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MIXED-MODE INTERFACIAL FRACTURE TESTING USING DUAL ACTUATOR TEST FRAME

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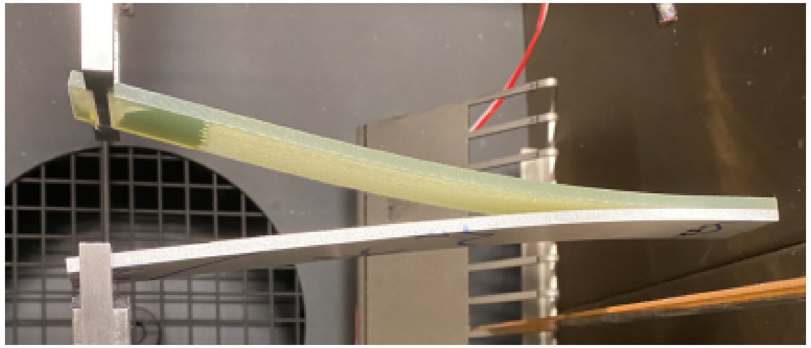
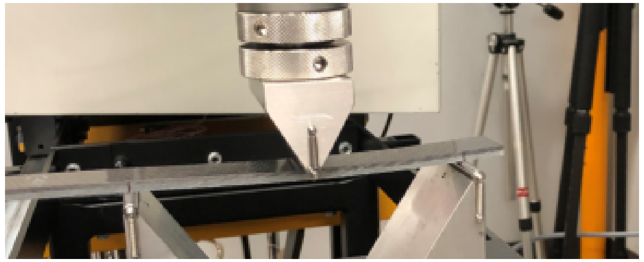
INTERFACIAL FRACTURE

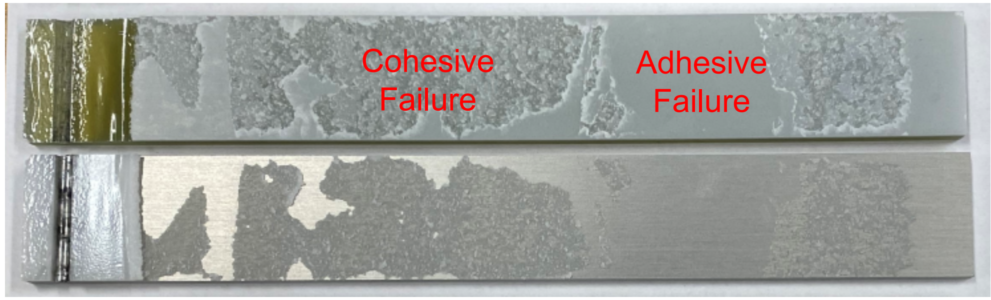
- Manufacturing defects or in-service damage can lead to fracture based failure
- Isotropic materials fracture under Mode I
- Laminated materials activate more energetic fracture modes
  - Anisotropy
  - Preferential fracture paths
- Bonded joints tend to fail either at the interface (adhesive failure) or within the adhesive (cohesive failure)
- Rarely are any failures pure Mode I or pure Mode II



Mode I – DCB experiment with co-bonded GFRP to Aluminum



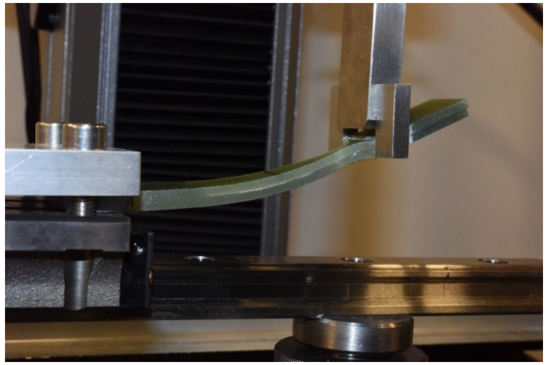
Mode II – ENF experiment with co-cured GFRP to CFRP



Failure surface of Mode I DCB with GFRP secondarily bonded to Aluminum with epoxy, mixture of adhesive and cohesive failure

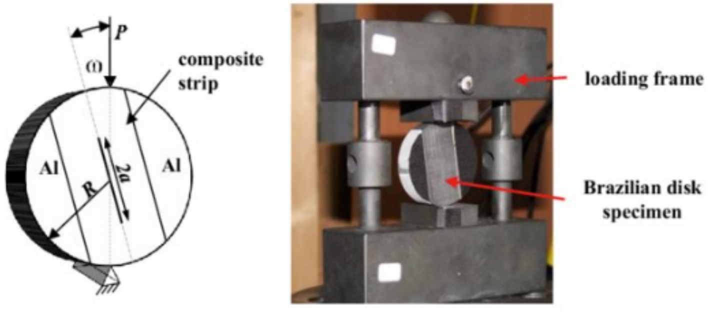
FRACTURE TESTING

- Mode I
  - Double cantilever beam (DCB)
  - Wedge insertion
  - Compact tension
  - Single edge notched bending
- Mode II
  - End notched flexure (ENF)
  - End loaded split (ELS)
- Mixed mode I/II
  - Mixed mode bending (MMB)
  - Asymmetric DCB
  - Single leg bending
  - Brazilian disc
  - **Dual actuator loading**
- Many others

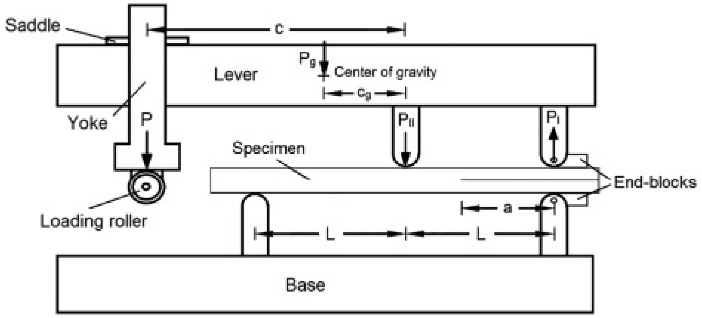


End loaded split (ELS)

End notched flexure (ENF)



Brazilian disc test[1]



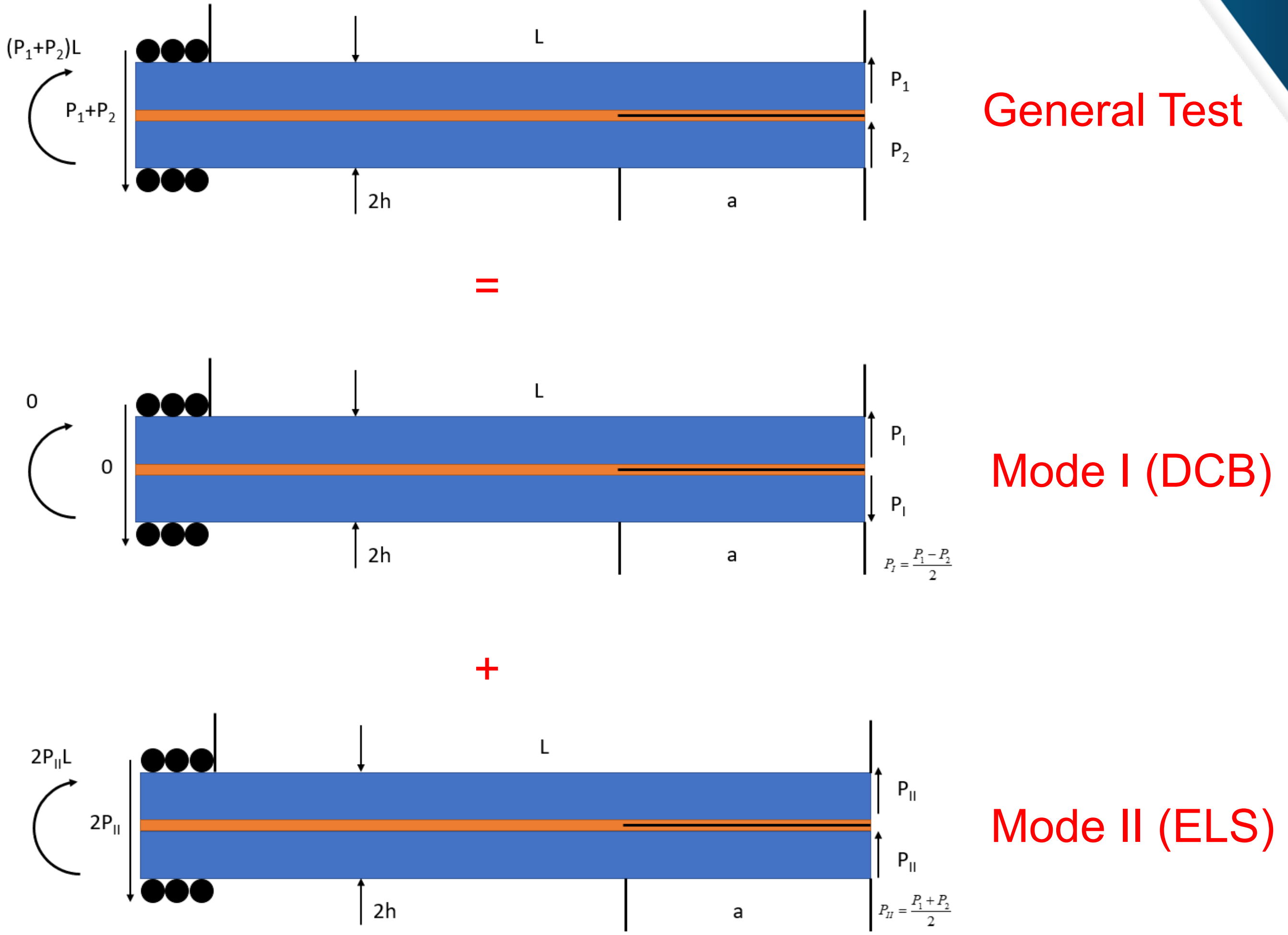
Mixed mode bending (MMB)[2]

[1]Mega, Mor & Banks-Sills, Leslie. (2018). Testing of Brazilian Disk Specimens With a Delamination Between a Transversely Isotropic and a Tetragonal Composite Ply. Procedia Structural Integrity. 13. 123-130. 10.1016/j.prostr.2018.12.021.

[2]Bamber Blackman, et.al, 17 - Understanding fracture mode-mixity and its effects on bond performance, Editor(s): David A. Dillard, In Woodhead Publishing in Materials, Advances in Structural Adhesive Bonding (Second Edition), Woodhead Publishing, 2023, Pages 579-613

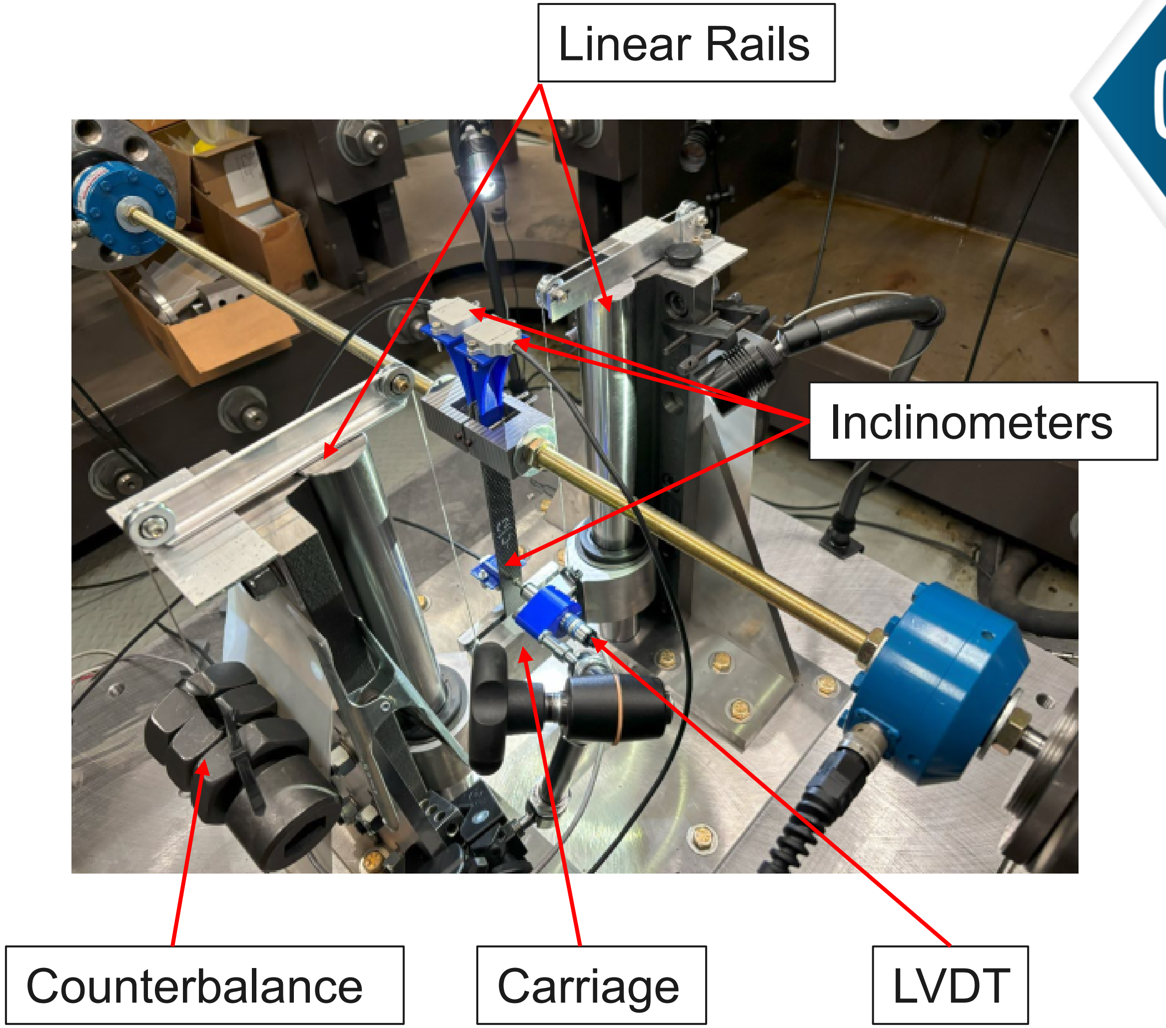
DUAL ACTUATOR TESTING

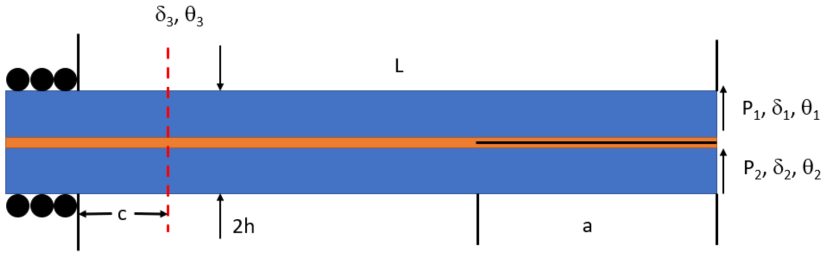
- Developed by Dillard et al.
- Current work by Liechti et al.
- Independent loading of each adherend
  - Superposition of DCB and ELS
  - Displacement, load, or moment control
- Assumptions in this work (ongoing)
  - Linear elastic
  - Plane strain
  - Slender beams – no shear contribution
  - Small deformations/rotations
- Current testing is displacement controlled
- Simple beam theory and two J-integral based data reduction schemes investigated



EXPERIMENTAL FIXTURE DESIGN

- Selected use of existing MTS servo-hydraulic bi-axial load frame
  - Four horizontal 550-kip actuators placed 90 degrees apart
  - One pair used for this testing
  - Unlike other setups, actuators are fixed and cannot pivot, possibility for actuator to impart a moment on pull rods
  - Approx. 180cm of space between actuators
- Steel work table supports fixturing
- Two linear rails support clamping carriage
  - Counterbalanced
  - Block easy view for DIC along length of specimen
  - Extension rods at hinge points can have speckled flags for DIC
- Two 1-kip load cells are used in series
- Pull/push rods are steel 5/8"-18 all-thread
- Inclinometers used to measure specimen rotations

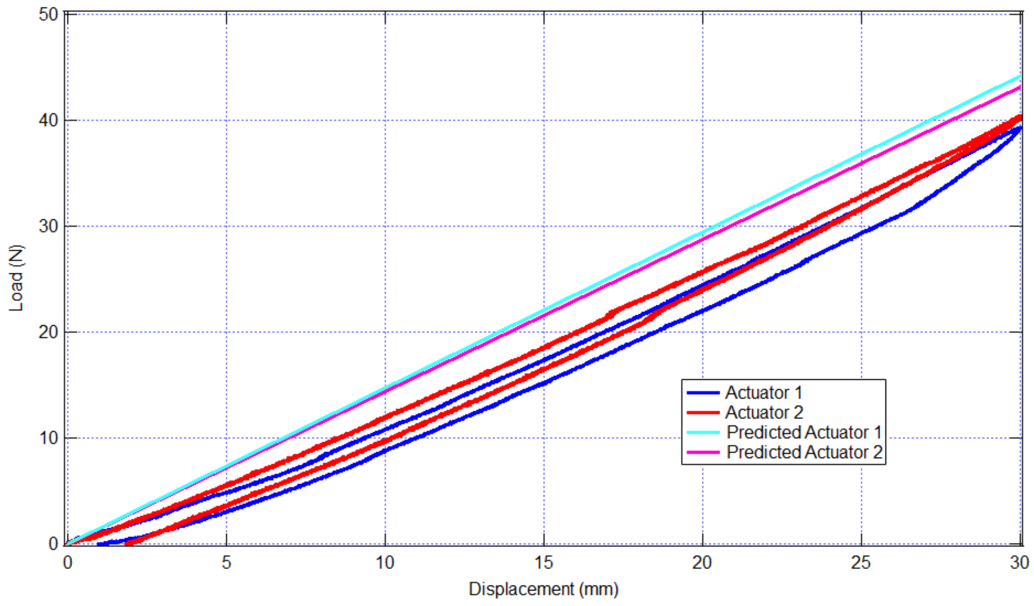




Monitored signals during test

COMPLIANCE CHECK

- 6061 Aluminum bar (225mmx25mmx3.175mm) clamped in carriage
- Loaded with a single actuator – only in tension (need to check compression)
- Stroke compared to predicted beam deflection
- Nonlinearity in beginning of loading
- Some hysteresis, relief of slack in system
- Produces similar terminal compliance at higher force
- Initial nonlinearity produces around 10% error
- Can be corrected with compliance correction
  - Laser displacement sensors or LVDTs can be used to improve displacement accuracy
  - Required for effective crack length determination
  - J-integral approaches do not rely on displacements



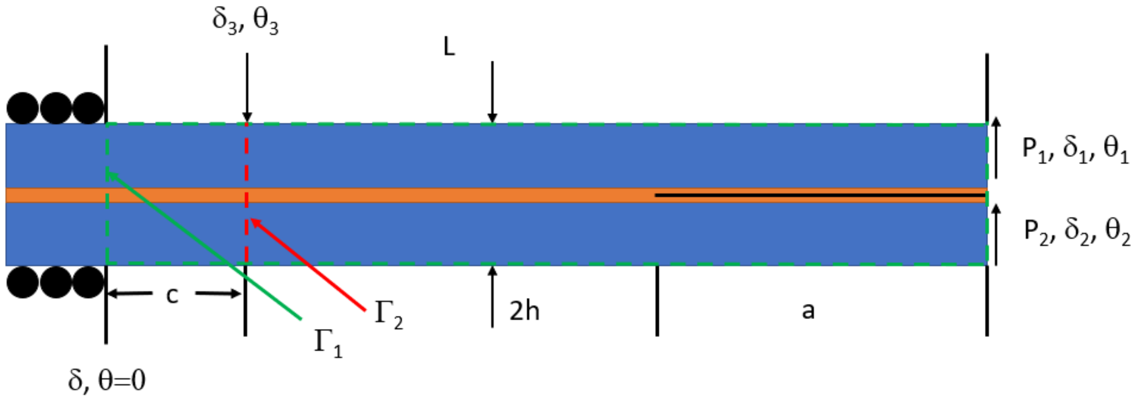
DATA REDUCTION

- Mode I/II partitioning
- Crack length measurement
  - Difficult for Mode II
  - DIC methods, not used here
  - Simple beam theory calculation

$$P_I = \frac{P_1 - P_2}{2} \qquad \delta_I = \delta_1 - \delta_2 \qquad \theta_I = \frac{\theta_1 - \theta_2}{2}$$

$$P_{II} = \frac{P_1 + P_2}{2} \qquad \delta_{II} = \frac{\delta_1 + \delta_2}{2} \qquad \theta_{II} = \frac{\theta_1 + \theta_2}{2}$$

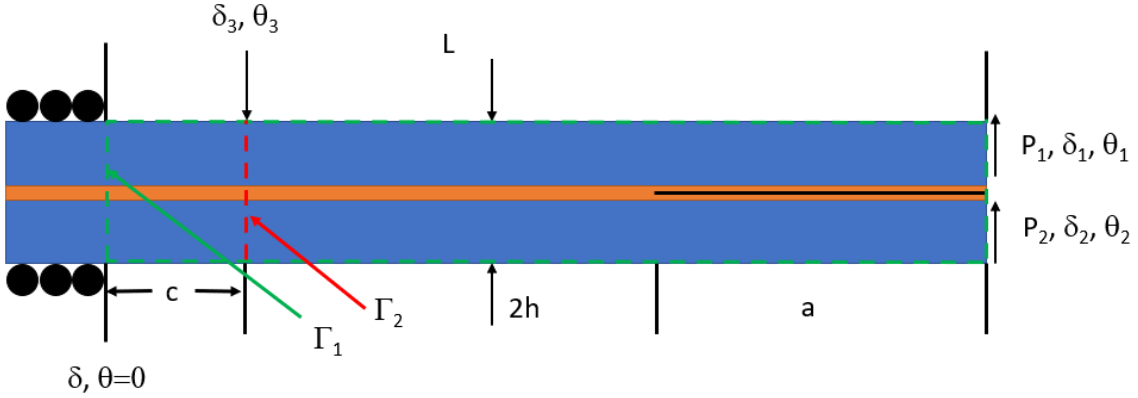
$$a_I^{eff} = \left[\frac{Ebh^3(\delta_1 - \delta_2)}{4(P_1 - P_2)}\right]^{\frac{1}{3}} \qquad a_{II}^{eff} = \left[\frac{Ebh^3(\delta_1 - \delta_2)}{3(P_1 + P_2)} - \frac{L^3}{3}\right]^{\frac{1}{3}}$$



Measurements Used	Simple Beam Theory	J-Integral (Γ_1)	J-Integral (Γ_2)
δ_1, δ_2	X	-	-
P_1, P_2	X	X	X
θ_1, θ_2	-	X	X
θ_3	-	-	X

DATA REDUCTION

- Strain Energy Release Rates, G_I, G_{II}, G_{total}



$$a_I^{eff} = \left[\frac{Ebh^3(\delta_1-\delta_2)}{4(P_1-P_2)}\right]^{\frac{1}{3}} \qquad a_{II}^{eff} = \left[\frac{Ebh^3(\delta_1-\delta_2)}{3(P_1+P_2)}-\frac{L^3}{3}\right]^{\frac{1}{3}}$$

Method	G_I	G_{II}	G_{total}
Simple Beam Theory	$\frac{3(P_1-P_2)^2 a_I^2}{Eb^2h^3}$	$\frac{9(P_1+P_2)^2 a_{II}^2}{4Eb^2h^3}$	$\frac{3}{4Eb^2h^3}\left(4(P_1-P_2)^2 a_I^2+3(P_1+P_2)^2 a_{II}^2\right)$
J-Integral (Γ_1)	$\frac{(P_1-P_2)}{2b}(\theta_1-\theta_2)$	$-\frac{3(P_1+P_2)^2 L^2}{4Eb^2h^3}+\frac{P_1+P_2}{2b}(\theta_1+\theta_2)$	$\frac{(P_1-P_2)}{2b}(\theta_1-\theta_2)-\frac{3(P_1+P_2)^2 L^2}{4Eb^2h^3}+\frac{(P_1+P_2)}{2b}(\theta_1+\theta_2)$
J-Integral (Γ_2)	$\frac{(P_1-P_2)}{2b}(\theta_1-\theta_2)$	$-\frac{3(P_1+P_2)^2(L-c)^2}{4Eb^2h^3}-\frac{P_1+P_2}{2b}(2\theta_3-\theta_1-\theta_2)$	$\frac{(P_1-P_2)}{2b}(\theta_1-\theta_2)-\frac{3(P_1+P_2)^2(L-c)^2}{4Eb^2h^3}-\frac{P_1+P_2}{2b}(2\theta_3-\theta_1-\theta_2)$

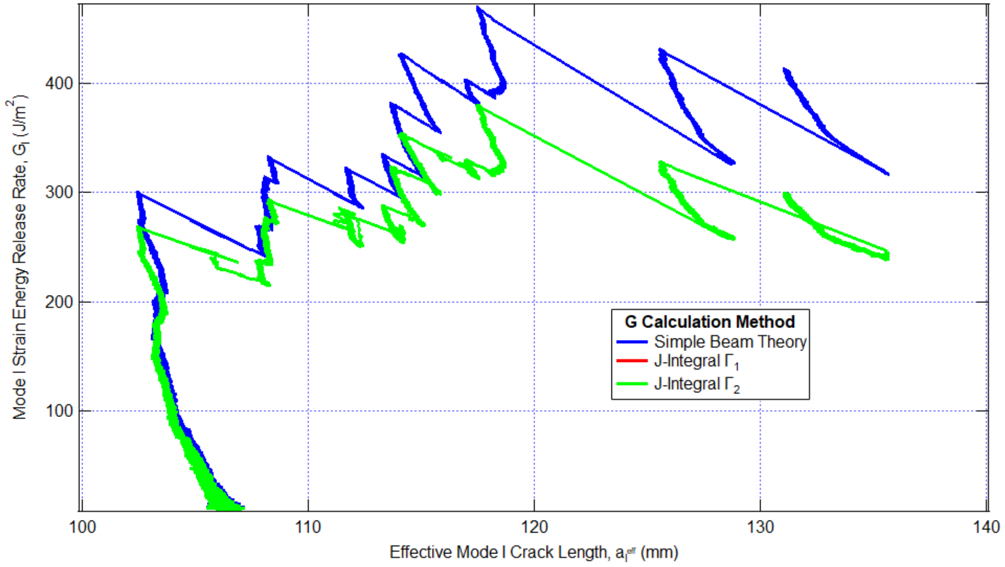
EXPERIMENTS

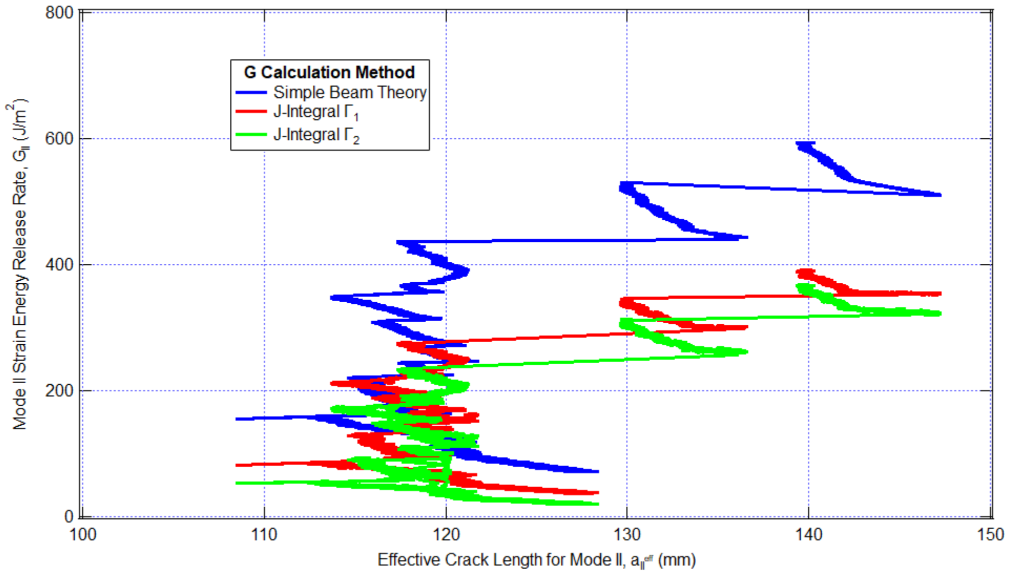
- Material
  - AS4/3362-100 8HS woven carbon composite
  - Layup: 12 plies - $[(0/90)_{3s}]_s$
  - 300mm x 300mm panel
    - Autoclave cured
    - 50mm Teflon precrack (125μm thickness)
  - Specimens approx. 25mm x 300mm, tile saw cut
  - Bonded piano hinges, pin loaded
  - Crack extended in Mode I to around 115mm
  - Clamped length – approx. 50mm
- Test Matrix
  - Varied displacement rate for two actuators
  - Pure Mode I to near pure Mode II loading

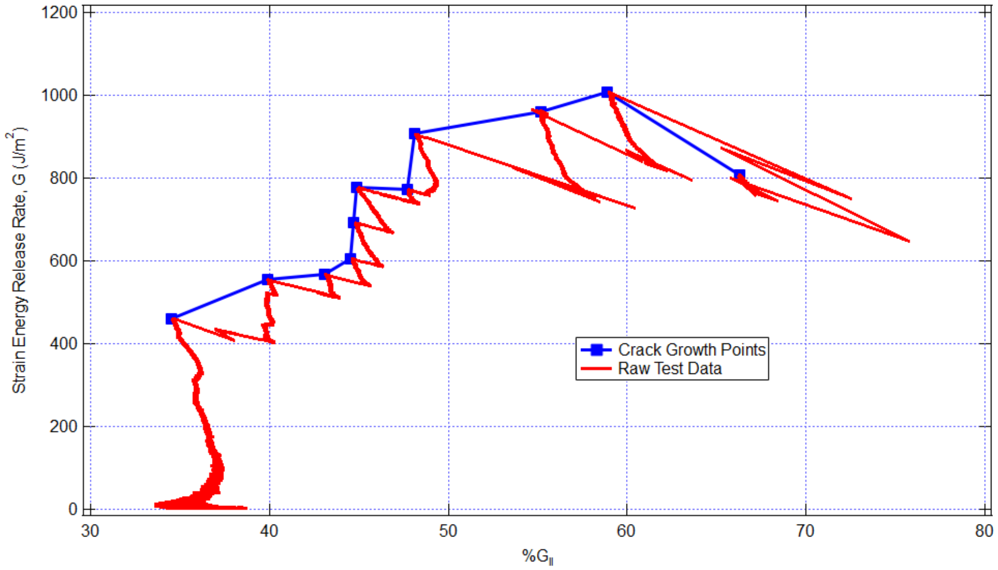
Test Run	V_1 (mm/min)	V_2 (mm/min)
1	2.54	2.54
2	2.54	1.27
3	2.54	0
4	2.54	-1.27
5	2.54	-1.905
6	2.54	-2.49

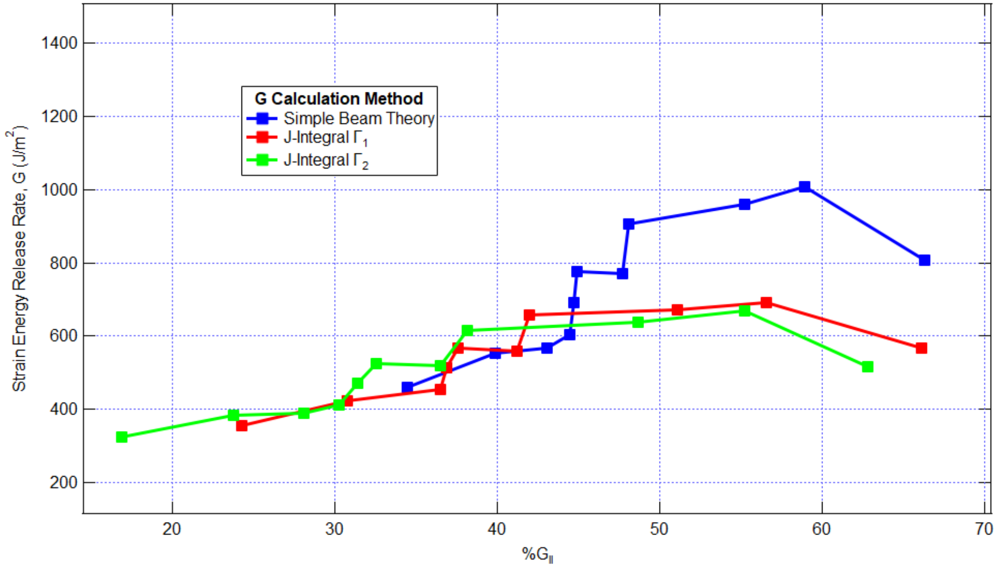
Positive displacement rate is tension

TYPICAL RESULTS (V_1=2.54 MM/MIN, V_2=-1.27 MM/MIN)

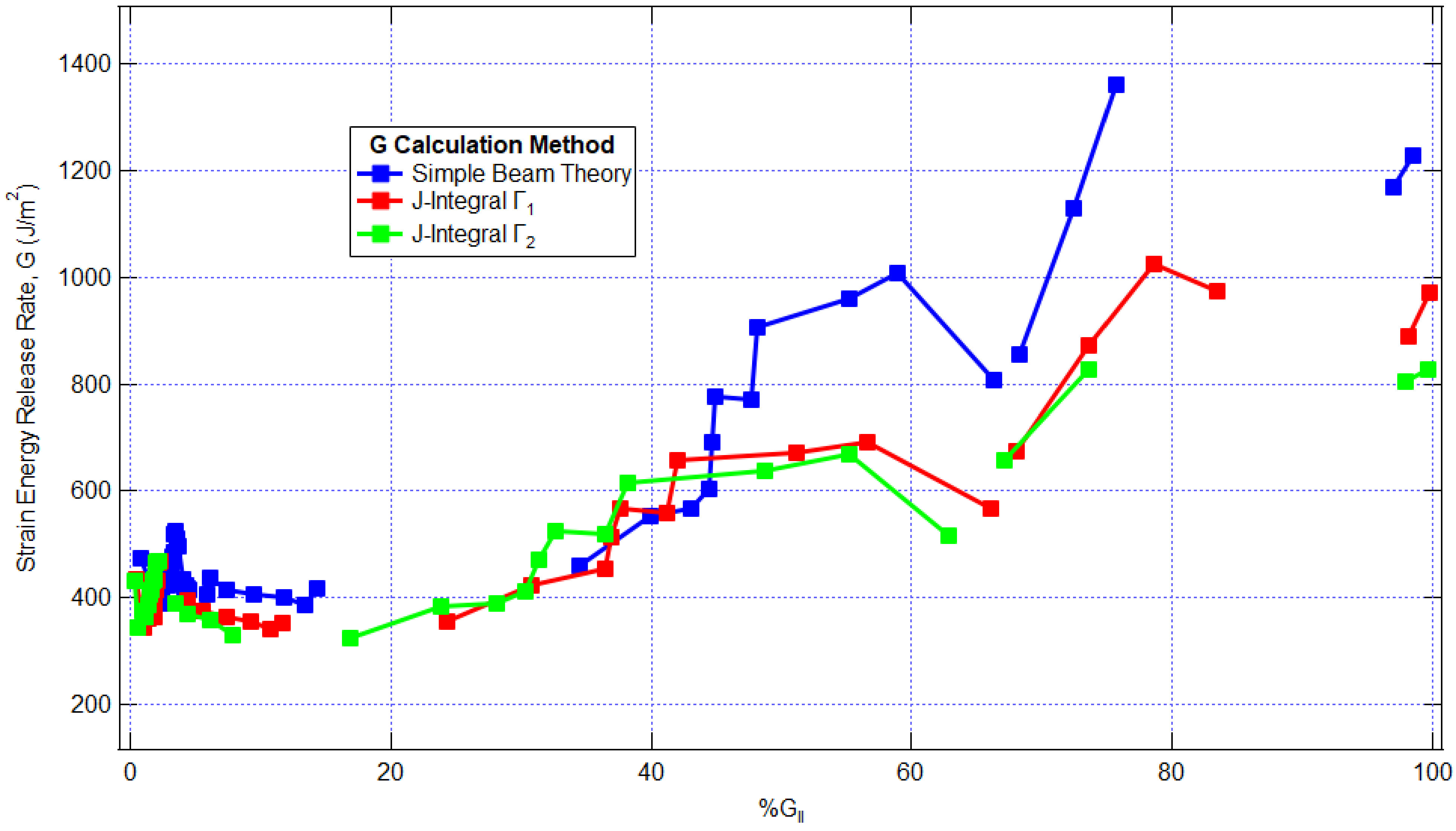








INITIAL RESULTS



FURTHER CHECKS/IMPROVEMENTS

- Improve load/displacement measurements
  - Laser displacement sensor
  - Check compliance in compression
    - Add 6-axis load cell
    - Stiffen push rod
  - Smaller load cell for more compliant specimens
- Add shear contributions (Timoshenko beam theory)
- Decompose load components into normal and shear
- Try with more stable crack growth fabric (GFRP)

ACKNOWLEDGEMENTS

- LWSL for laying up and curing the panels (Brian McKay, Gus Nungaray)
- Danielle Oteri for extending the cracks using standard DCB test techniques
- Ethan Dike for performing 3-pt bend tests to verify the bending modulus and helping run the experiments