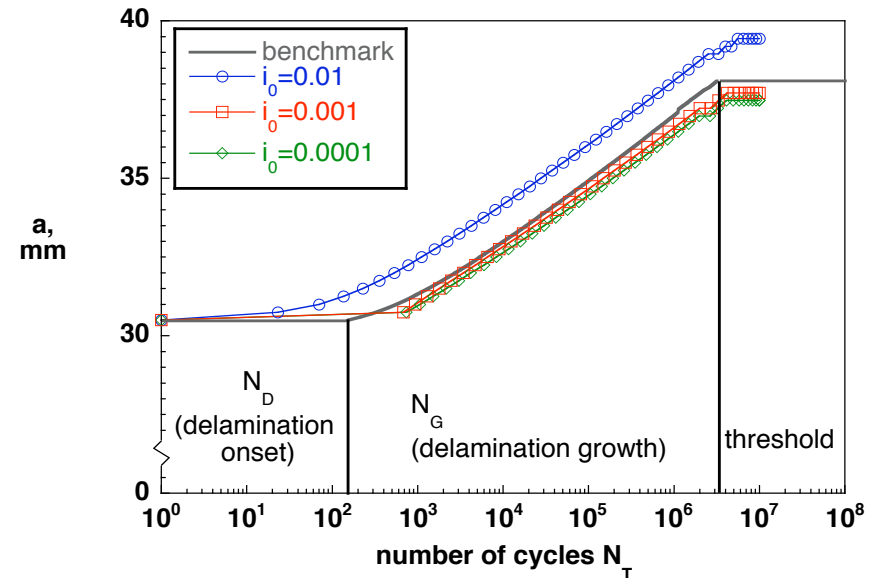
*DIRECT CYCLIC, fatigue
 $i_0, 0.1, , , n_i, n_{max}, \Delta n, 200$
 $, , 10000000, ,$

case	1	2	3	4	5
n_i	1	2	11	22	5
n_{max}	1	2	11	22	50
Δn	1	1	5	5	5



• Initial time increment i_0

*DIRECT CYCLIC, fatigue
 $i_0, 0.1, , , n_i, n_{max}, \Delta n, 200$
 $, , 10000000, ,$



*DIRECT CYCLIC, fatigue
 $0.001, 0.1, , , 1, 1, 1, 200$
 $, , 10000000, ,$

used for the remainder of the study



INFLUENCE OF INPUT PARAMETERS ON COMPUTED RESULTS (continued)



- Amplitude definition

$$\delta/2 = [A_0 + A_1 \cos \omega(t - t_0) + B_1 \sin \omega(t - t_0)] * 0.67$$

- Sine curve $A_1=0, B_1=0.45$

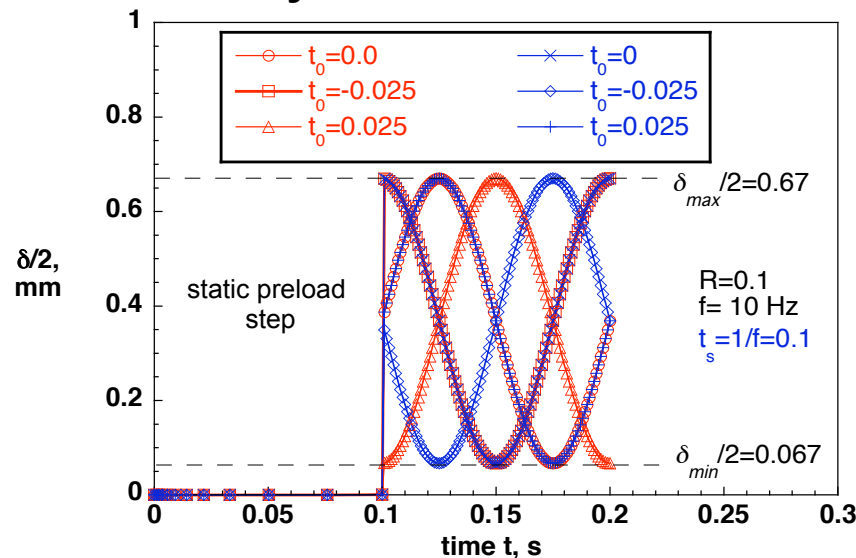
- Cosine curve $A_1=0.45, B_1=0$

*AMPLITUDE, NAME=test, DEFINITION=PERIODIC

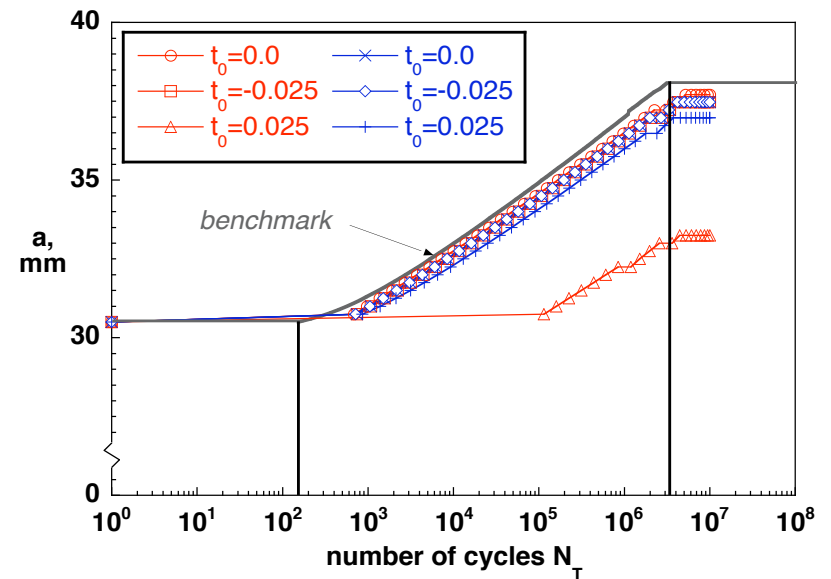
1, ω , t_0 , A_0

A_1, B_1

- First load cycle



- Computed growth



- Unclear why different curve definition causes dramatically different result!

- Sine curve $A_1=0, B_1=0.45, t_0=0$. used for the remainder of the study

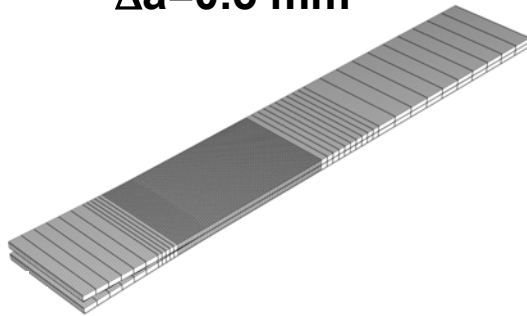


INFLUENCE OF MESH SIZE AND ELEMENT TYPE ON COMPUTED RESULTS

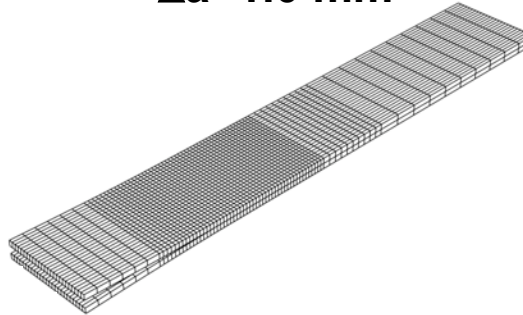


- 3D models (C3D8I, SC8R)

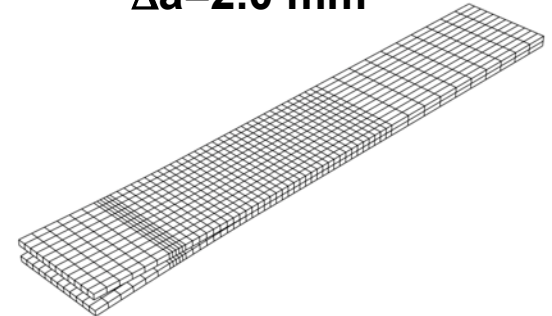
- $\Delta a = 0.5$ mm



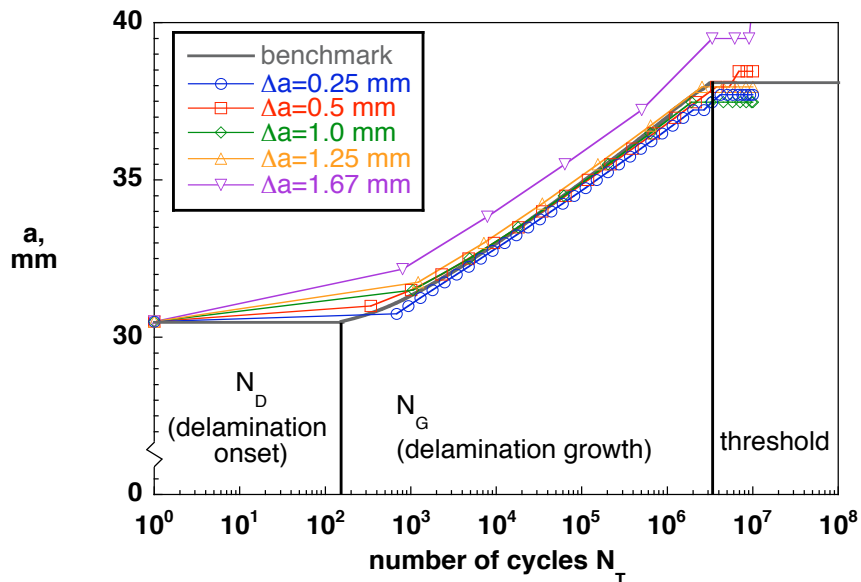
- $\Delta a = 1.0$ mm



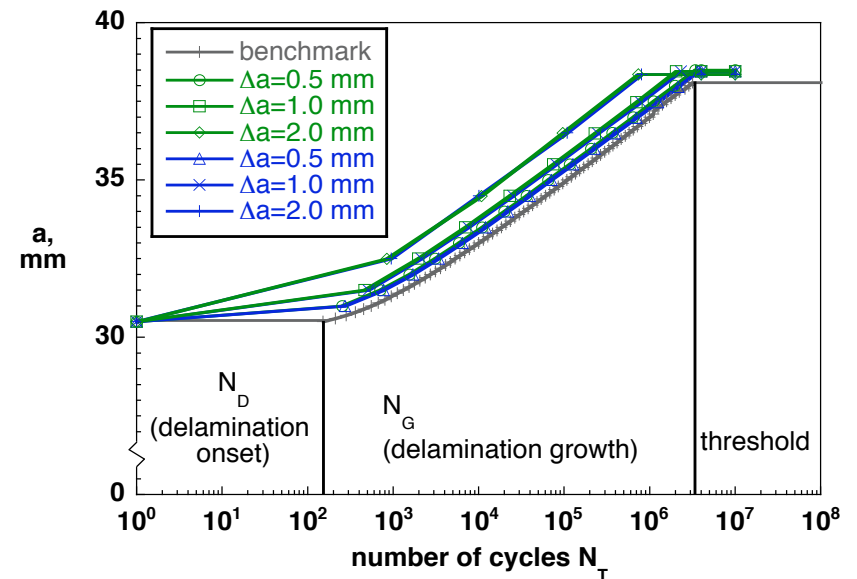
- $\Delta a = 2.0$ mm



- Results from 2D plane strain model



- Results from 3D model (C3D8I, SC8R)

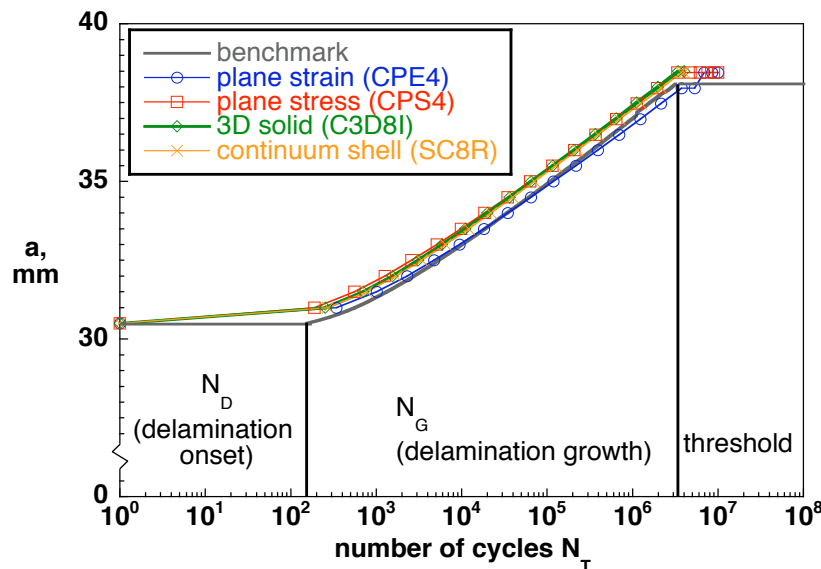




INFLUENCE OF ELEMENT TYPE AND CONTROLS ON COMPUTED RESULTS



- **Benchmark case and results from 2D and 3D analyses ($\Delta a=0.5$ mm)**



- **CPU time on Dual-Core AMD Opteron(tm) Processor 8220 SE**

- 2D analyses required between 80s and 1050s depending on mesh size
- 3D analyses required between 5800s and 7 days depending on mesh size
- 3D shell elements reduced the time required by about a factor of 2.7

- **Solution controls**

*controls,type=direct cyclic
 I_{PI} , CR_n , CU_n , CR_0 , CU_0 ,

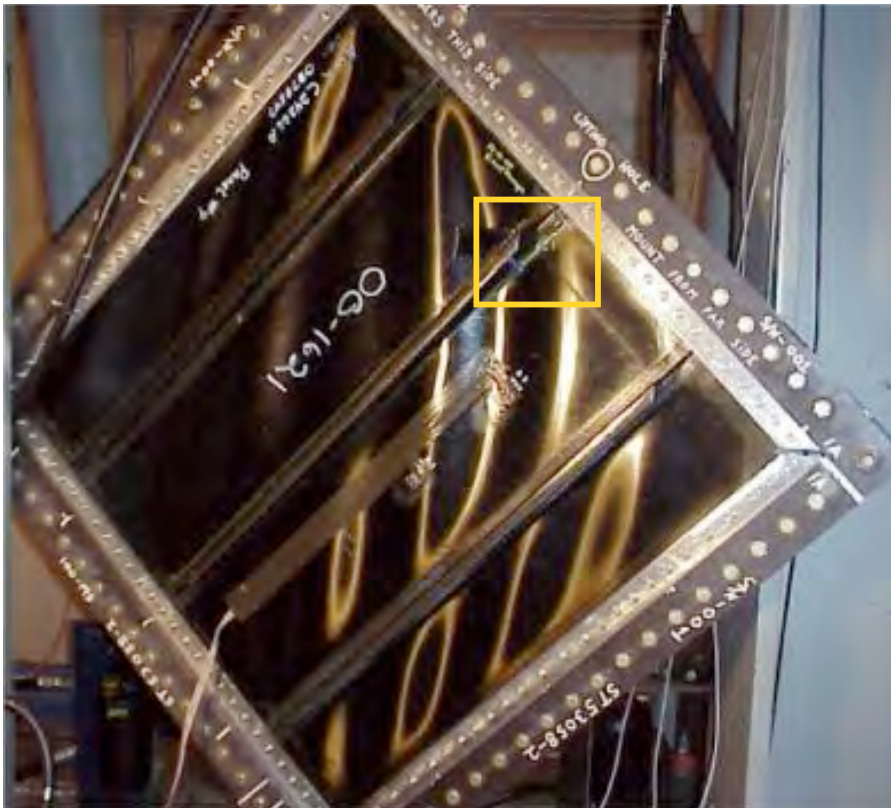
- Used in ABAQUS® Standard DCB example input file
- Controls had to be used to reduce computation time
- $CR_n > 0.1$ reduced the computation time by a factor of 10
- Varying the parameters between $10^{-4} < CR_n, CU_n, CR_0, CU_0 < 100$ had no effect on the results
- Meaning and significance of the parameters remains unclear



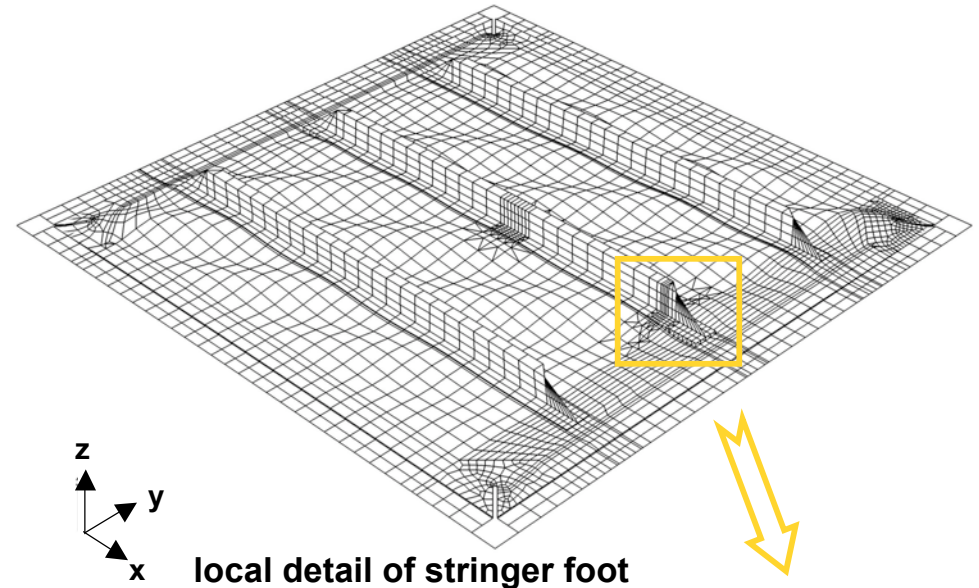
EXAMPLE APPLICATION: STRINGER STIFFENED PANEL



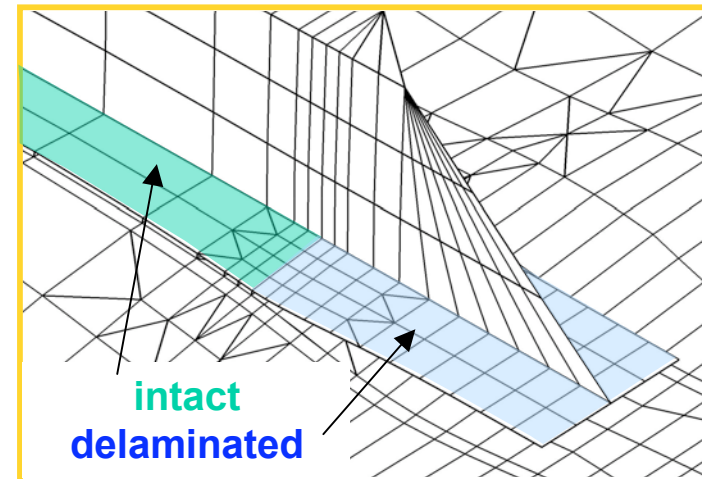
- Testing of Stiffened Shear Panel
Boeing, Philadelphia



- Original ABAQUS Shell Model

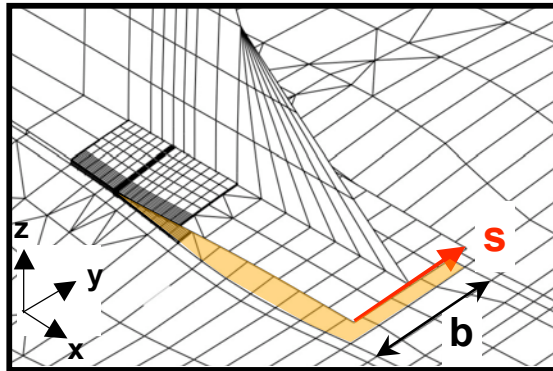


local detail of stringer foot





COMPUTED ENERGY RELEASE RATES AND MIXED-MODE RATIO



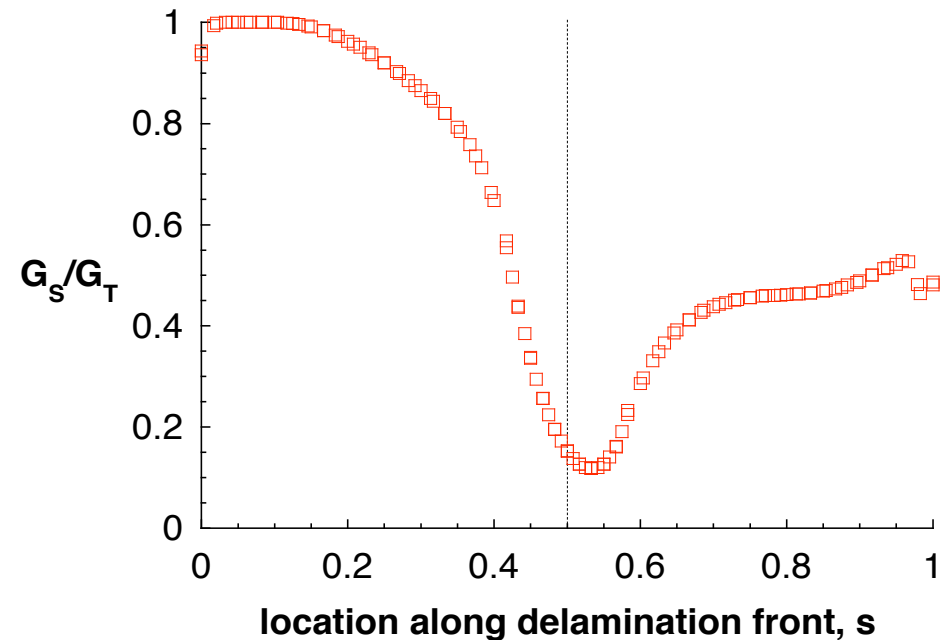
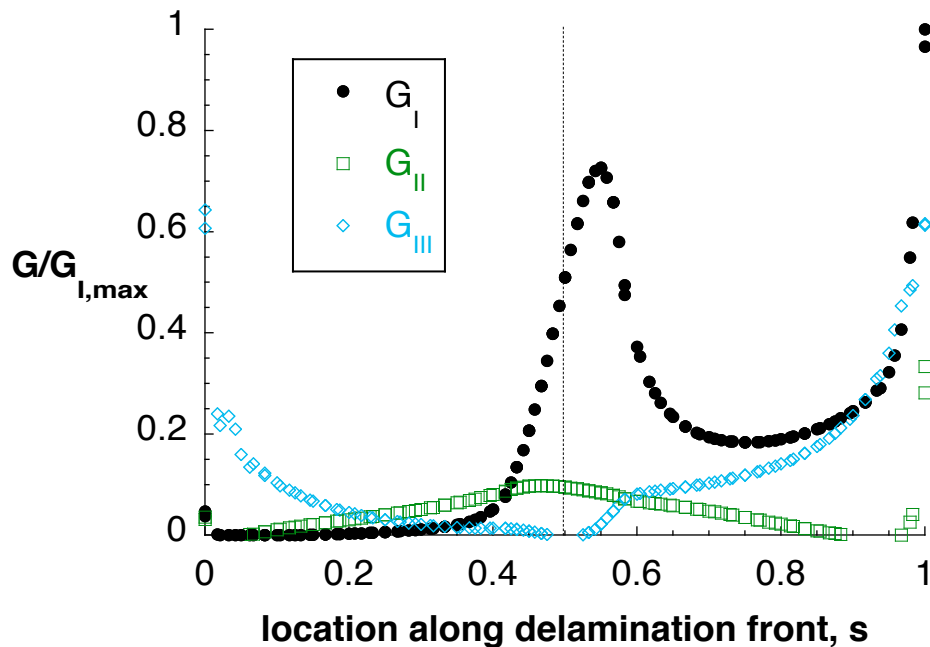
$$0 \leq s \leq 1; s = \frac{y}{b}$$

- Mixed-mode ratio across stringer width

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

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

- Energy release rates across stringer width





CONCLUDING REMARKS

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- **A benchmark example for cyclic delamination growth prediction was developed and demonstrated**
 - **Results from growth analyses were in general in good agreement with the benchmark**
 - **Selecting the appropriate input parameters was not straight forward**
 - The meaning and significance of the solution controls parameters remains unclear
 - The input for the direct cyclic analysis procedure appeared complicated
 - A phase-shift of the sine wave in the amplitude definition had a negative influence on the results. It remains unclear why!
 - Computation time for a simple specimen using 3D models was very long
- **Future applications require**
 - **Input of mixed-mode failure criterion for onset and growth**
 - **Geometrically nonlinear analysis**
 - **No limitations on contact conditions**
 - **Analysis of delamination propagation and branching which includes matrix cracking**



ACKNOWLEDGEMENTS

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Thanks to Babu Aminjikai and Brian Baillargeon of the SIMULIA Eastern Region office for their support and advice in getting this analysis started.



BACKUP SLIDES

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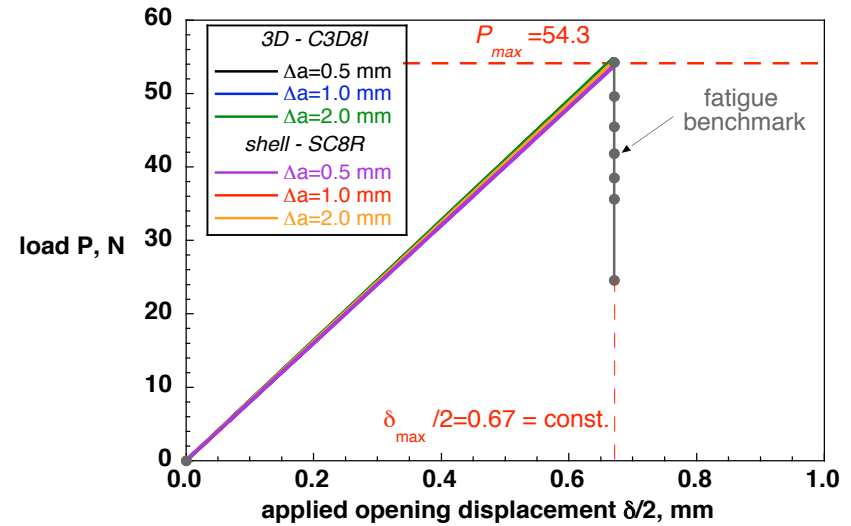
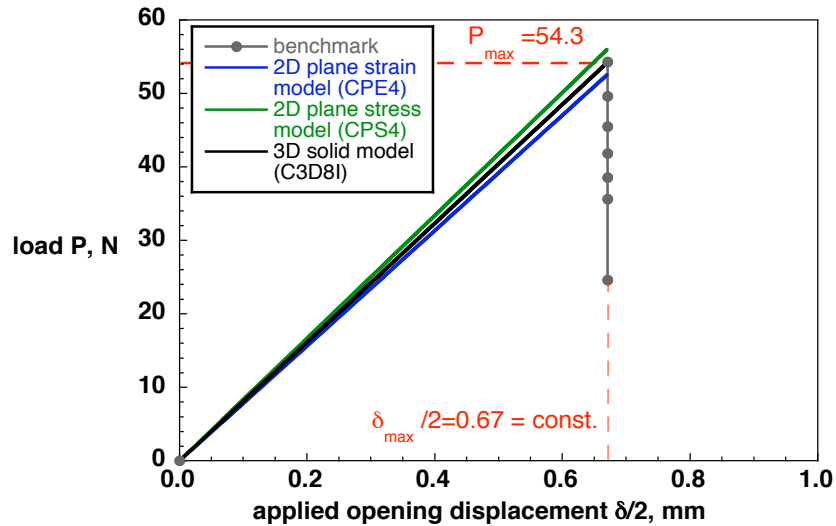




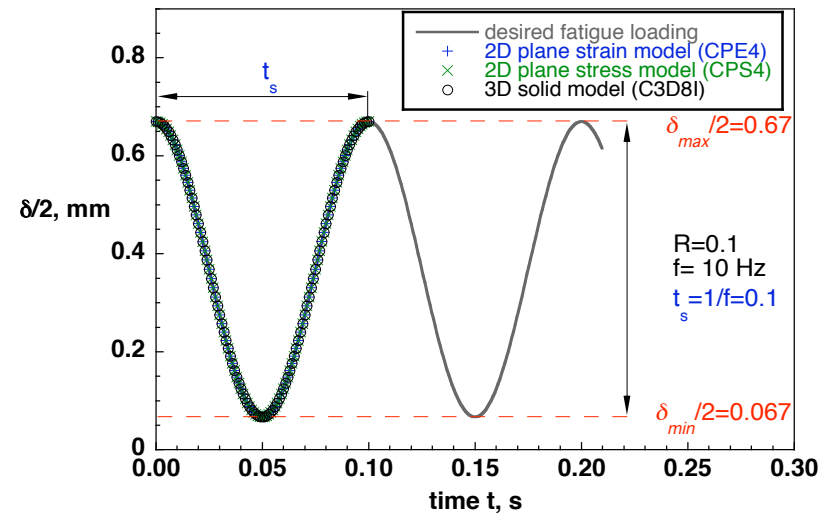
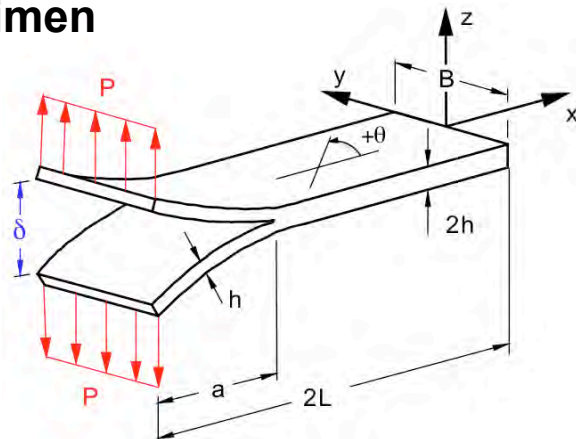
VERIFICATION OF INPUT DATA



- Load/displacement plot obtained from different models



- Cyclic opening at the tip of the DCB specimen





COMPUTED ENERGY RELEASE RATES



- Target: $G_{\max} = 0.8 G_{Ic} = 0.1362 \text{ kJ/m}^2$
 $G_{\min} = 0.00136 \text{ kJ/m}^2$

- Energy release rate distribution across the width of the DCB specimen

- Energy release rate for one cycle

