Failure of Notched Laminates Under Out-of-plane Bending

The Joint Advanced Materials and Structures Center of Excellence

Failure of Notched Laminates Under Out-of-plane Bending

- Motivation and Key Issues

  Develop analysis techniques useful in design of composite aircraft structures under out-of-plane bending

- Objective

  Determine failure modes and evaluate capabilities of current models to predict failure

- Approach
  - Experiments: Four point bending
  - Modeling: Progressive damage development and delamination (ABAQUS)

FAA Sponsored Project Information

- Principal Investigators & Researchers

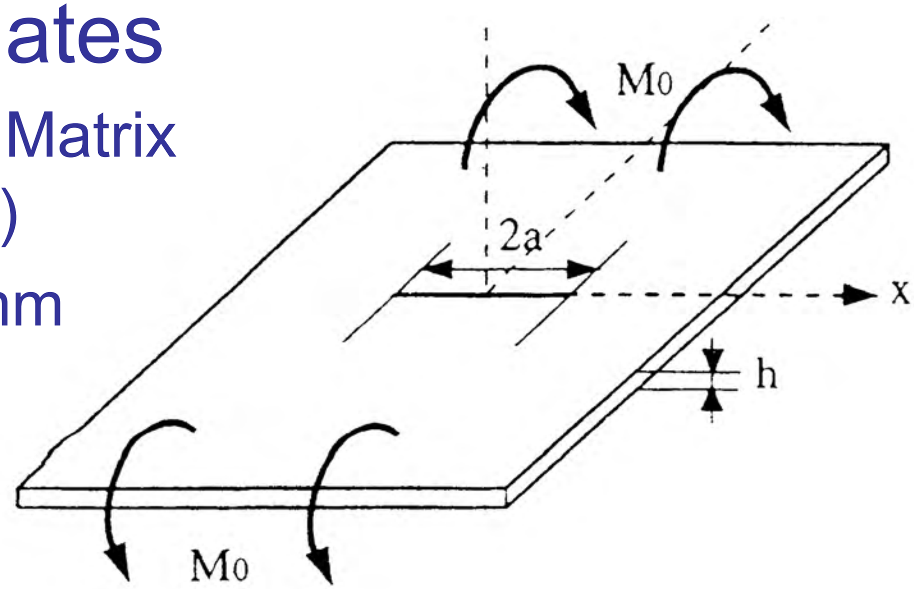
  John Parmigiani (OSU) & Tim Kennedy (OSU)
- FAA Technical Monitor

  Curt Davies & Lynn Pham
- Other FAA Personnel Involved

  Larry Ilcewicz (technical advisor)
- Industry Participation
  - Gerry Mabson, Boeing (technical advisor)
  - Tom Walker, NSE Composites (technical advisor)

Composites Studied

Center-notched laminates



- Carbon Fiber / Epoxy Matrix Composite (T300/913)
- 25.4-mm and 101.6-mm ovaloid notches
- 20 and 40 ply thicknesses
- 10%, 30%, and 50% zero-degree plies
- Total of twelve different specimen types

Experiments

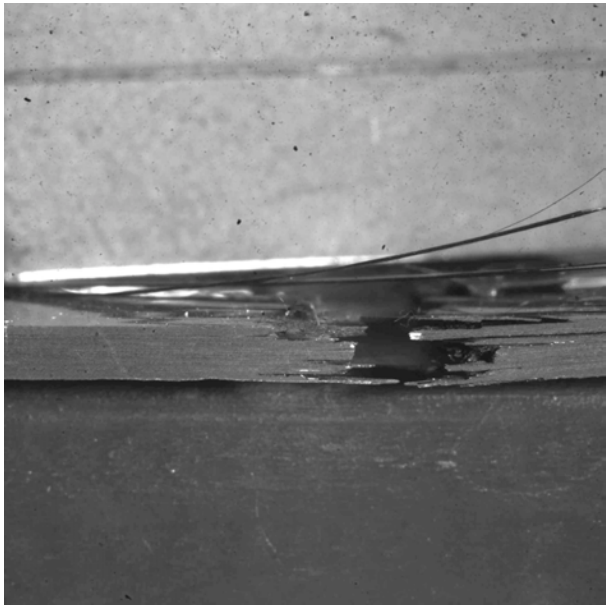
Approach

- Four-point bending
- Three replicates of each specimen
- Primary interest
  - Method of failure
    - Visible damage
    - Delamination
  - Maximum moment (failure load)

Experiments

Results: 20 ply

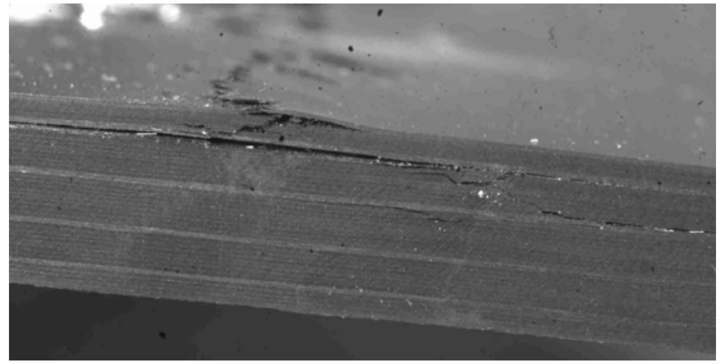
- Negligible visible damage before failure
- Failure was sudden
- Failure resulted in specimen fracture (two pieces)



- Failure load (average, 10%, 30%, 50% zero degree plies)
  - 25.4-mm notch: 814, 859, 1094 N-mm/mm
  - 101.6-mm notch: 925, 836, 1014 N-mm/mm

Experiments

Results: 40 ply



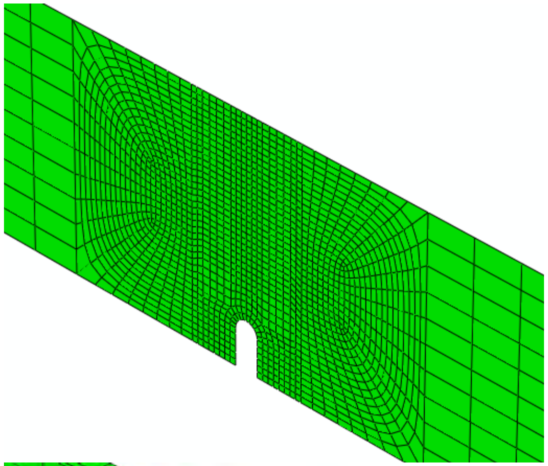
- Damage and delamination, primarily along 0° and outermost plies, prior to failure
- Failure was gradual
- Failure resulted in buckled plies on compression side

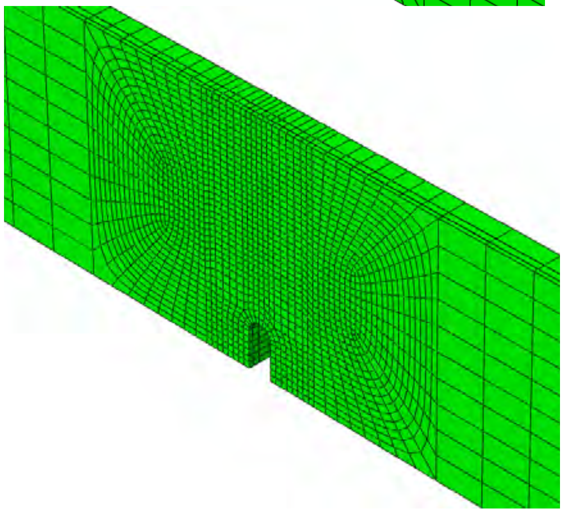
- Failure load (average, 10%, 30%, 50% zero degree plies)
  - 25.4-mm notch: 2691, 3292, 4030 N-mm/mm
  - 101.6-mm notch: 2882, 2971, 4244 N-mm/mm

Modeling

Approach: elements

- ABAQUS FEA
- Half-symmetry model (weak coupling between bending and twisting found to be negligible)
- Conventional shell elements not appropriate, need “stackable” elements to capture delamination
- Continuum shell elements provide this capability





Modeling

Approach: Damage

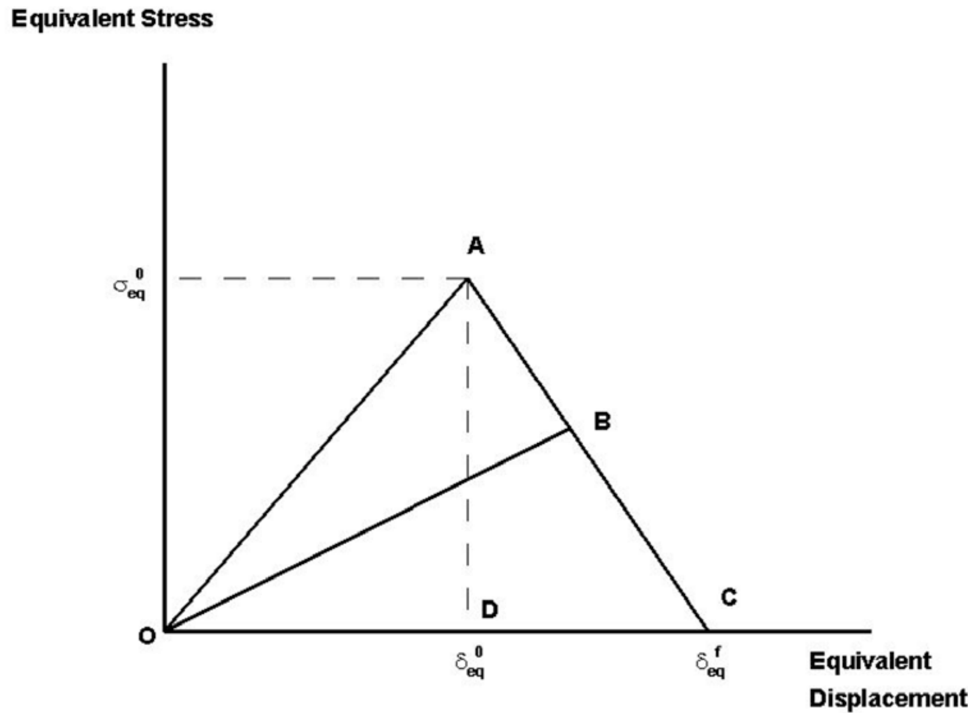
- Out-of-plane bending causes non-uniform strain through the thickness
- Requires a composite damage theory that treats damage progression on a ply-by-ply level
- The model used here, from ABAQUS, is that of Hashin
- Hashin model uses concepts from damage mechanics
  - Damage reduces effective load a carrying area
  - Damage variable d varies 0 (no damage) to 1 (failed)

$$\hat{\sigma} = \frac{\sigma}{1-d}$$

Modeling

Approach: Damage

- Damage occurs via
  - Fiber tension
  - Fiber compression
  - Matrix tension
  - Matrix compression
- Damage initiation at A
- Damage evolution AC
- Unloading AO (undamaged), BO (damaged)
- Strain softening: use elements of equal size where damage is expected



Modeling

Approach: Delamination

- Delamination was modeled using the Virtual Crack Closure Technique (VCCT)
- Based on LEFM, crack propagation occurs when a critical energy release rate, G_c is attained
- Mixed-mode combined via a linear failure criteria

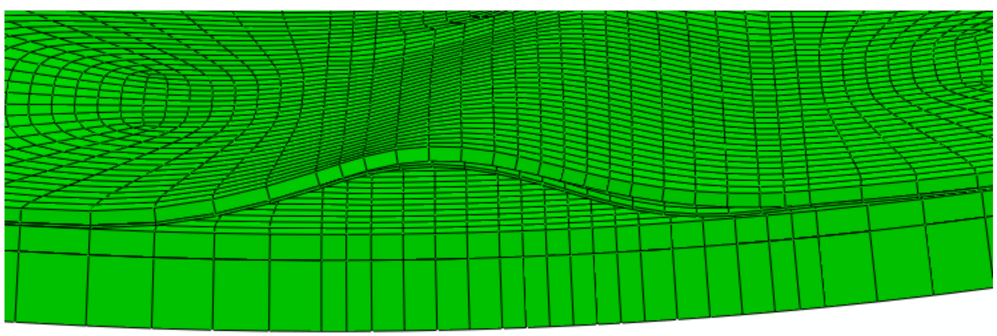
$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} + \frac{G_{III}}{G_{IIIc}} = 1$$

- Delamination can only occur in the model where interfaces are provided

Modeling

Approach: Delamination

- When interfaces are included in the model, buckling behavior from experiment is captured in the model



Modeling

Results: No interfaces

- Initially no interfaces included (delaminationn not possible)
- Agreement for 20-ply laminates is ~ <10%
- Much greater error for 40 ply cases
- Corresponds to experimental observation

Number of Plies	Notch Length [mm]	Percent Zero-degree plies	FEA: Percent Difference from Experiment		
			No Interfaces	Two Interfaces	Four Interfaces
20	25.4	10	-2.7%		
		30	-2.2%		
		50	9.5%		
	101.6	10	-11.5%		
		30	-3.7%		
		50	-6.4%		
40	25.4	10	21.2%		
		30	20.8%		
		50	28.4%		
	101.6	10	14.8%		
		30	15.7%		
		50	0.1%		

Modeling

Results: Two interfaces

- Interfaces added
  - Below outer-most 0° ply
  - Below second-outer-most 0° ply
- Agreement still good for 20-ply case
- Significant change for 40 ply case

Number of Plies	Notch Length [mm]	Percent Zero-degree plies	FEA: Percent Difference from Experiment		
			No Interfaces	Two Interfaces	Four Interfaces
20	25.4	10	-2.7%	7.1%	
		30	-2.2%	1.3%	
		50	9.5%	-1.2%	
	101.6	10	-11.5%	9.1%	
		30	-3.7%	-0.5%	
		50	-6.4%	-5.3%	
40	25.4	10	21.2%	3.0%	
		30	20.8%	-0.9%	
		50	28.4%	3.0%	
	101.6	10	14.8%	-18.1%	
		30	15.7%	-15.6%	
		50	0.1%	-11.5%	

Modeling

Results: Four interfaces

- Interfaces added
  - Below outer-most 0° ply
  - Below second-outer-most 0° ply
  - Below outer-most ply
  - Above outer-most 0° ply
- Agreement still good for 20-ply case
- No significant change for 40 ply case

Number of Plies	Notch Length [mm]	Percent Zero-degree plies	FEA: Percent Difference from Experiment		
			No Interfaces	Two Interfaces	Four Interfaces
20	25.4	10	-2.7%	7.1%	1.7% *
		30	-2.2%	1.3%	-5.4%
		50	9.5%	-1.2%	-3.4%
	101.6	10	-11.5%	9.1%	
		30	-3.7%	-0.5%	
		50	-6.4%	-5.3%	
40	25.4	10	21.2%	3.0%	8.7%
		30	20.8%	-0.9%	1.8%
		50	28.4%	3.0%	8.7%
	101.6	10	14.8%	-18.1%	
		30	15.7%	-15.6%	
		50	0.1%	-11.5%	

* three interfaces

Conclusions

- The Hashin damage criteria appears to be a useful tool for predicting failure loads in laminate composites under out-of-plane bending when delamination-driven buckling does not occur
- When such buckling does occur, it appears necessary to also include a means of allowing ply delamination to occur (e.g. VCCT) in order to obtain reasonable estimates of failure loads.
- The addition of delamination interfaces to the model when buckling does not occur, does not appear to have a significant effect on predicted failure load