Compression Testing for UD Carbon – Work in Progress…

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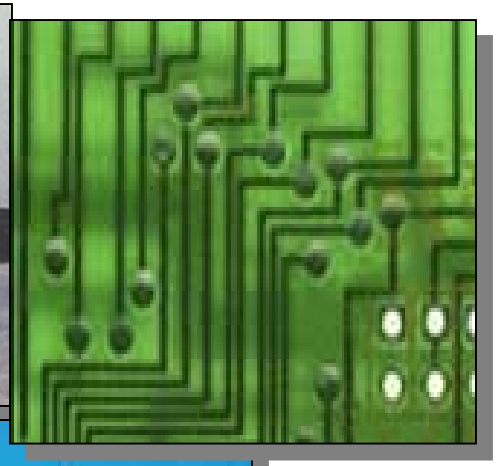
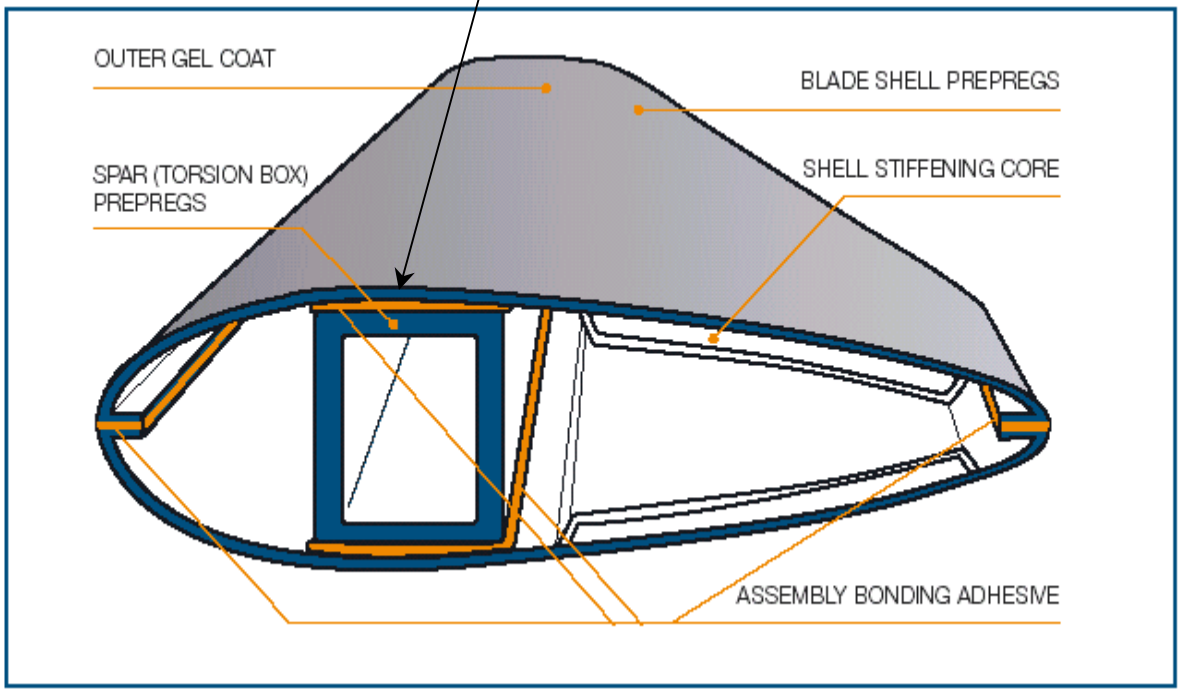


HEXCEL IS COMMITTED TO WIND ENERGY

HEXCEL commitment through capital investment, but also product development AND Customers/Wind Energy Industry Support…

As blades become larger substituting glass for carbon in some locations can make sense

Spar Caps are the most structural part of the blade airfoil



USING UD CARBON IN SPAR CAP PROVIDES HIGHEST PERFORMANCE/COST BENEFIT

UD Glass versus UD Carbon

- Modulus of carbon UD (standard modulus) is nearly 4 times as high as E glass UD
- Compression strength of carbon UD is nearly 2 times as high as E glass UD

	MODULUS, Tension	MODULUS, Comp	STRENGTH Tension	STRENGTH Comp
UD, Glass	43 Gpa	42 Gpa	1100 Mpa	900 Mpa
UD Carbon	170 Gpa	159 Gpa	2400 Mpa	1600 Mpa
RATIO	**4**	**3.6**	**2.4**	**1.7**

Issues with compression testing of UD carbon

- Fiber alignment with load is critical
- Very sensitive to defects > scatter
- Very sensitive to buckling
- Anti-buckling fixtures can introduce errors
- **Bottom Line: Can you use test results for design?**

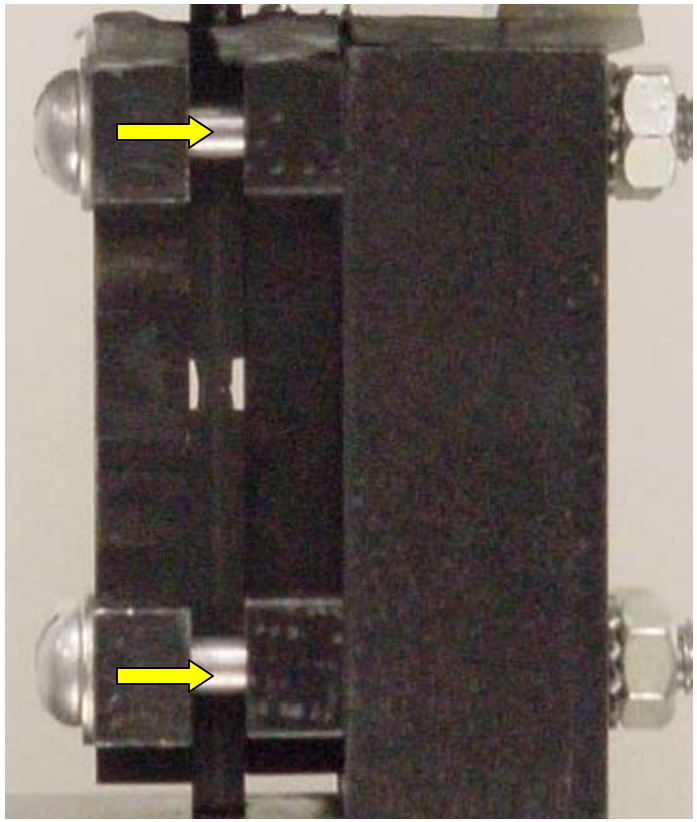
Compression Testing Methods used at Hexcel

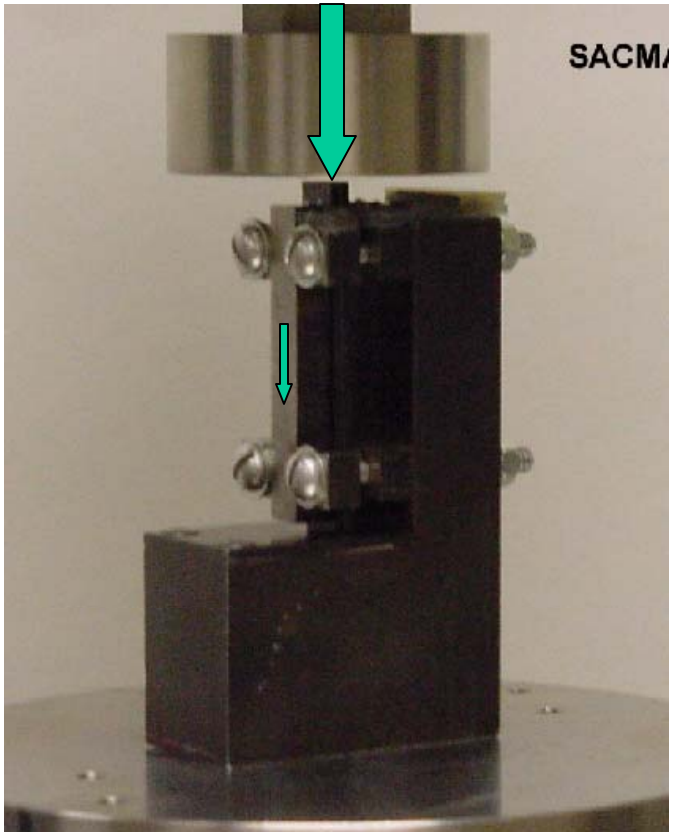
- SACMA SRM 1R-94: Most commonly used (US and EU) 1-2 mm thick specimens
- EN 2850B: EU only, same as above 2mm thick specimens. Tab failure common
- EN2850A: EU only, Celanese variation – difficult to get to work – Used mainly with multi-angular outer plies + machining
- IITRI: Not done at Hexcel anymore (not a standard)… but has merits
- D3410 "beam test" HC sandwich laminate and steel skins – not an option of 3410 anymore. Failure hard to detect, particularly in fatigue
- ASTM D 6641: Wyoming Test Fixture –US only –Fairly new but some customers requiring this specific test.

1st Trials: SACMA SRM 1R-94 Fixture

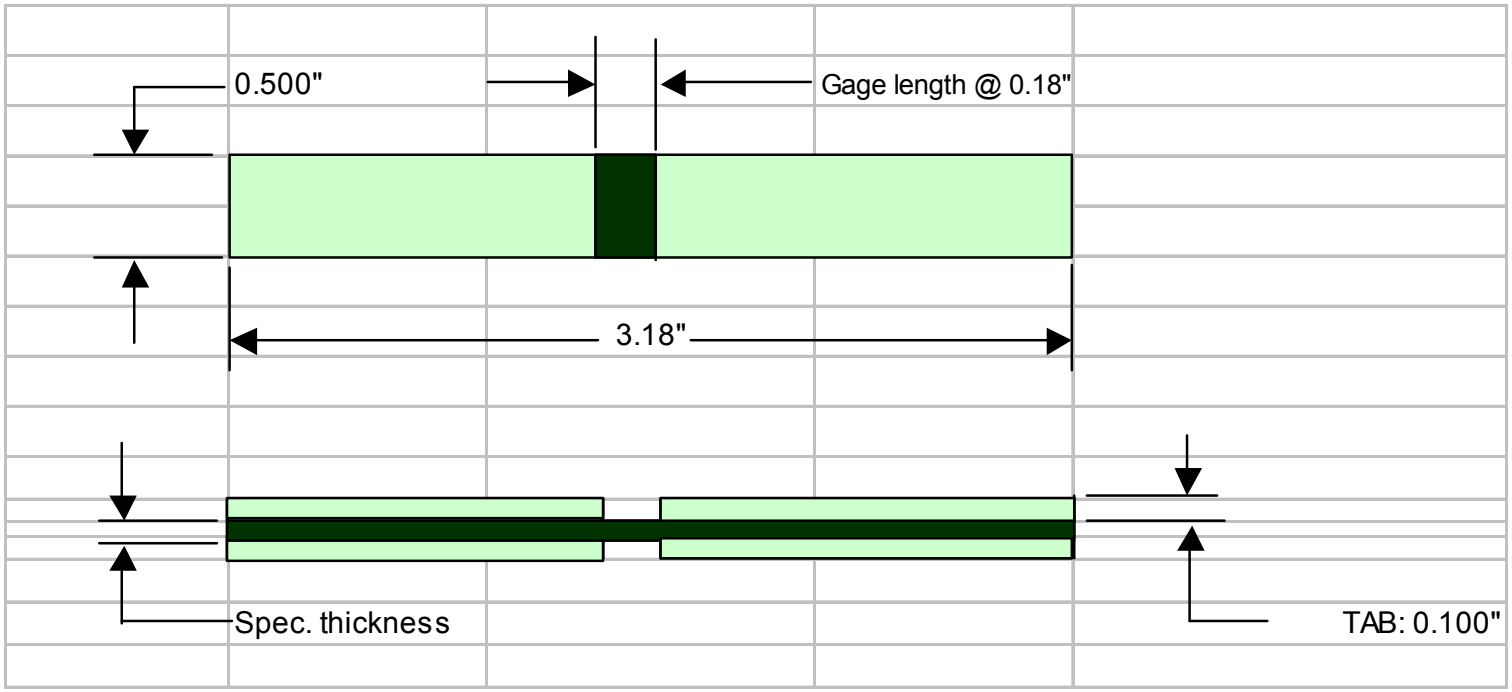
> End loading only

> Parallel load path (bolt torque critical)

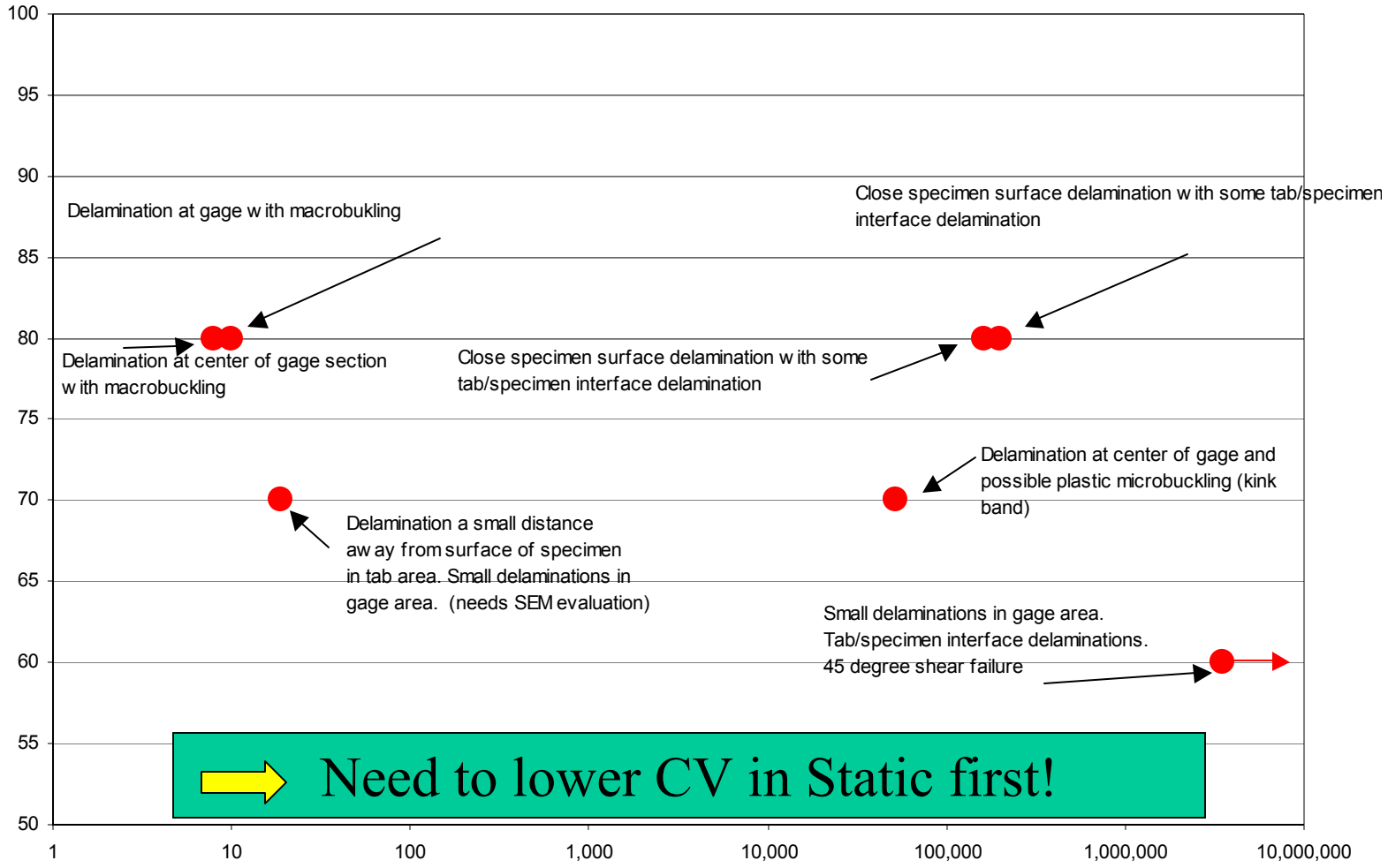




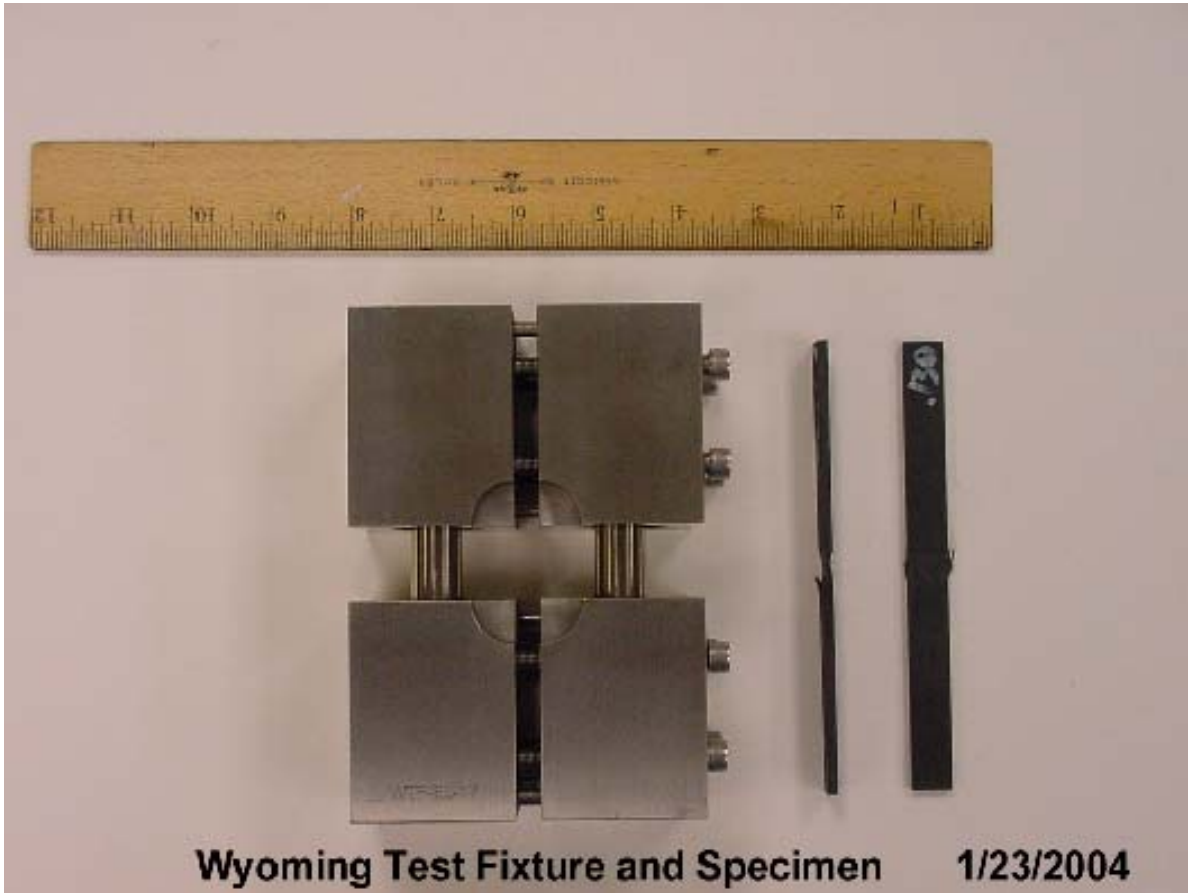
SACMA SRM 1R-94 Specimens



S-N curve in % of Static Strength vs. Nf (using SACMA Compression Fixture) With Optical Microscopy Observations

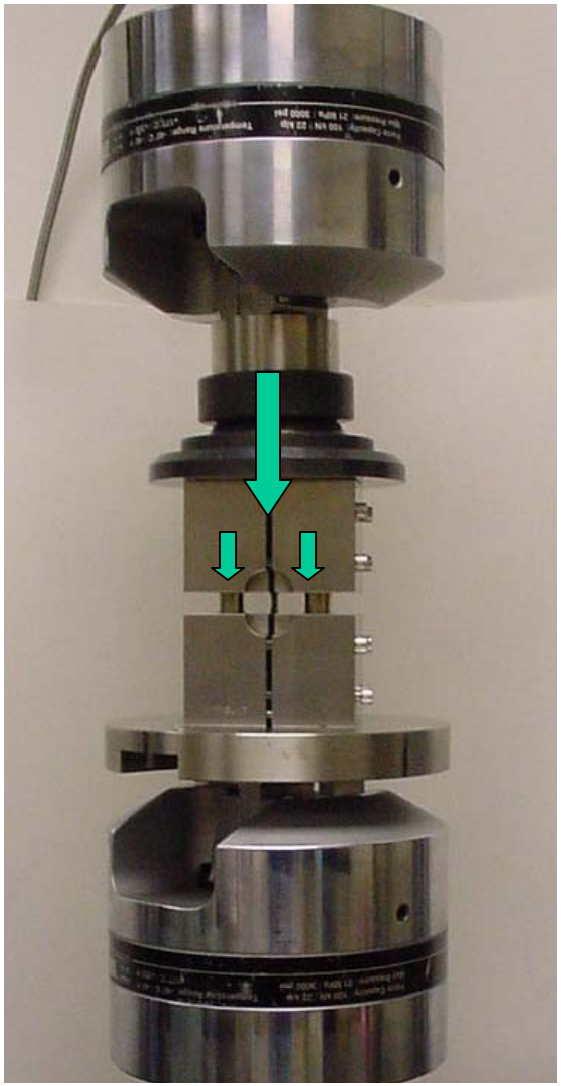


2nd Trials: Wyoming Test Fixture

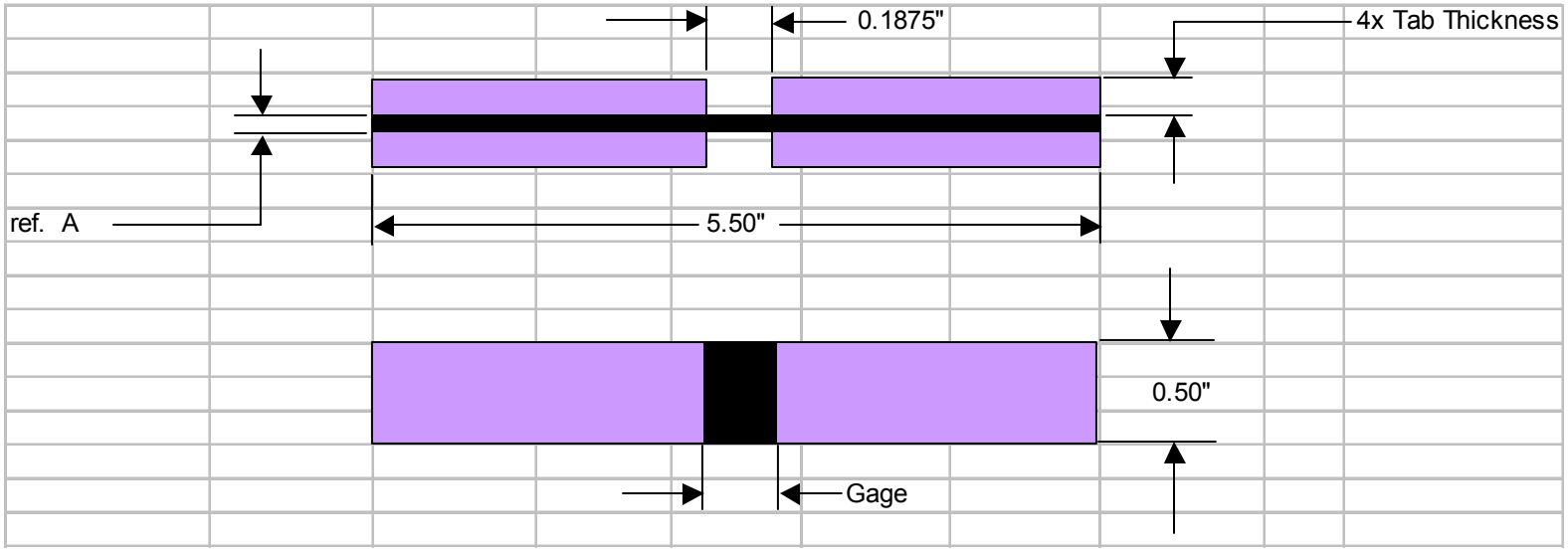


Wyoming Test Fixture

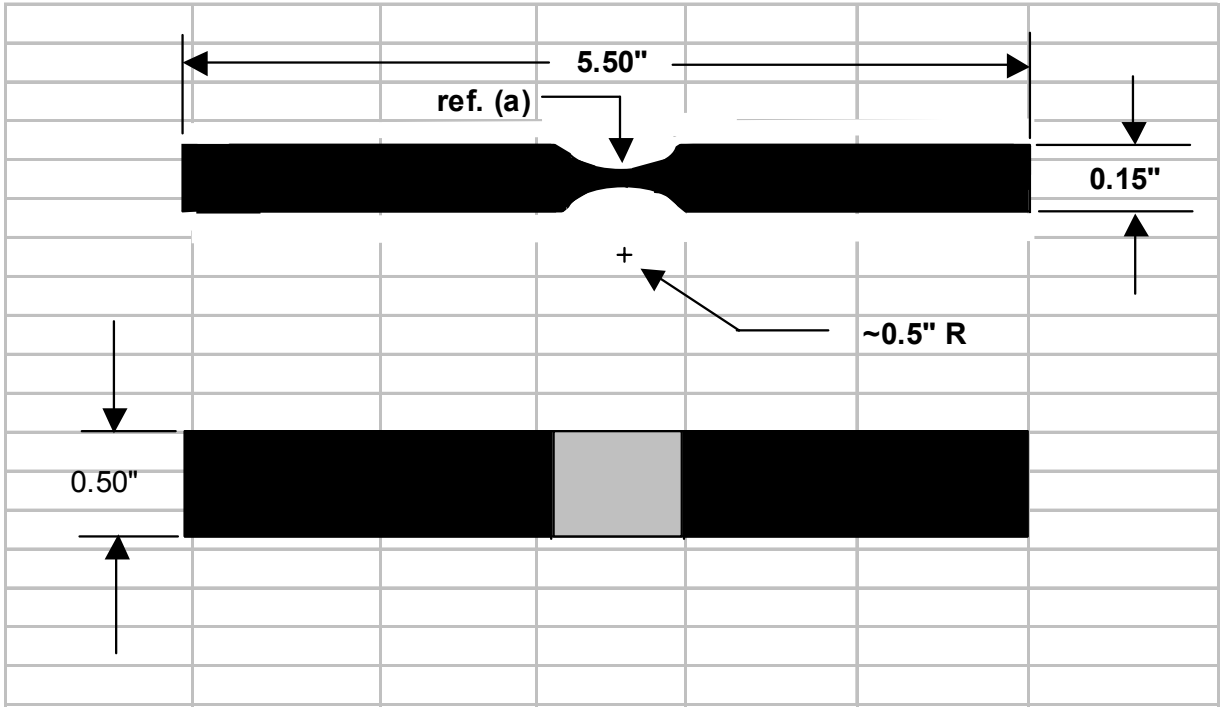
- Load Introduction:
  End + Shear loading
- No parallel Load path
  in gage area



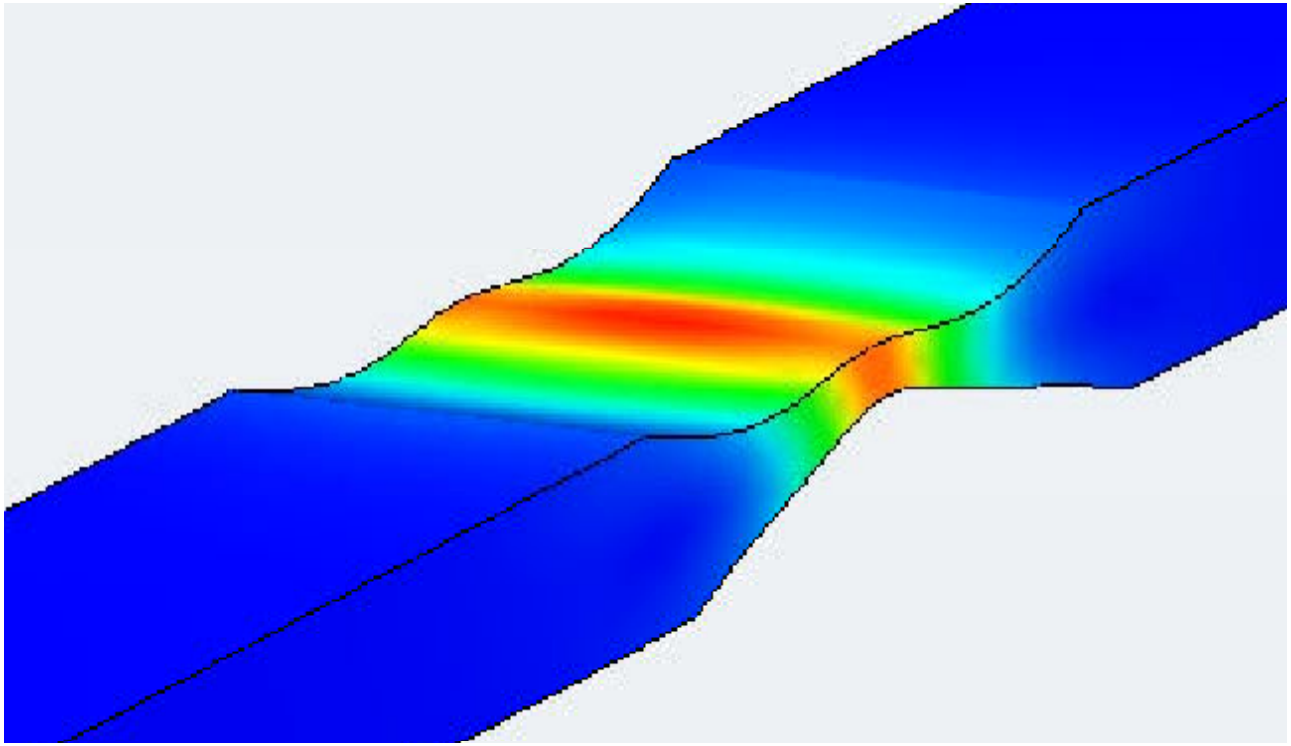
Wyoming Test Fixture Tabbed Specimens



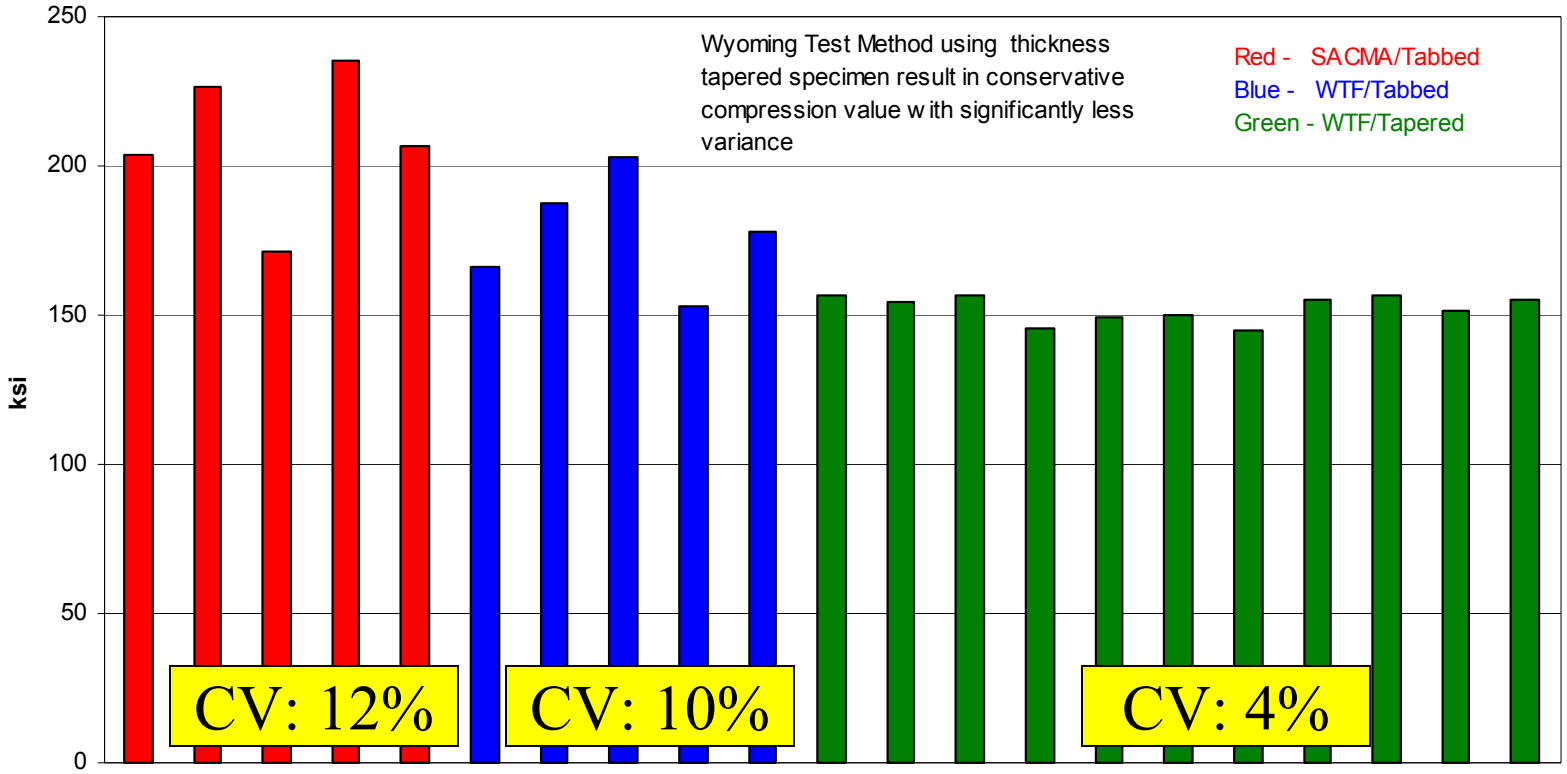
Wyoming Test Fixture Machined Specimens



Tapered specimen very resilient to buckling. Buckling stress > 12X compression strength



Comparison of Test Methods to Determine Static Compressive Strenth of a Vacuum-Bag Processed Unidirectional Epoxy/Carbon Laminate

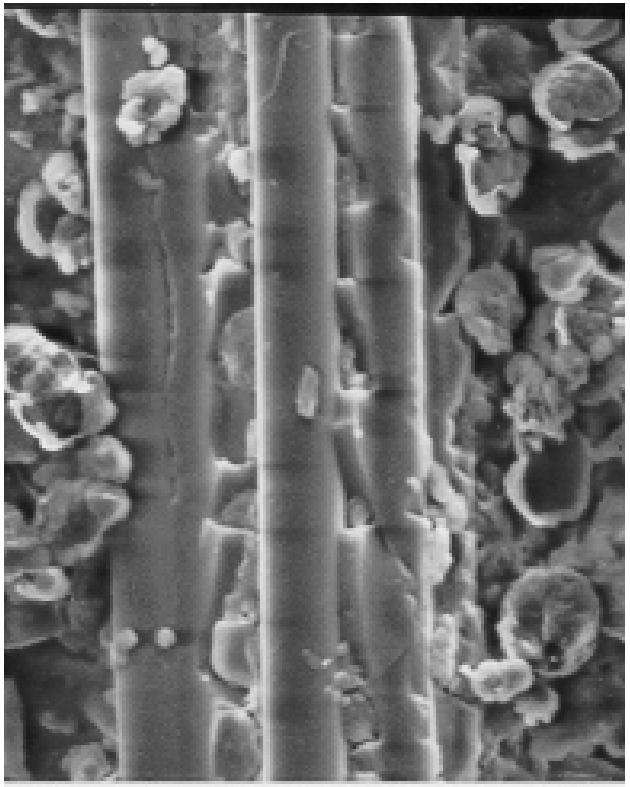


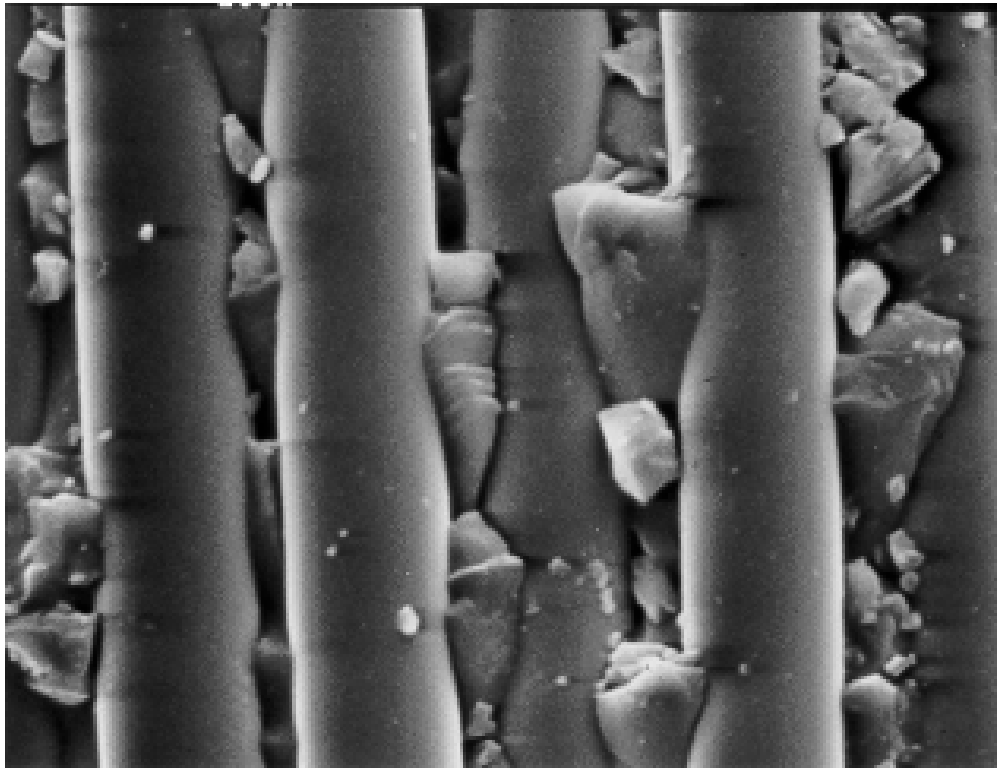
Wyoming Test Fixture Fatigue Results

- Work in Progress (R=0.1, f=5Hz, load control)
- So far, very high life at 90% of static strength: majority over 3 millions cycles
- No macro-buckling seen
- No end crushing
- **Because less scatter in static, more confident of % static load for each specimen**

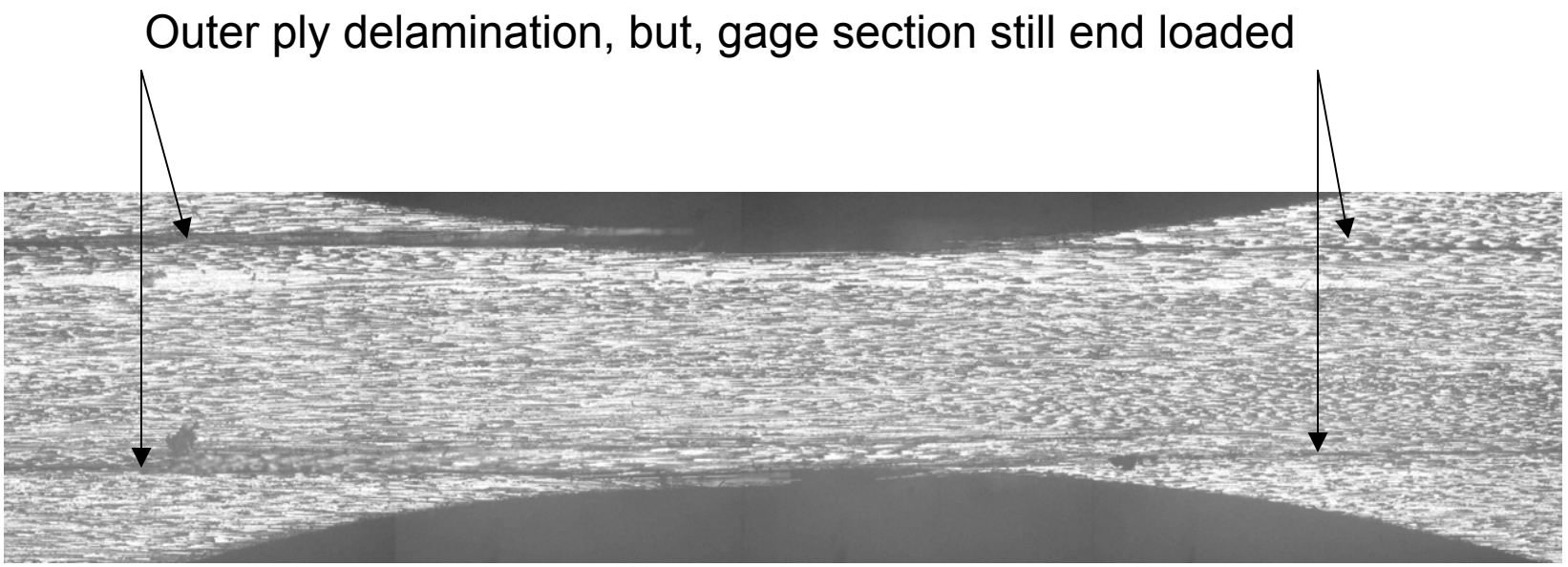
Wyoming Test Fixture Typical Fatigue Failure Mode

“Pure” Compression Fatigue: Fibers showing compression rings after 3 million cycles

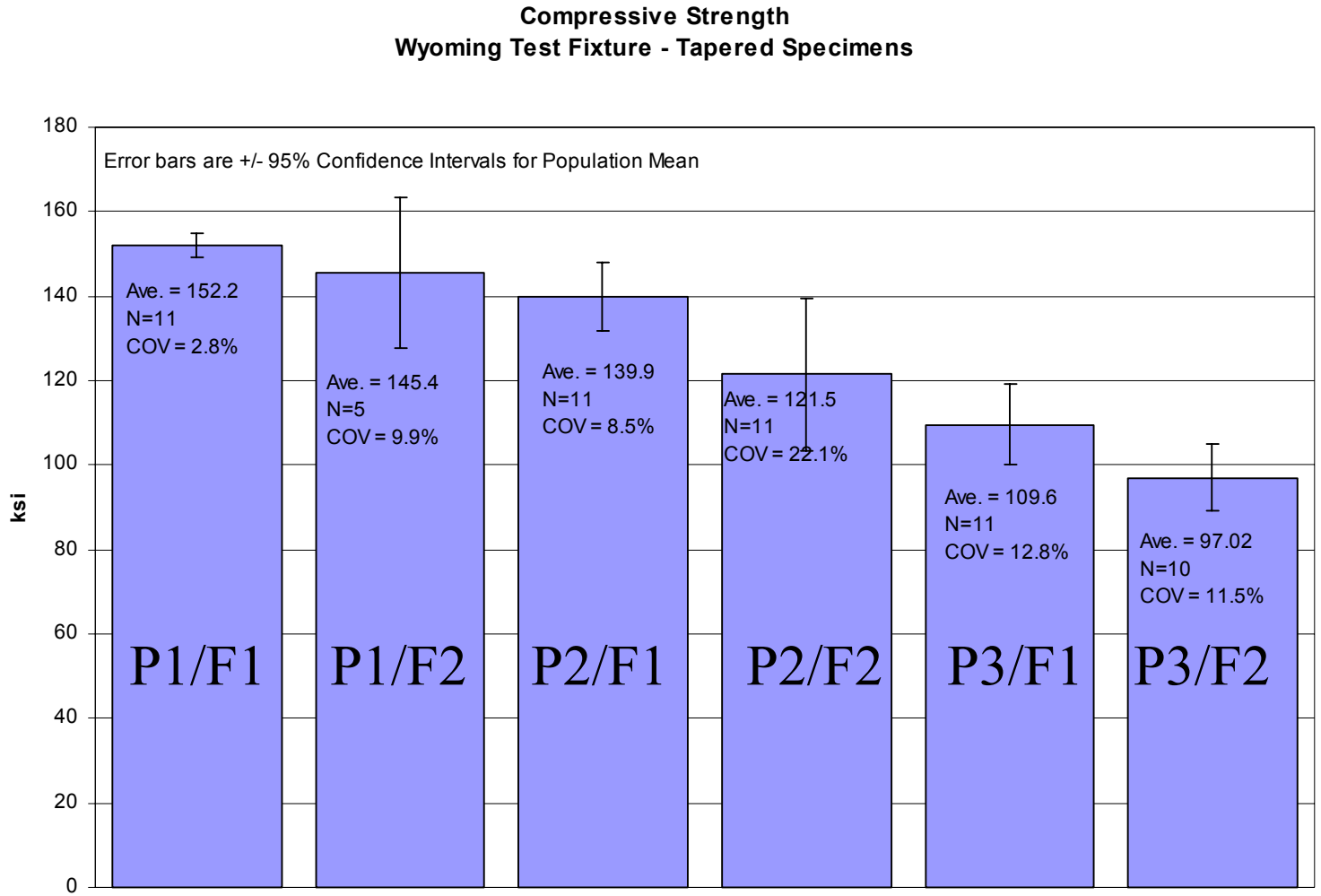




Typical Outer Ply Delamination Seen in Fatigue of Tapered Specimen



Process/Fiber Ranking using WTF/tapered specimens



Results Highlights and Discussion

- Thickness tapered specimens greatly reduced "parasitic" failure modes such as tab failure, buckling. Static scatter is reduced.
- Thickness tapered specimens allow for testing thick laminates.
- More validation tests needed. This test was however successfully used to rank processes and fibers (validated by outside lab).
- Development of strain measurement techniques are planned

Future Development

- Need cooperative work with Universities, National Laboratories, industry members to facilitate introduction of carbon fibers in WE blades:
  - Validate compression testing technique of UD carbon for static and fatigue > standard ?
  - Develop test for defects “tolerance” to go from coupons to real blades
  - Develop NDE techniques