CRACK DEVELOPMENT IN CYCLICALLY LOADED PRESSURIZED CYCLINDRICAL CARBON FIBER SHELL STRUCTURES

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AMTAS
Advanced Materials in Transport Aircraft Structures

OBJECTIVE

- Determine the contribution of the bulging effect in crack development for Fiber-Polymer Composites (FPCs).
- Determine the relationship between fiber orientation and the bulging effect on FPCs.
- Present a sound bench scale test that can be used to study the bulging phenomenon.
- The ultimate goal is to provide engineers with a relationship between measurable changes in geometry around the crack lip and damage evolution on FPCs.

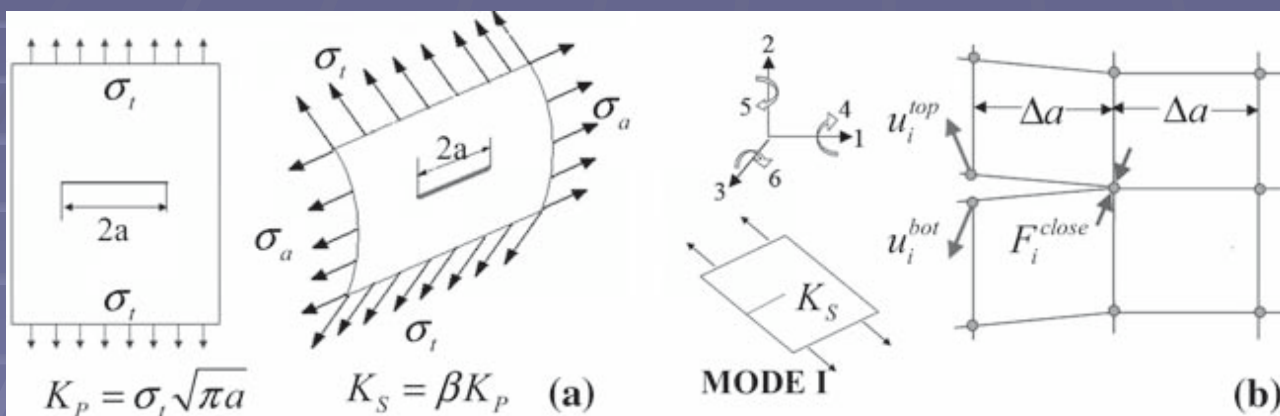
Failure Mechanisms Involved In Crack Development

Ductile Isotropic materials (Clean failure):
1. Crack initiation
2. Crack propagation
3. Sudden fracture

Fiber-Polymer Composites (Dirty failure):
1. Crack initiation
2. Edge crack increase without inward propagation
3. Transverse crack propagation

Concept of Bulging Factor

Bulging is the consequence of the presence of a crack on a pressurized cylindrical shell structure that leads to complex stress and displacements fields resulting in nonlinear out-of-plane deformations.



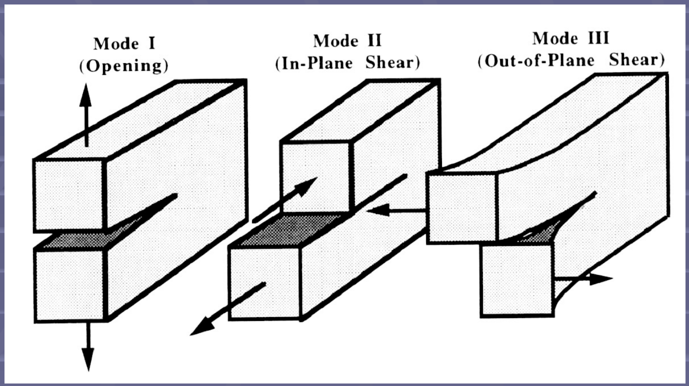
$$\beta = \frac{K_{1curved}}{K_{1flat}}$$

$$K_{1flat} = \frac{pR}{t}\sqrt{\pi a}$$

$$\chi = \frac{\sigma_{long}}{\sigma_{hoop}}$$

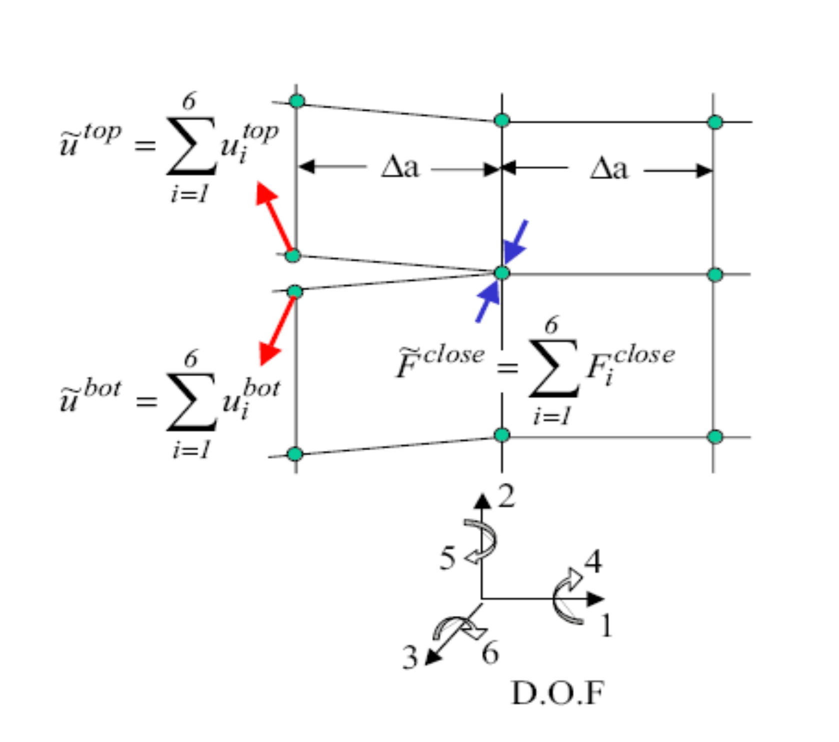
$$\beta = \sqrt{1 + \frac{5}{3\pi}\frac{Eta}{R^2 p}\frac{0.316}{\sqrt{1+18\chi}}\tanh\left(0.06\frac{R}{t}\sqrt{\frac{pa}{Et}}\right)}$$

3-D Modified Crack Closure Integral



$$u_x = \frac{K_I}{2\mu}\sqrt{\frac{r}{2\pi}}\cos\left(\frac{\theta}{2}\right)\left[\kappa - 1 + 2\sin^2\left(\frac{\theta}{2}\right)\right] \qquad \mu = \frac{E}{2(\nu+1)}$$

$$u_y = \frac{K_I}{2\mu}\sqrt{\frac{r}{2\pi}}\sin\left(\frac{\theta}{2}\right)\left[\kappa - 1 + 2\cos^2\left(\frac{\theta}{2}\right)\right] \qquad \kappa = \left(3-\nu\right)/\left(1-\nu\right)$$



$$W_i = \frac{1}{2t\Delta a}\left[F_i^{close}\left(u_i^{top} - u_i^{bottom}\right)\right]$$

$$W_2 + W_6 = \frac{K_1^2}{E}$$

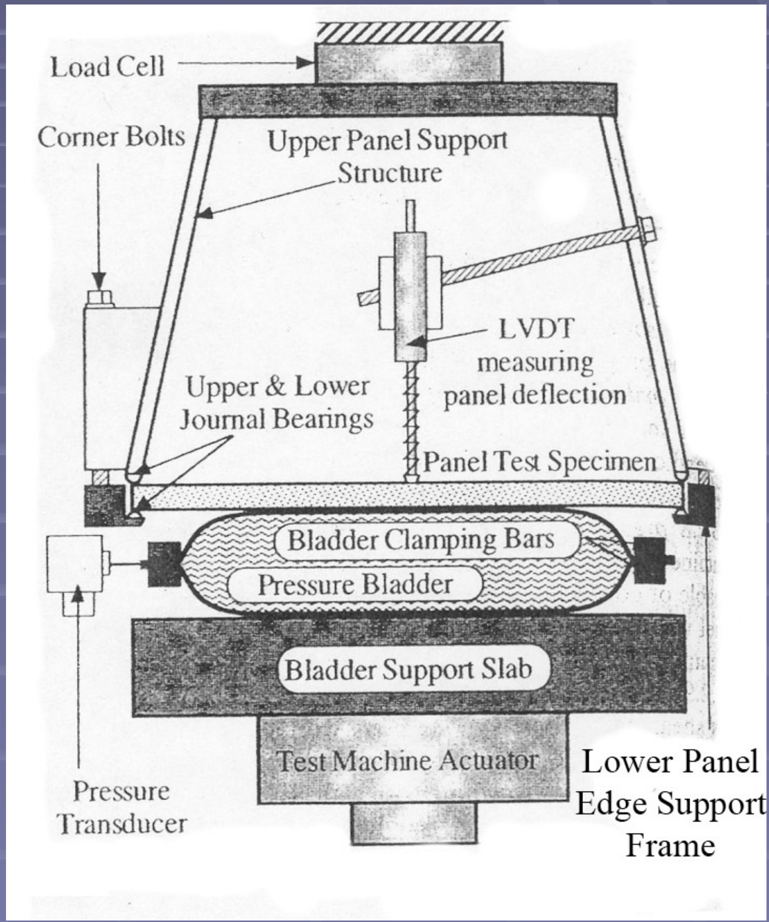
$$W_1 = \frac{K_2^2}{E}$$

$$W_4 = \frac{k_1^2\pi}{3E}\left(\frac{1+\nu}{3+\nu}\right)$$

$$W_3 + W_5 = \frac{k_2^2}{3E}\left(\frac{1+\nu}{3+\nu}\right)$$

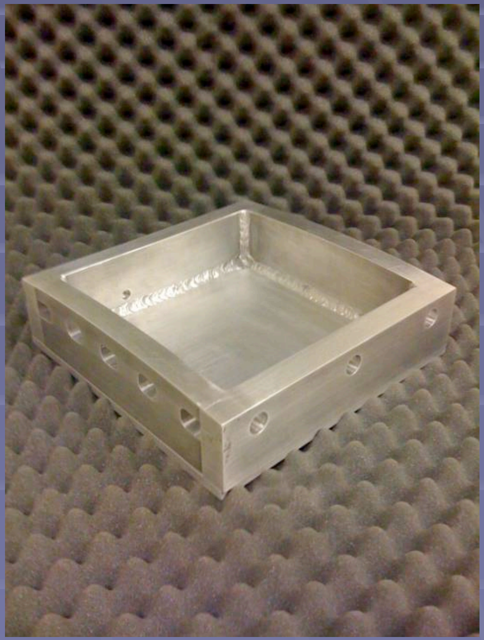
Test Infrastructure

ASTM D 6416/D 6416: This standard was designed to determine the two-dimensional flexural properties of sandwich composite plates under a distributed load. This standard consists of a square specimen, steel clamping frame and pressure bladder.
All these elements are mounted on an Universal Testing Machine (UTM). The loading fixture is made up of a two-piece rigid part that is bolted to the crosshead that is then fixed at the top and is pressed against a bladder filled-up with fluid to provide an evenly distributed pressure.

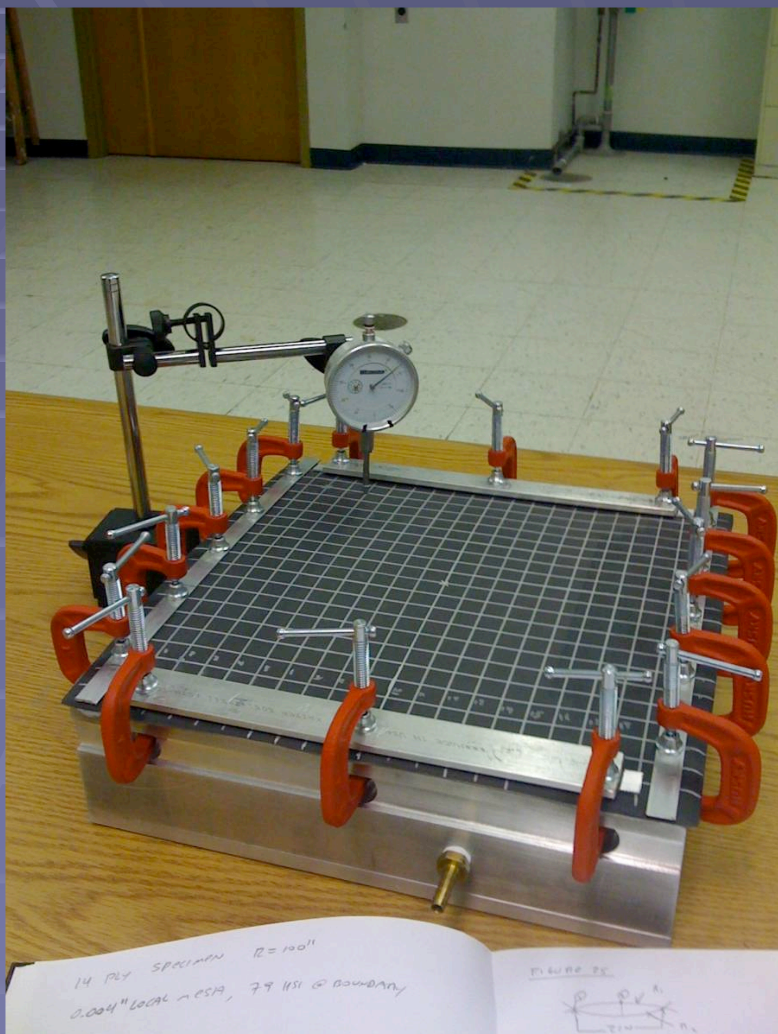


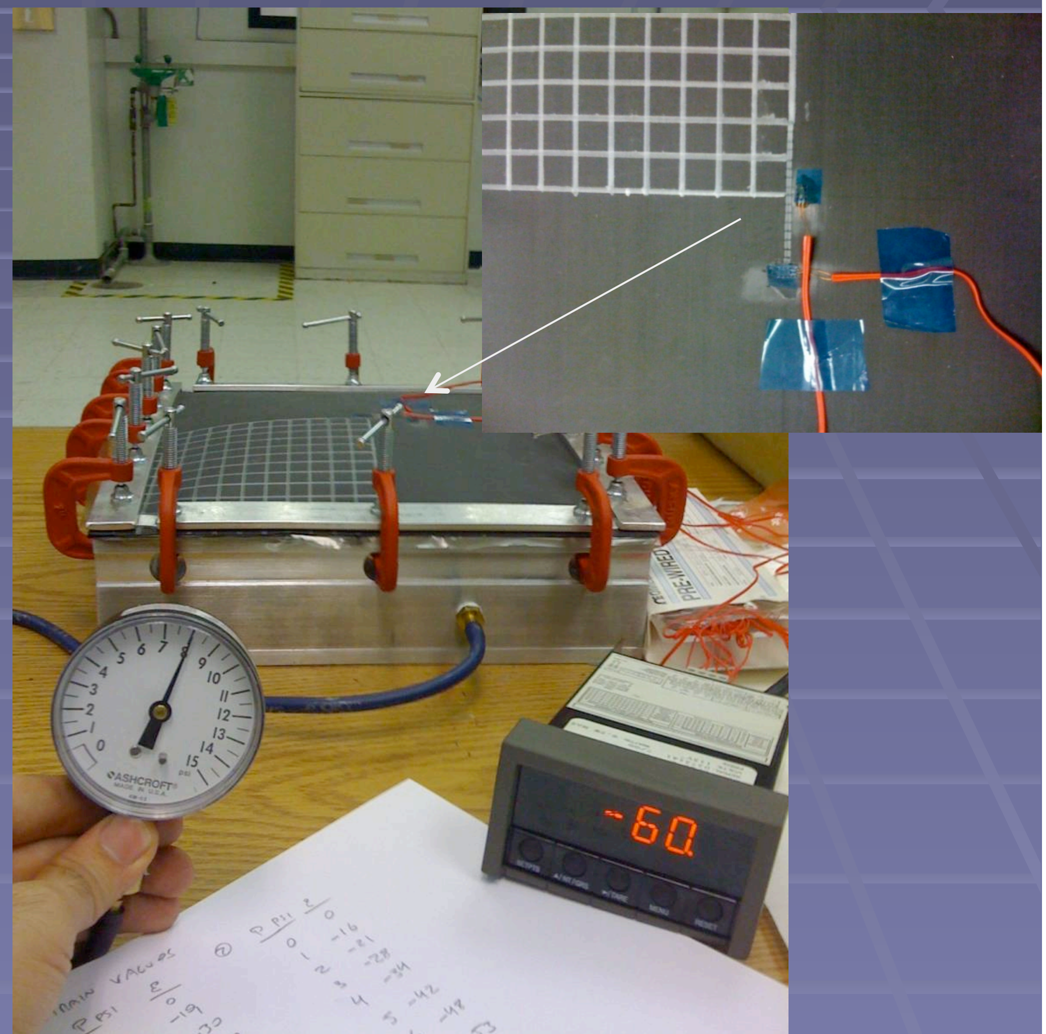
Experimental Test Bed

The pressure chamber was designed to accommodate a 12” X 12” specimen having the same curvature as a hatch service door from a Boeing 727. One of the major challenges was to replicate the curvature of the part accurately. This factor is extremely important since it is the basis for the bulging phenomenon.



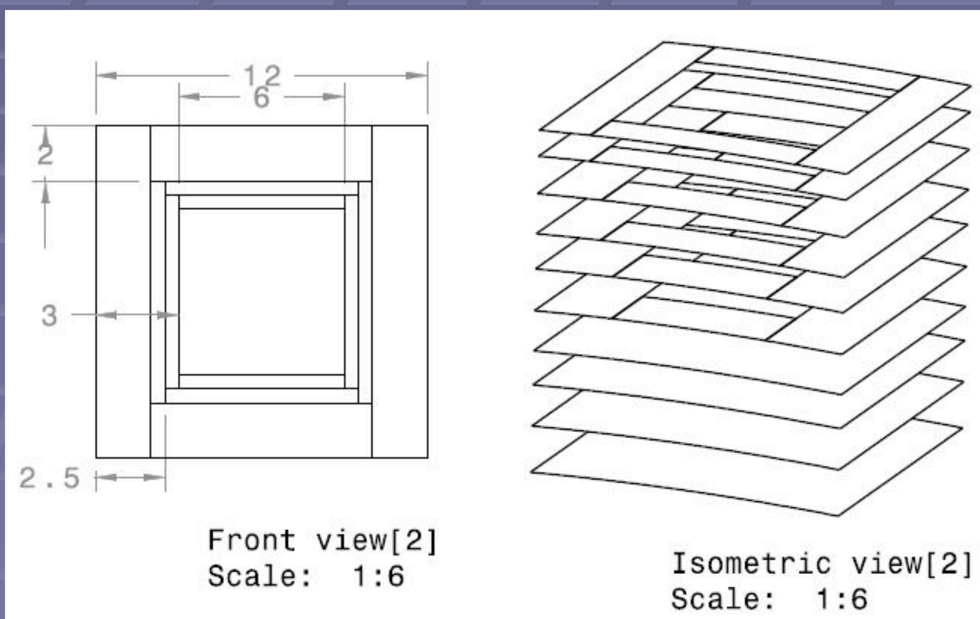
Experimental Test Bed

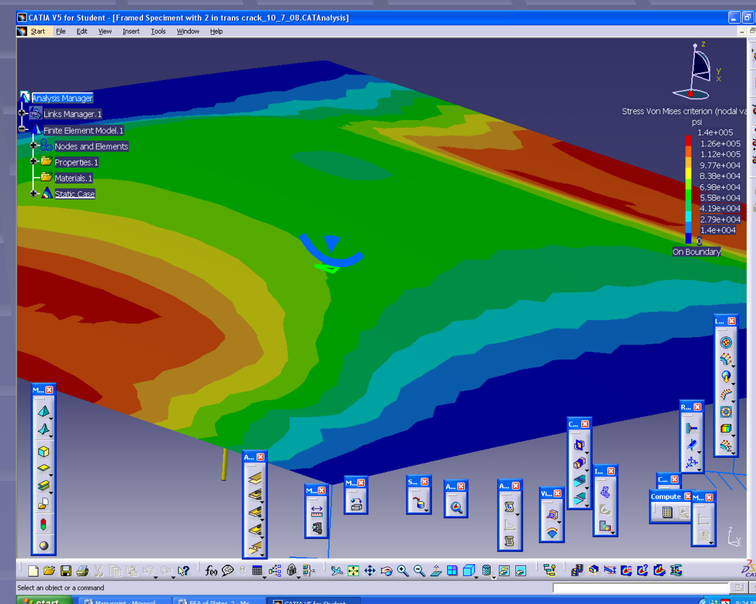




Proposed Specimen Design

In order to drive failure areas away from the edges, a gradual increase of the number of plies is staggered toward the critical zones





Validation of Numerical Methodology (Al Curved Shell)

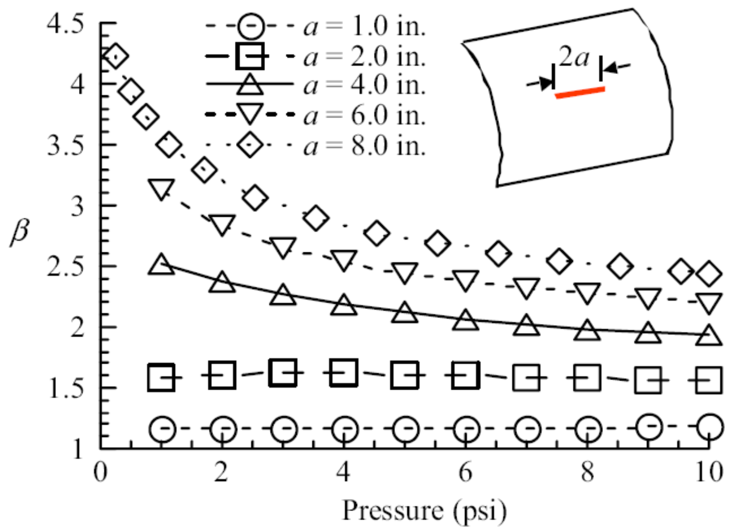


TABLE 3. KIRCHOFF SIF AND β FOR A LONGITUDINAL CRACK IN AN UNSTIFFENED FUSELAGE WITH R = 80 in. AND a = 2.0 in.

p (psi)	$K_{1\ flat}$ (psi·$\sqrt{\text{in}}$)	K_1 (psi·$\sqrt{\text{in}}$)	K_2 (psi·$\sqrt{\text{in}}$)	k_1 (psi·$\sqrt{\text{in}}$)	k_2 (psi·$\sqrt{\text{in}}$)	β
1.00	4.178e+03	6.583e+03	0	1.874e+03	0	1.576
2.00	8.355e+03	1.342e+04	0	3.917e+03	0	1.607
3.00	1.253e+04	2.030e+04	0	5.721e+03	0	1.620
4.00	1.671e+04	2.704e+04	0	7.190e+03	0	1.618
5.00	2.089e+04	3.364e+04	0	8.395e+03	0	1.610
6.00	2.507e+04	4.010e+04	0	9.413e+03	0	1.600
7.00	2.924e+04	4.645e+04	0	1.029e+04	0	1.588
8.00	3.342e+04	5.271e+04	0	1.107e+04	0	1.577
9.00	3.760e+04	5.889e+04	0	1.178e+04	0	1.566
10.00	4.178e+04	6.500e+04	0	1.242e+04	0	1.556

Pressure	Calculated B.F.	B.F. Chen	B.F. FAA	% Error (Chen)
2	1.792	1.758	1.61E+00	1.9
4	1.792	1.563	1.62E+00	12.8
6	1.792	1.466	1.60E+00	18.2
8	1.792	1.405	1.58E+00	21.6

Calculation of Bulging Factor on Composites Laminates

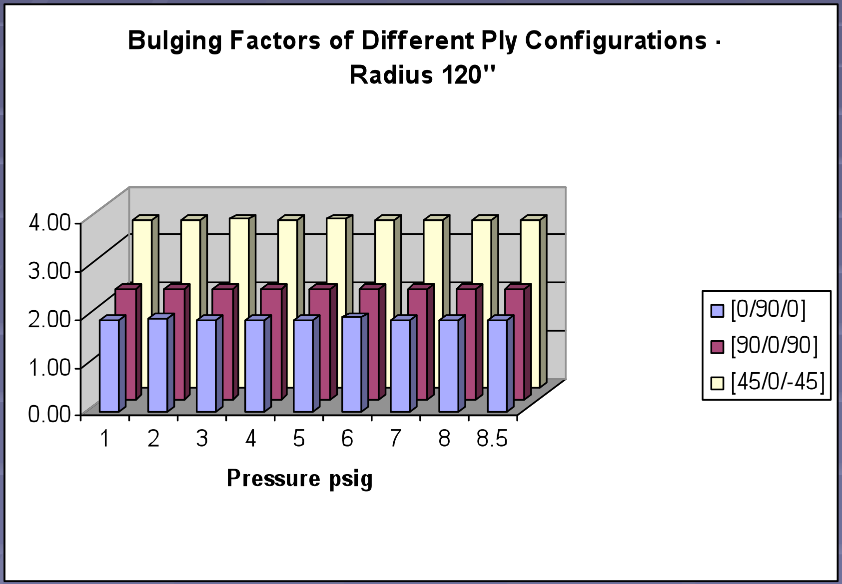
Composite
[0/90/0]

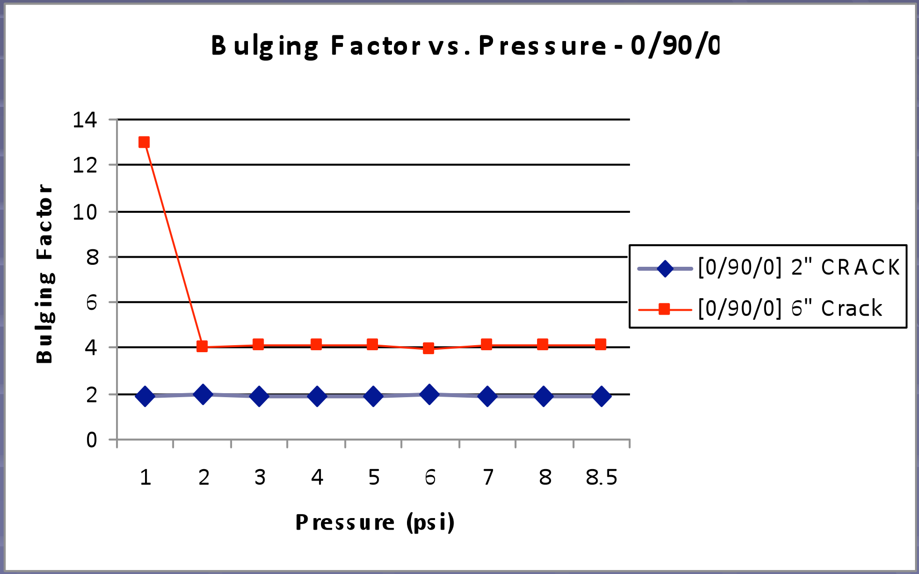
R = 120
El = 1.32E+07
Et= 7.33E+06
t= 0.018

Pressure	Force	Moment	Displ	W2	W6	KI (Long)	KI (Hoop)
1	47.81	5.89	0.00071	125.723	15.489	4.312E+04	3.217E+04
2	95.62	11.78	0.00145	513.515	63.263	8.716E+04	6.502E+04
3	143.42	17.67	0.00213	1131.424	139.397	1.294E+05	9.651E+04
4	191.23	23.56	0.00284	2011.456	247.816	1.725E+05	1.287E+05
5	239.04	29.45	0.00355	3142.933	387.213	2.156E+05	1.609E+05
6	286.85	35.34	0.00448	4759.585	586.382	2.653E+05	1.980E+05
7	334.66	41.23	0.00497	6160.223	758.937	3.019E+05	2.252E+05
8	382.46	47.12	0.00568	8045.825	991.265	3.450E+05	2.574E+05
8.5	406.37	50.06	0.00603	9075.597	1118.007	3.664E+05	2.733E+05

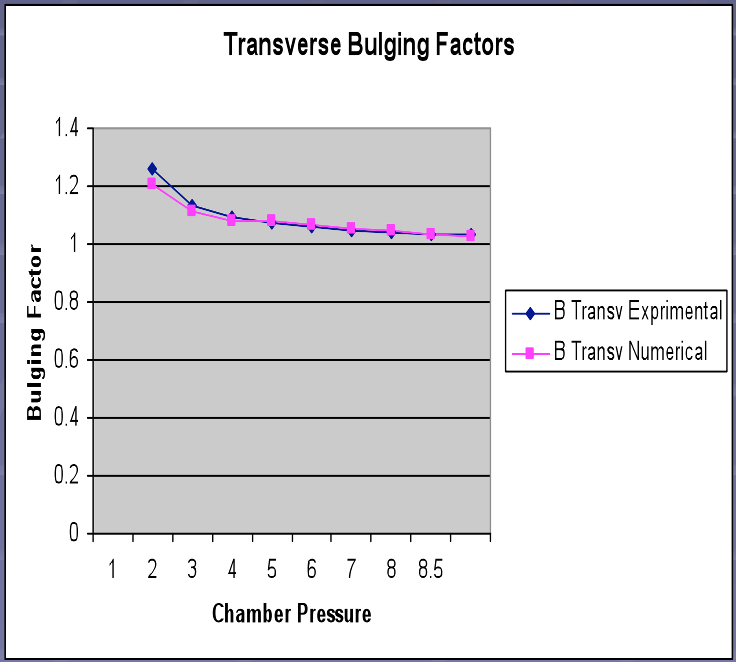
Pressure	K Flat	B.F.	B Chen
1	1.67E+04	1.925	1.752
2	3.34E+04	1.945	1.508
3	5.01E+04	1.925	1.388
4	6.68E+04	1.925	1.314
5	8.36E+04	1.925	1.264
6	1.00E+05	1.974	1.228
7	1.17E+05	1.925	1.200
8	1.34E+05	1.925	1.178
8.5	1.42E+05	1.924	1.169

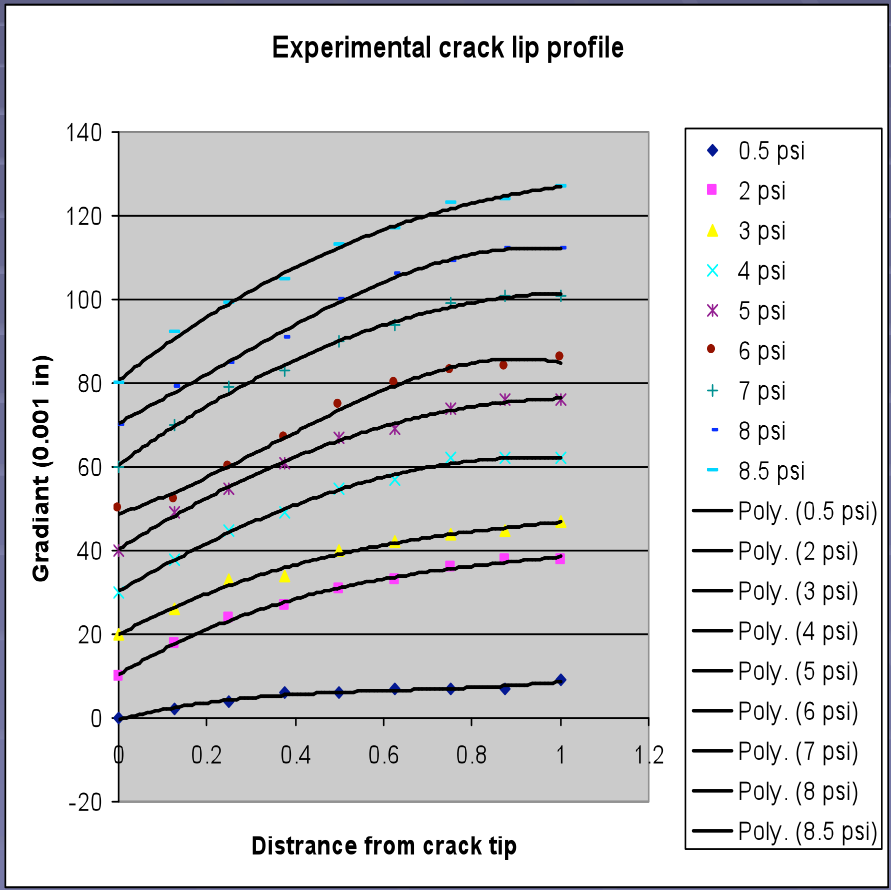
Calculation of Bulging Factor on Composites Laminates





Calculation of Experimental Bulging Factor on Composites Laminates





Conclusions

- For a two inch crack, the bulging factor was found to be independent of pressure.
- For FPCs, the stiffer the panel, the higher the bulging factor.
- MCCI method can be used to accurately determine stress intensity factors for FPCs.
- A small scale test bed was created that shows promise of measuring bulging factor characteristics.
- It was shown that significant accuracy can be obtained by including collapsed elements in the FE analysis.

Future Work

- The small specimen size utilized in this study resulted in a small variation in crack size (0.001”) during cycling. Larger specimens would provide for more accurate test measurements required for the MCCI method.
- These tests were conducted with panels without support. Larger panels with stringers would provide a more realistic representation of the aircraft fuselage.
- Characterize the failure stages for curved FPCs under pressurization/depressurization cyclic loading conditions.
- Optimize FEA results by using software that will include interlaminar shear stresses.