2008 Wind Turbine Blade Workshop

RECENT FATIGUE TEST RESULTS FOR BLADE MATERIALS

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PRESENTATION

- Overview of Current Research Program Areas

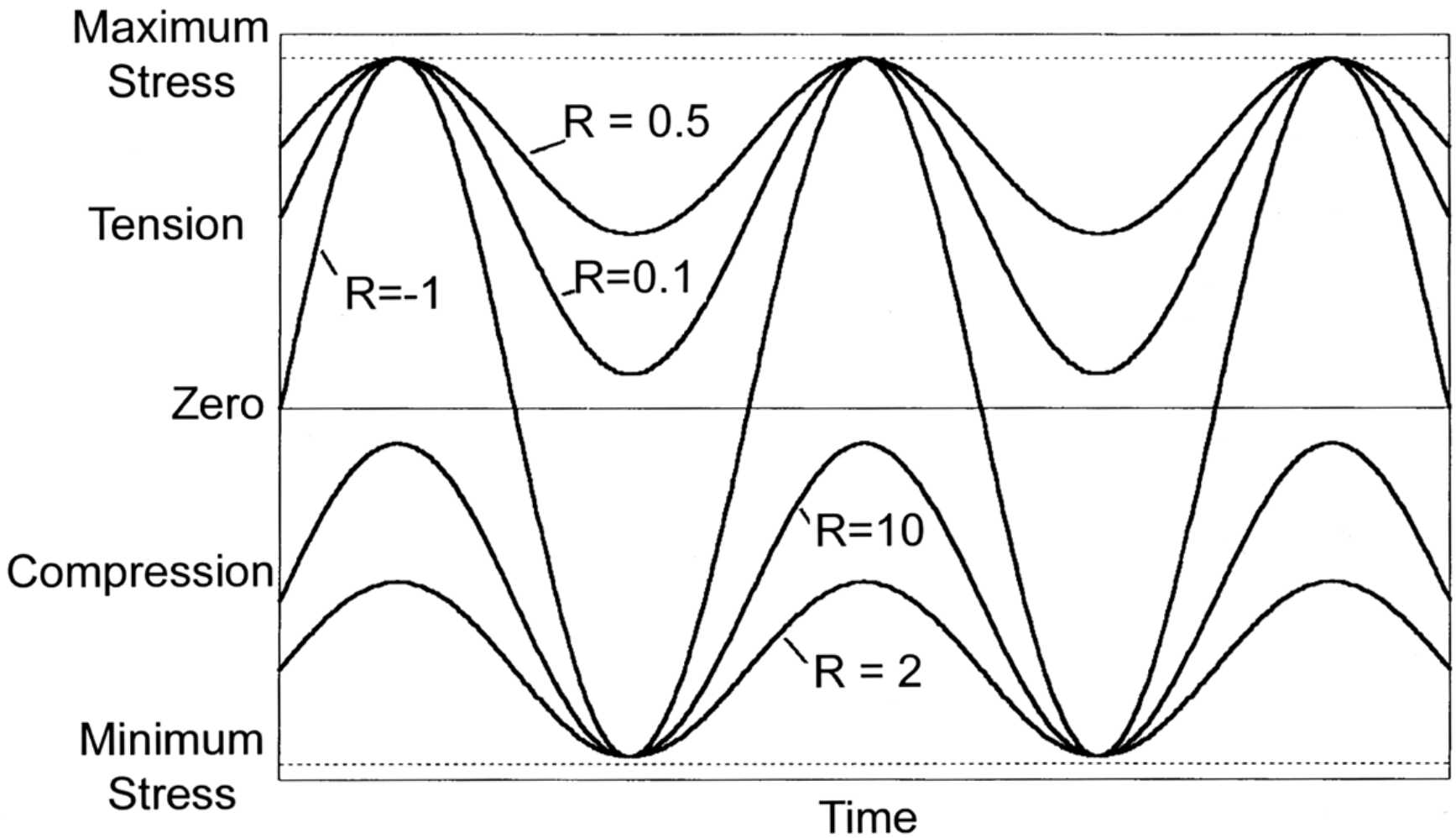
- Recent Results: Effects of Fiber Type, Fabric and Processing on Fatigue Resistance

MSU FATIGUE PROGRAM

- DOE/MSU Fatigue Database (SNL Website)
  - Over 190 Materials
  - 11,500+ test results
  - Updates each March
  - Trends analyzed in contractor reports

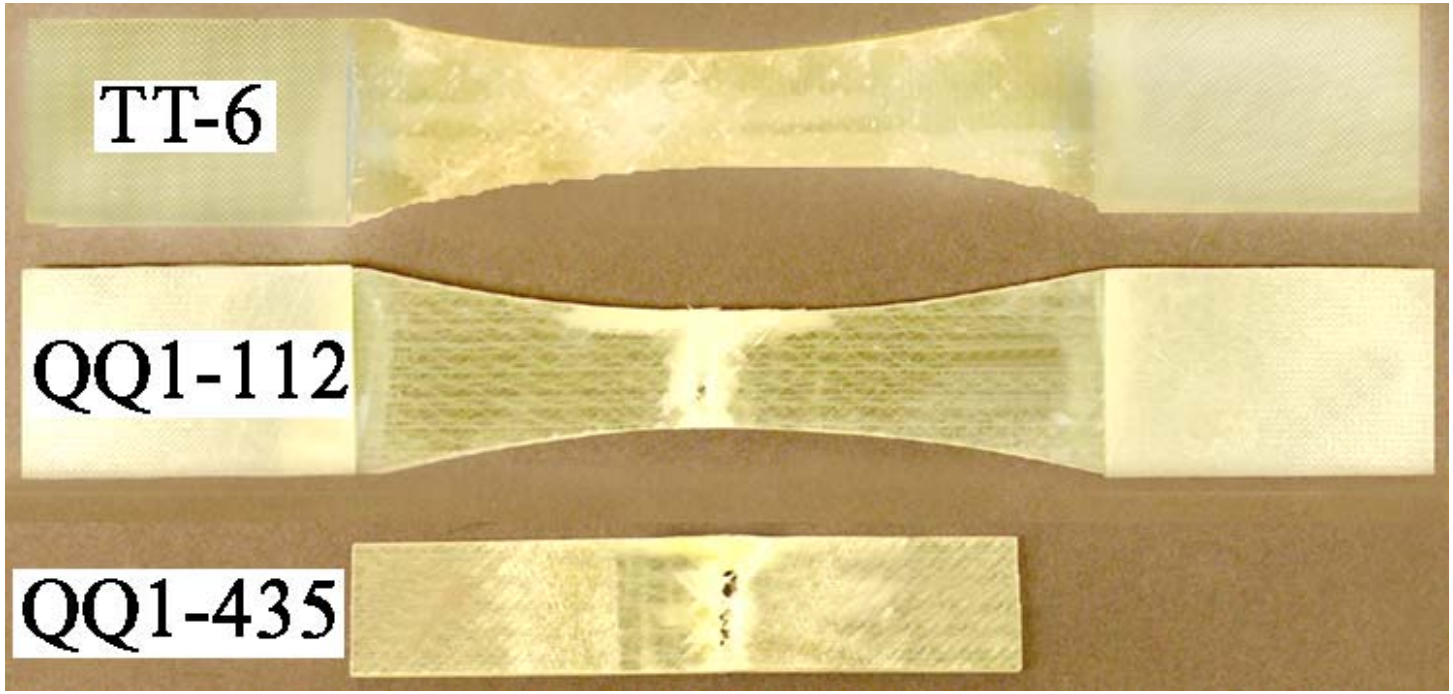
Typical Database Results

- Laminates supplied by industry or fabricated at MSU by infusion, prepreg or hand lay-up
- Static elastic and strength properties for stress analysis (FEA)
- Fatigue data for limited loading conditions
- For selected materials, sufficient loading conditions to construct Constant Life Diagrams used in spectrum loading predictions and design

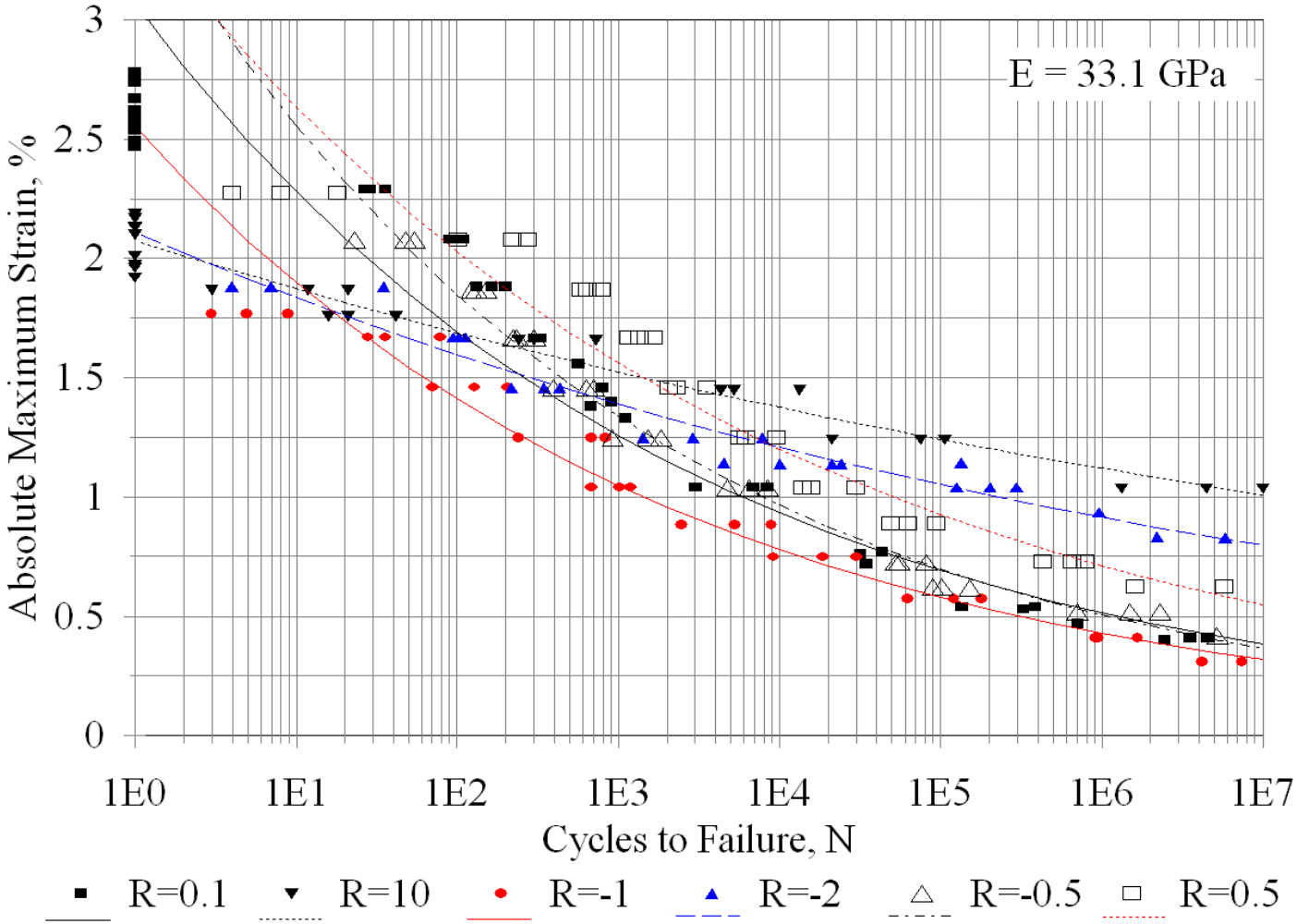


Constant Stress Amplitude Sine Waveforms for Different R-Values

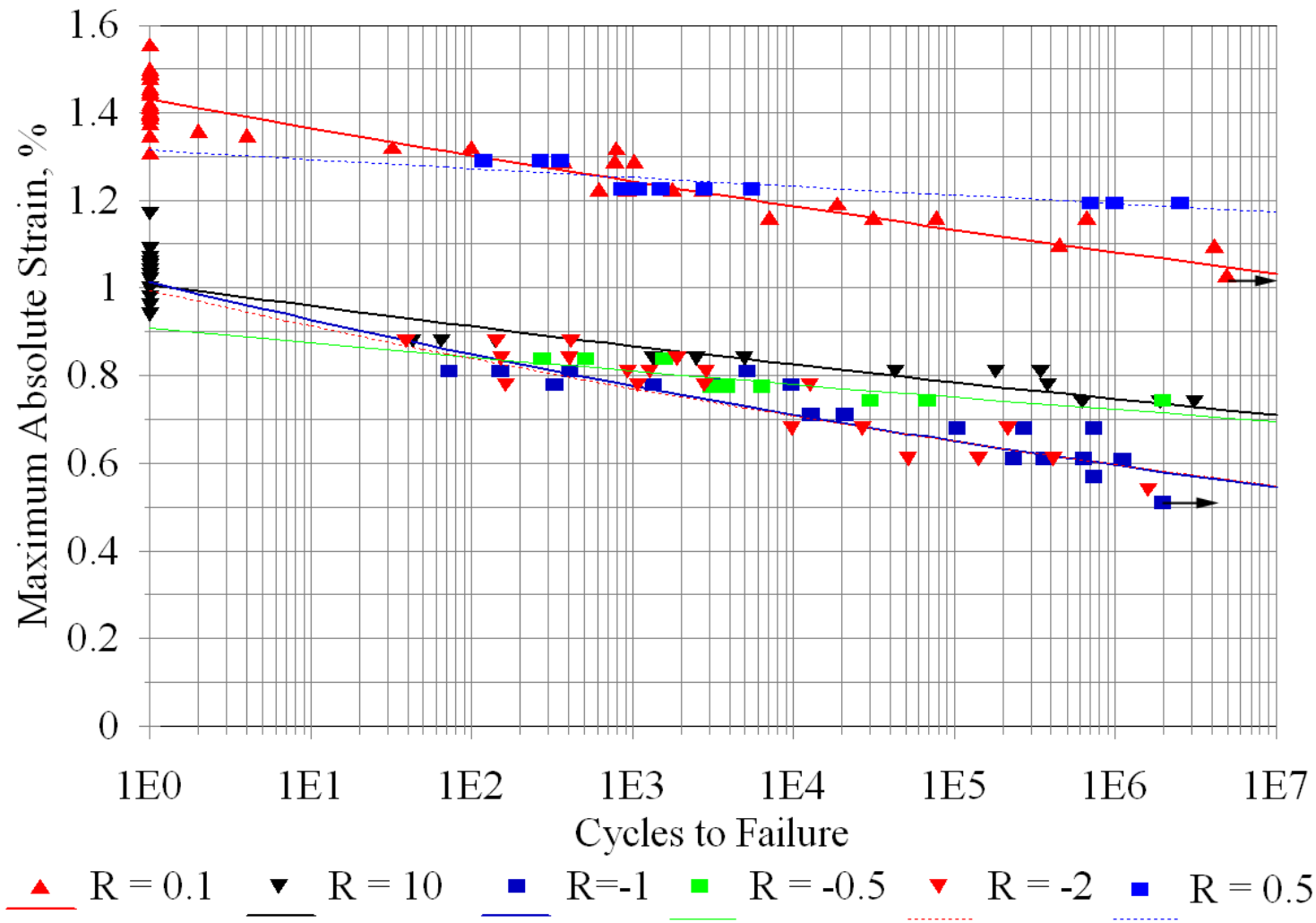
R-Value = (Minimum Stress / Maximum Stress)



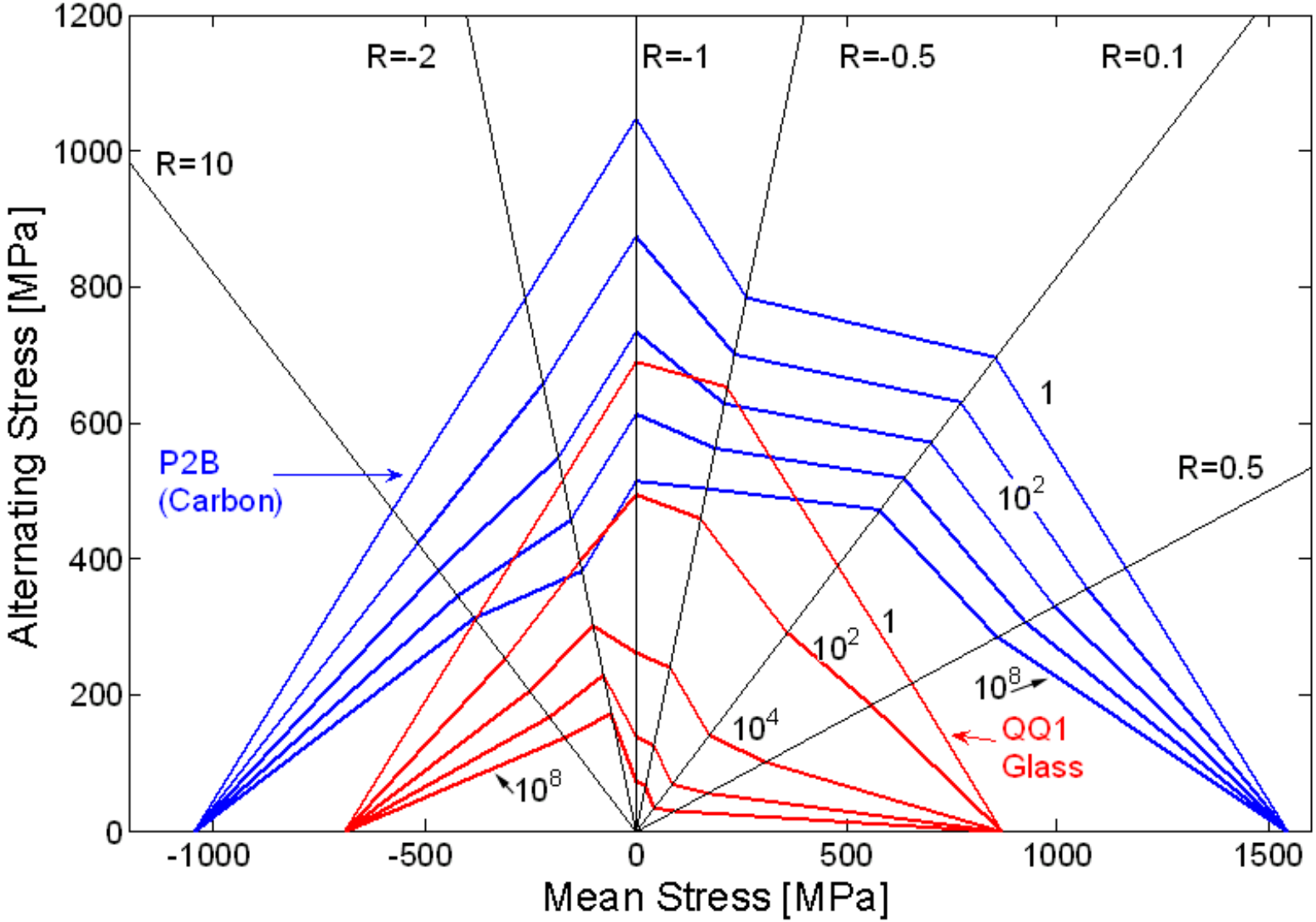
Failed fatigue dog-bone and rectangular specimens, showing grip-edge failure for a rectangular specimen (bottom) and gage section failure for a dog-bone specimen (7,8).



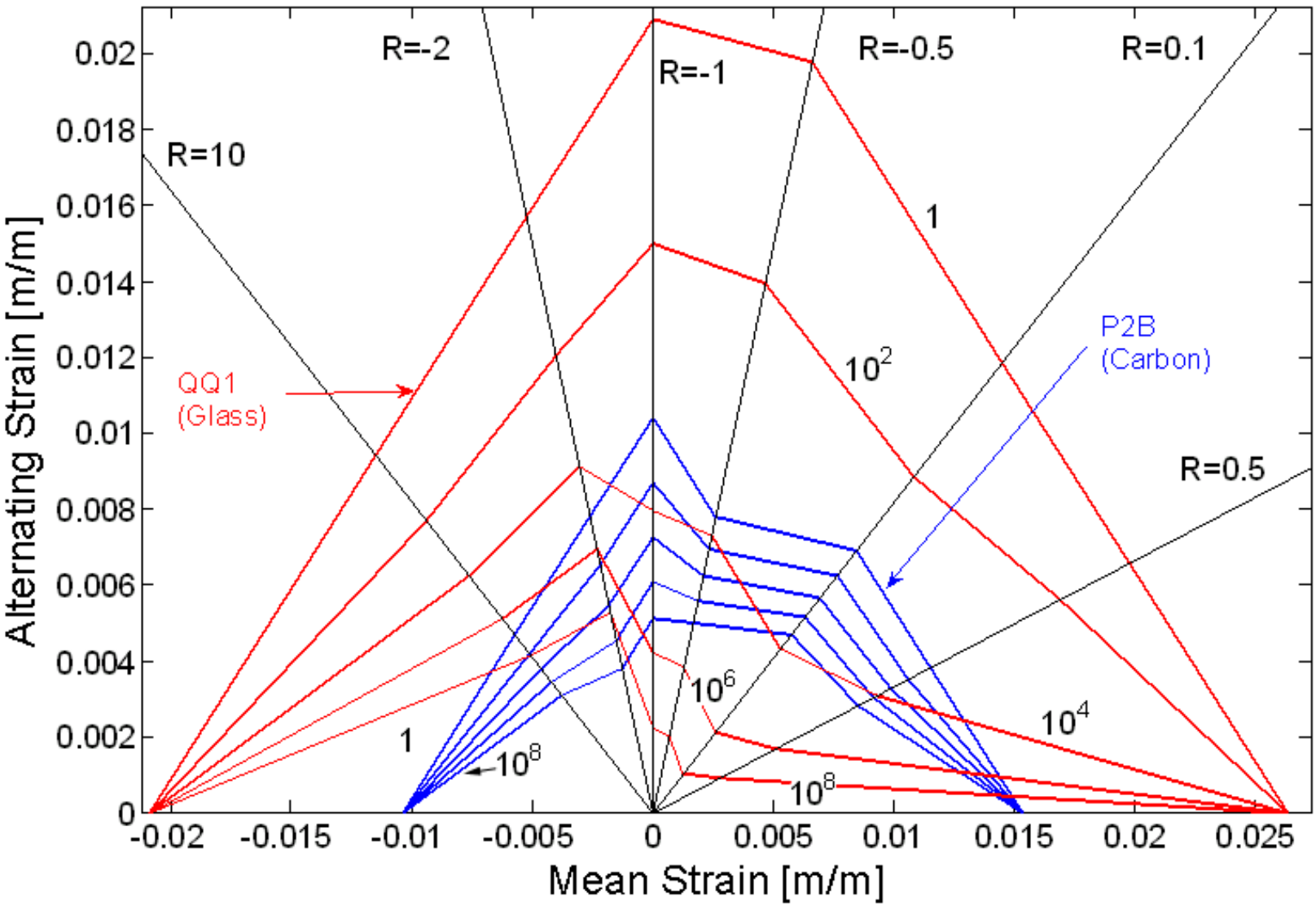
Effect of loading conditions (R-value) on fatigue strain vs. lifetime for E-glass/epoxy laminate (QQ1).



Maximum Absolute Strain to Failure Fatigue Data for [±45/0_8/±45] P2B Laminate, R=0.1, 10 and -1 (9).



Comparison of materials QQ1 (E-Glass) and P2B (carbon 0º plies), axial direction, mean stress constant life diagram (7).



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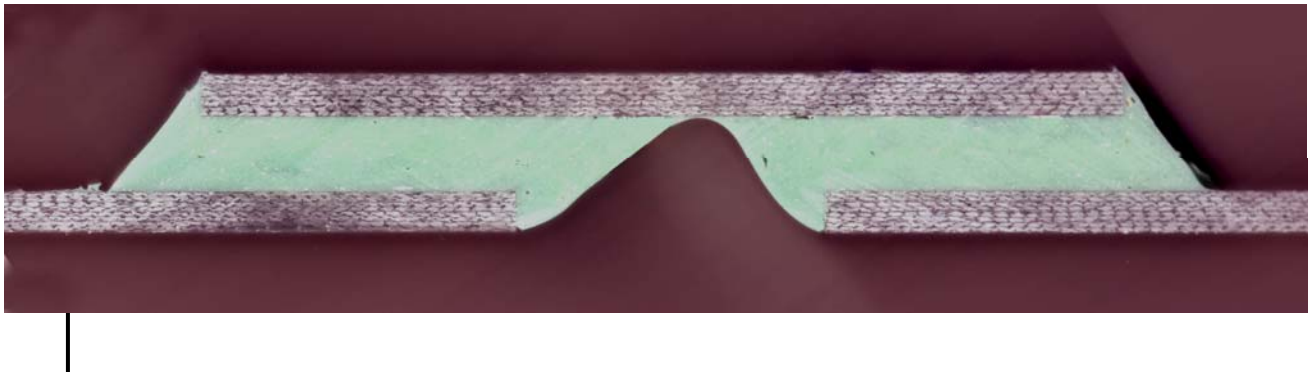
Spectrum Loading Effects

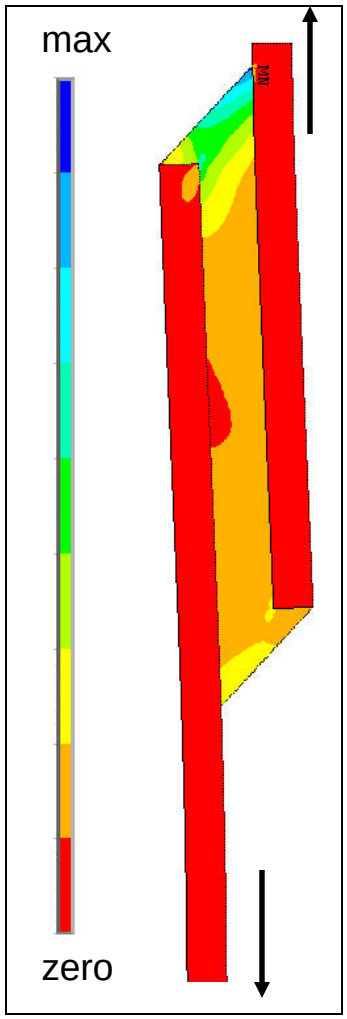
- Database and models necessary to predict the lifetime of typical and potential blade materials under representative blade loads spectra.
- Contractor Report SAND2006-7810P, Rogier Nijssen (joint research, MSU and OPTIMAT)

Thick Adhesive Joints

- **Generic Study**. Parameters: Materials, processing and loading variables, stress field (FEA), static and fatigue strength, statistics, crack propagation (post-doc Aaron Sears)
- **Blade Application**. Currently static and fatigue testing several typical blade joint geometries; specimens supplied by an industry partner (results will be available in the DOE/MSU Database)

- Initial Study: symmetric single lap shear
  - simple geometry
  - variable thickness
  - static and fatigue testing
  - variable R-value

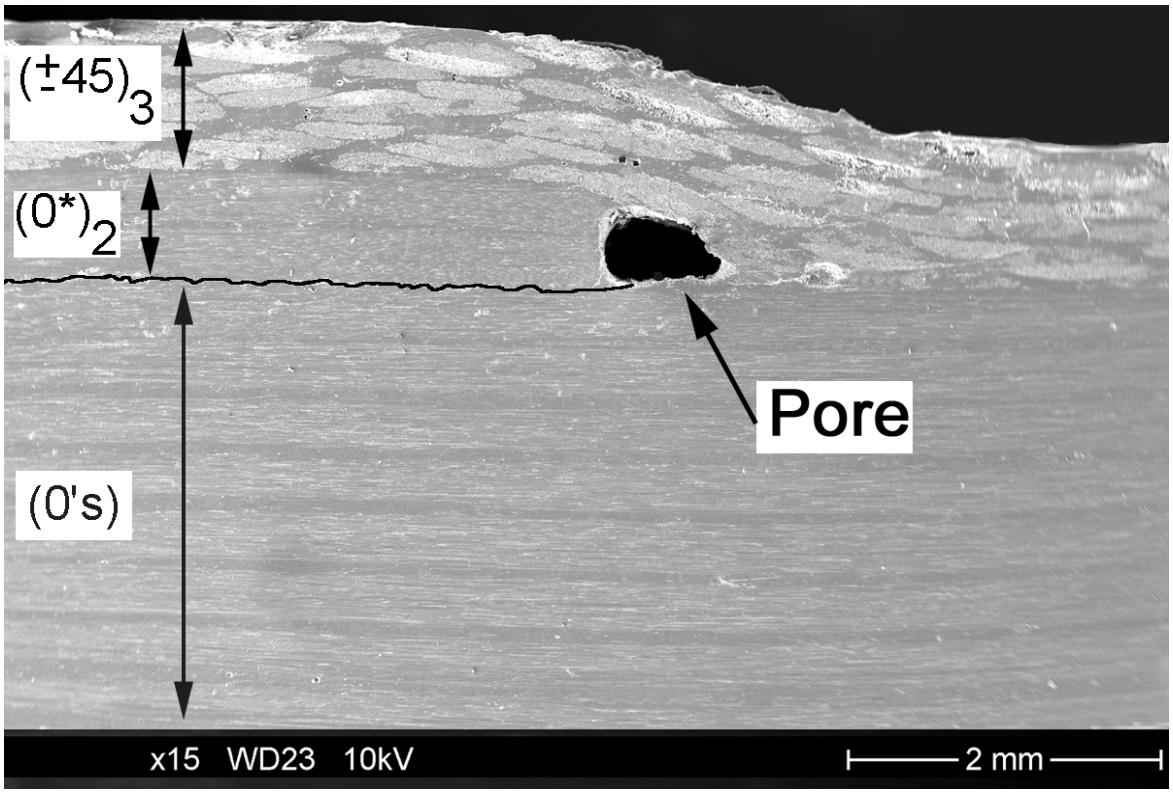




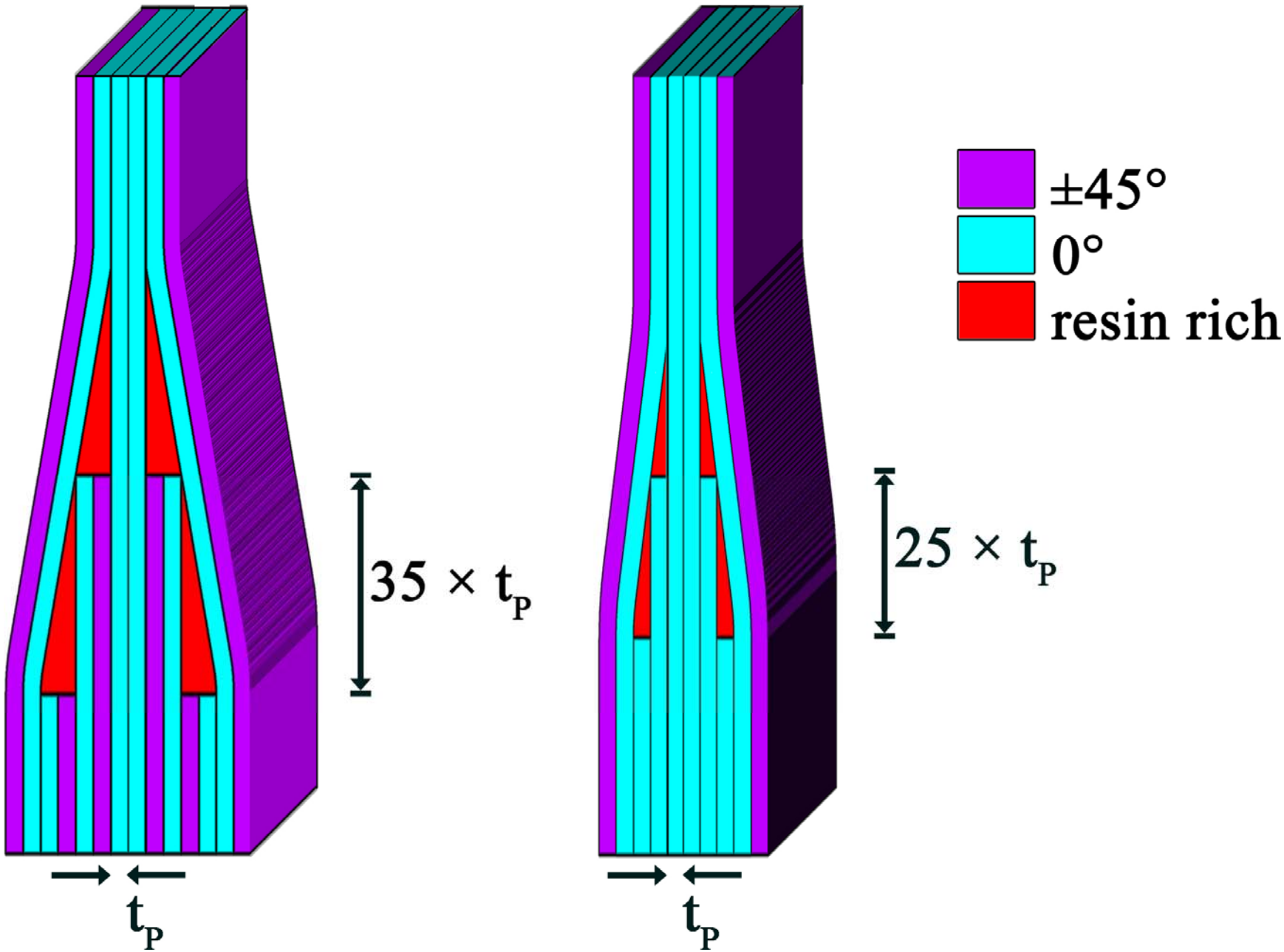
shear strain

Ply Delamination

- Ply delamination and other cracking at edges of material build-up and transition areas like ply drops; Coupons containing moderately thick ply drops fail by delamination at much lower strains in fatigue, compared to standard coupons. Carbon particularly sensitive
- Basic mixed mode delamination static and fatigue crack growth characterization
- Extensive data and FEA analysis for ply drops, carbon and glass, recent publications
- Next step: full fatigue damage growth FEA simulation and testing for more complex geometry



Photograph of delamination crack growing from pore ahead of double ply drop (see fig. 4), carbon 0° plies, compression fatigue (crack path enhanced) (9, 10).

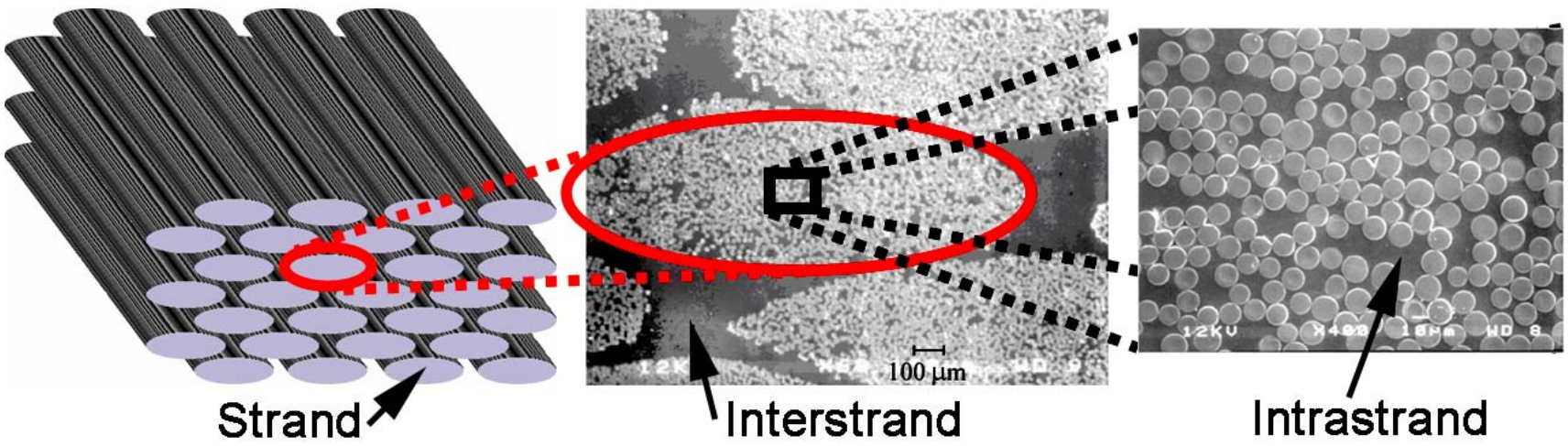

±45°
0°
resin rich
35 × t_P
25 × t_P
t_P
t_P

Recent Fatigue Testing Focus

- Materials variations, effects on fatigue
  - Fiber (E-glass, WindStrand, carbon)
  - Resin (epoxies and vinyl esters)
  - Reinforcing fabric, fiber content, and processing interactions
  - Transverse and shear directions

Unidirectional longitudinal elastic modulus for several fabrics (normalized to a fiber volume fraction of 0.53).

Fabric	Fiber	Matrix	0° Ply Modulus, E_L, GPa
Fabric B	E-glass	Epoxy	42.5
Fabric D	E-glass	Epoxy	41.6
Prepreg	**Carbon**	**Epoxy**	**123**
aligned strand	**Windtrand**	**Epoxy**	**48.3**



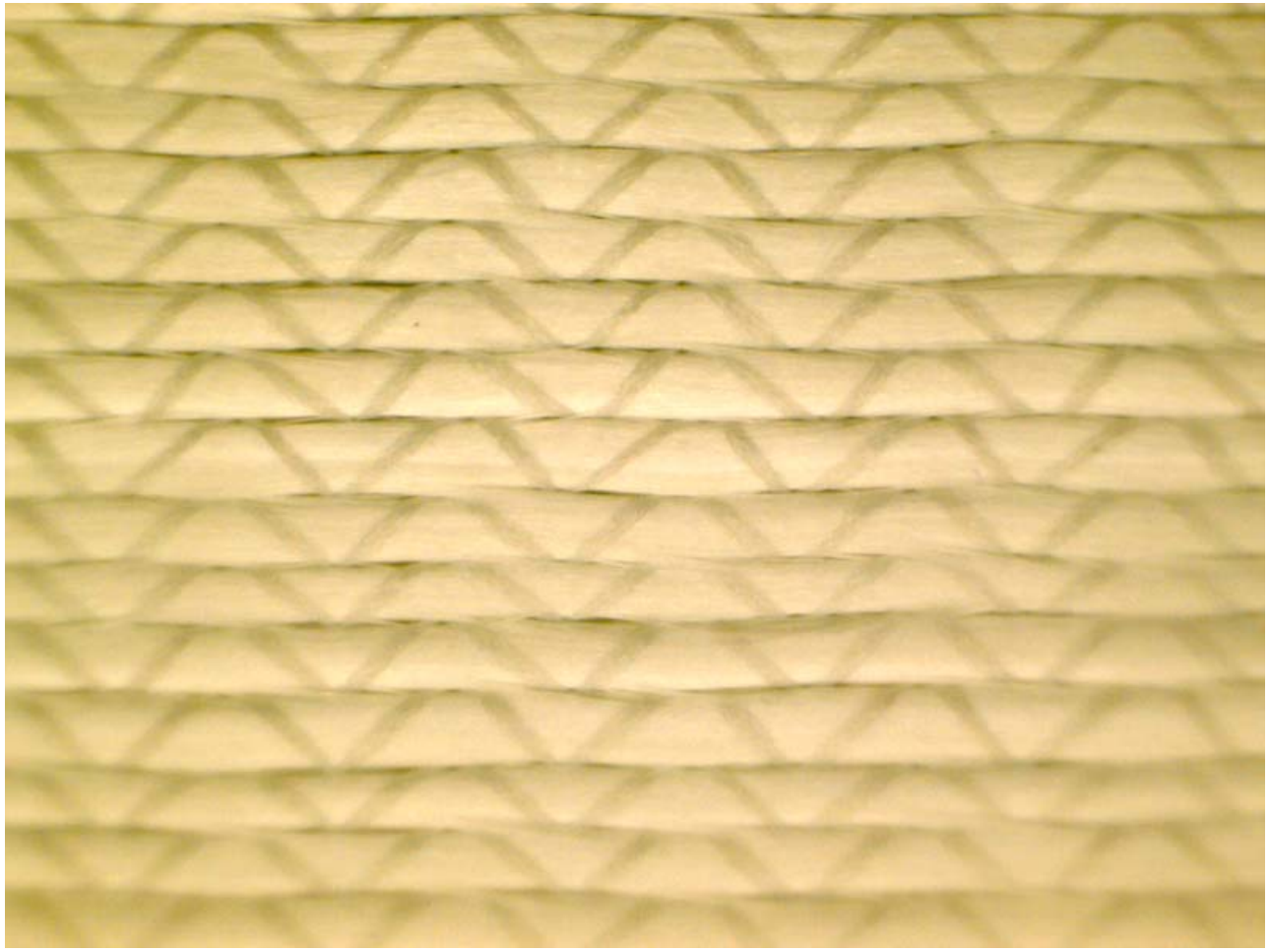
Exploded view of D155 Fabric A composite showing inter-strand channels and intra-strand structure (8).

Material	Lay-up	0° Fabric	±45° Fabric	0° %	V_F	Matrix
DD Series	[0/±45/0]s	A	E	72	varied	P
QQ1	$[\pm 45/0_2]_S$	B	F	64	0.53	E
QQ2	$[\pm 45/0/\pm 45]_S$			35	0.52	
QQ4	[±45/0/±45/0/±45]	C	G	56	0.57	E
QQ4-L					0.40	
QQ4-M					0.46	E
E-LT-5500-EP	[±45/0/±45/0/±45]	D	G	66	0.55	E
E-LT-5500-VE						V
TT						E
TT1A			F	66		E
TT1AH					0.63	
WS1	[±45/0/±45]	WS	WS	50	0.61	E
WS2	$[\pm 45/0/\pm 45]_S$				0.60	
P2B	$[\pm 45/0_4]_S$	carbon prepreg		85	0.55	E
MMWK-C/G-EP	$[(45/0/-45)_4]$	H (c-g triax)		75	0.56	E
CGD4E	$[\pm 45/0_3/\pm 45]$	A	I	76	0.50	E

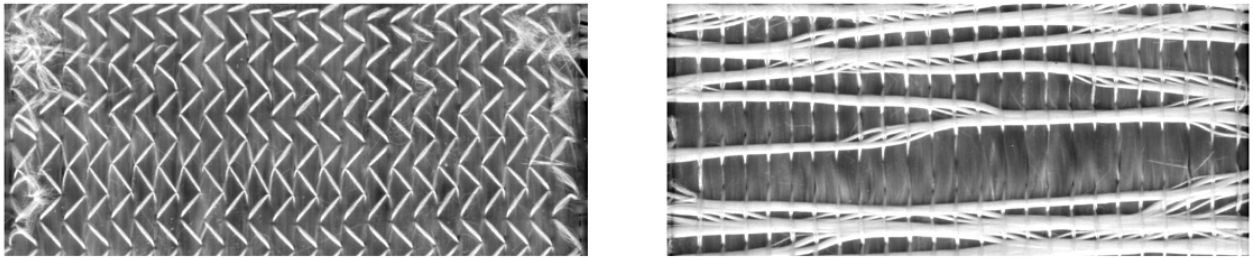
Table 1. Fabric specifications (from manufacturers).

	Manuf.	Designation	Fabric Weight, g/m^2	%0	%45	%90	%RM	%Stitching
A	Knytex	D155	527	99	0	0	0	1
B	Saertex	U14EU920-00940-T1300-100000	955	91	0	8	0	1
C	Saertex	S15EU980-01660-T1300-088000	1682	97	0	2	0	1
D	Vectorply	E-LT-5500	1875	92	0	6	0	2
E	Knytex	DB120	393	0	97	0	0	3
F	Saertex	VU-90079-00830-01270-000000	831	0	97	2	0	1
G	Knytex	DBM-1708	857	0	68	0	30	2
H	Saertex (11)	MMWK Triax glass/carbon/glass	970	69	31	0	0	NA
I	Toray	ACM-13-2 (300-48k-10C yarn)	600	100	0	0	0	NA

* Fabrics A-G are glass fiber, H is hybrid glass/carbon, and I is carbon.
All listed percentages are by weight.

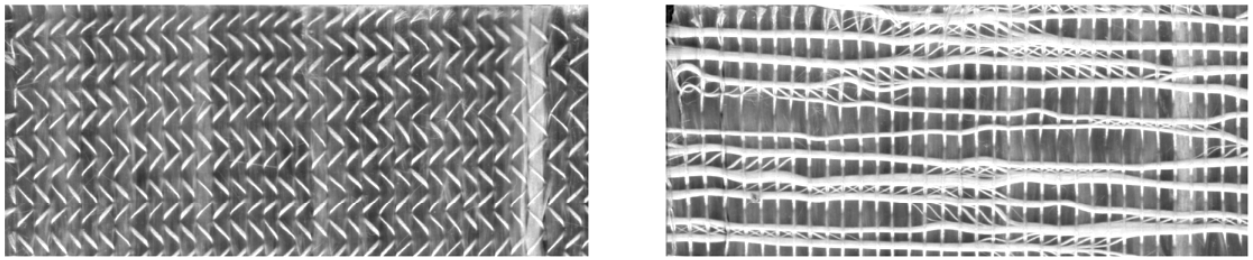


FRONT BACK



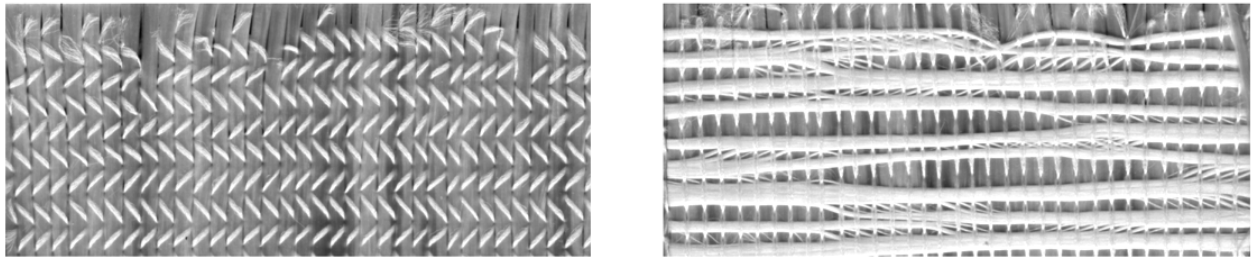
Fabric B

(0's - 864 g/m^2, 90's - 79 g/m^2, stitching - 12 g/m^2, total = 955 g/m^2)



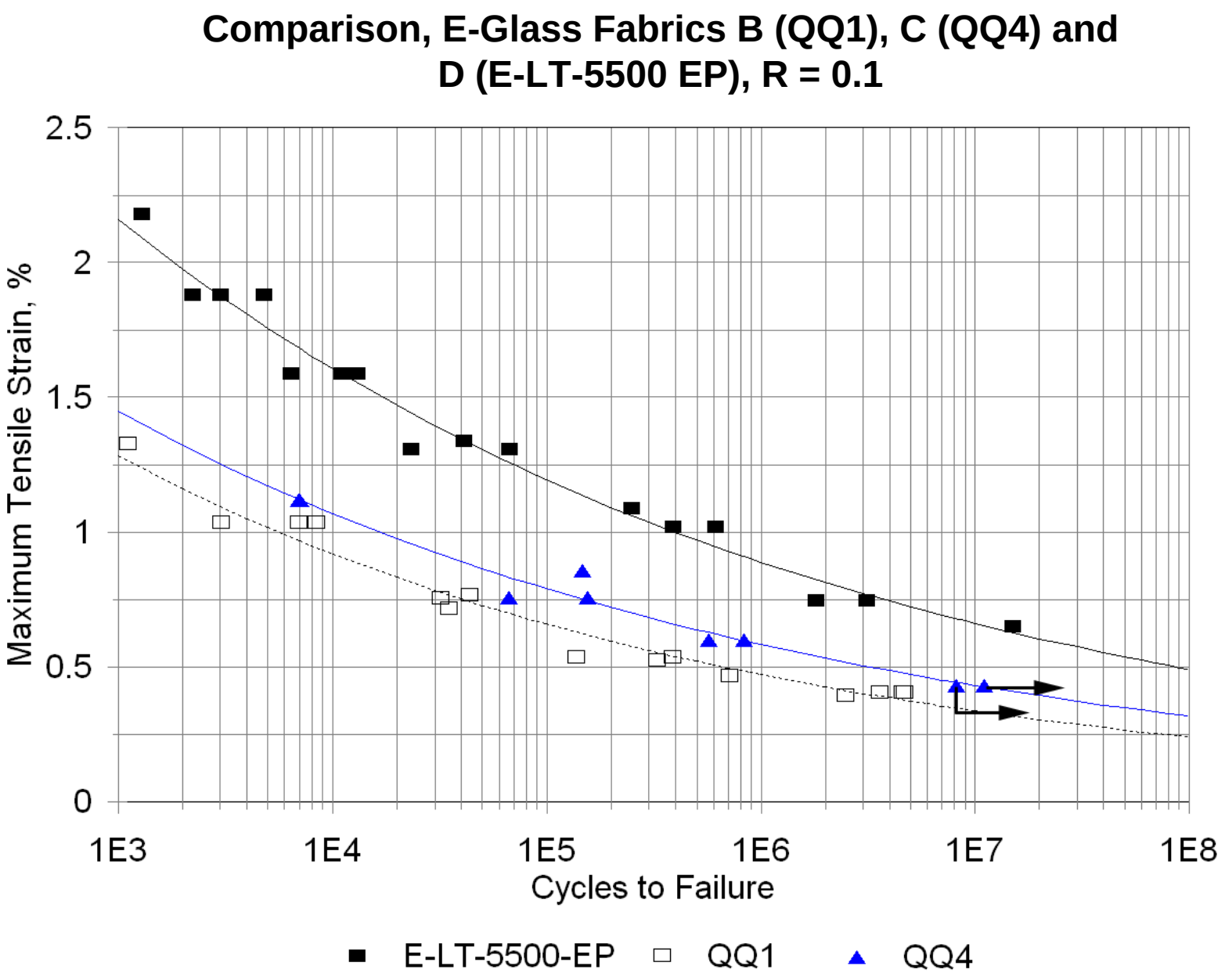
Fabric C

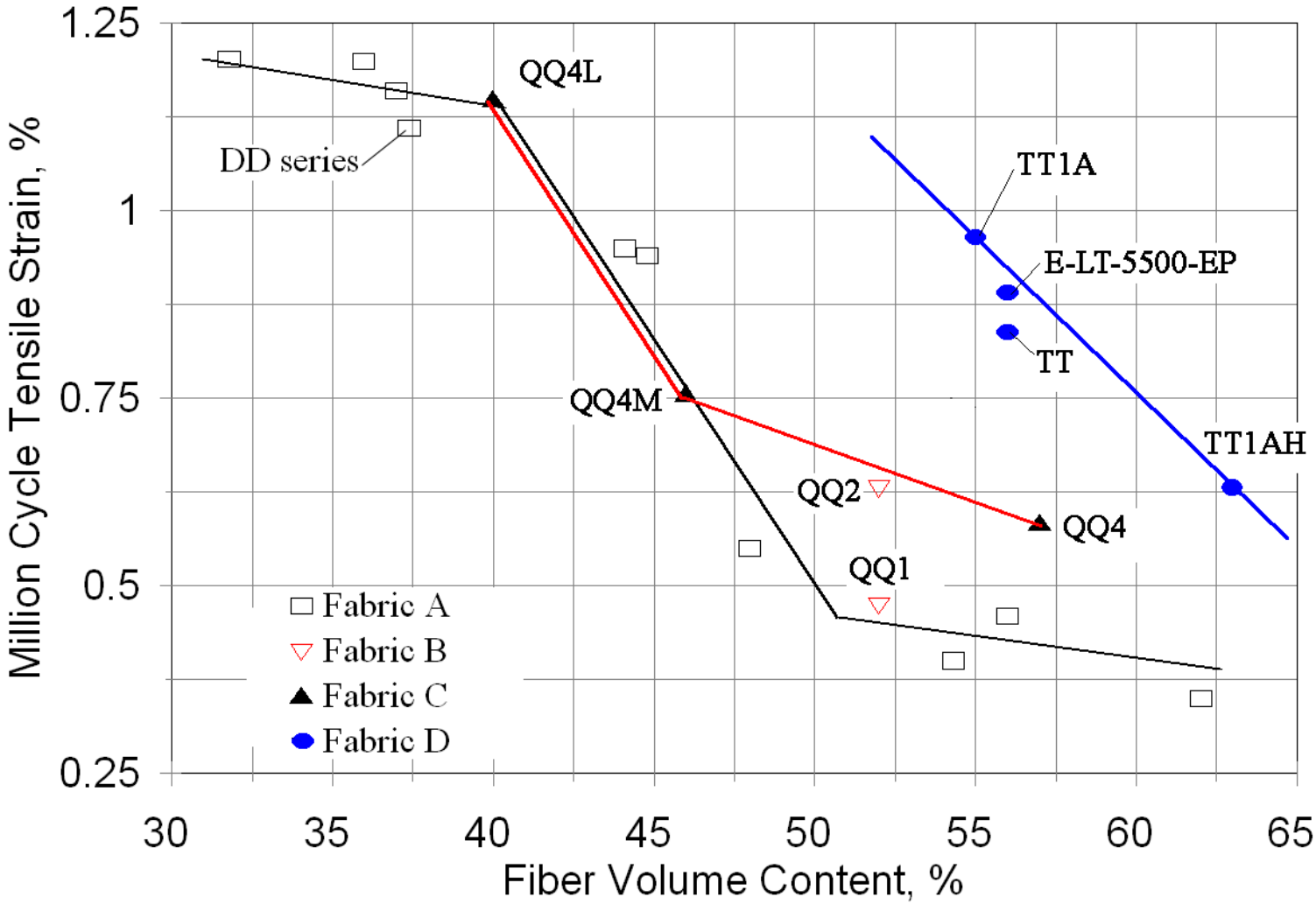
(0's - 1632 g/m^2, 90's - 32 g/m^2, stitching - 18 g/m^2, total = 1682 g/m^2)



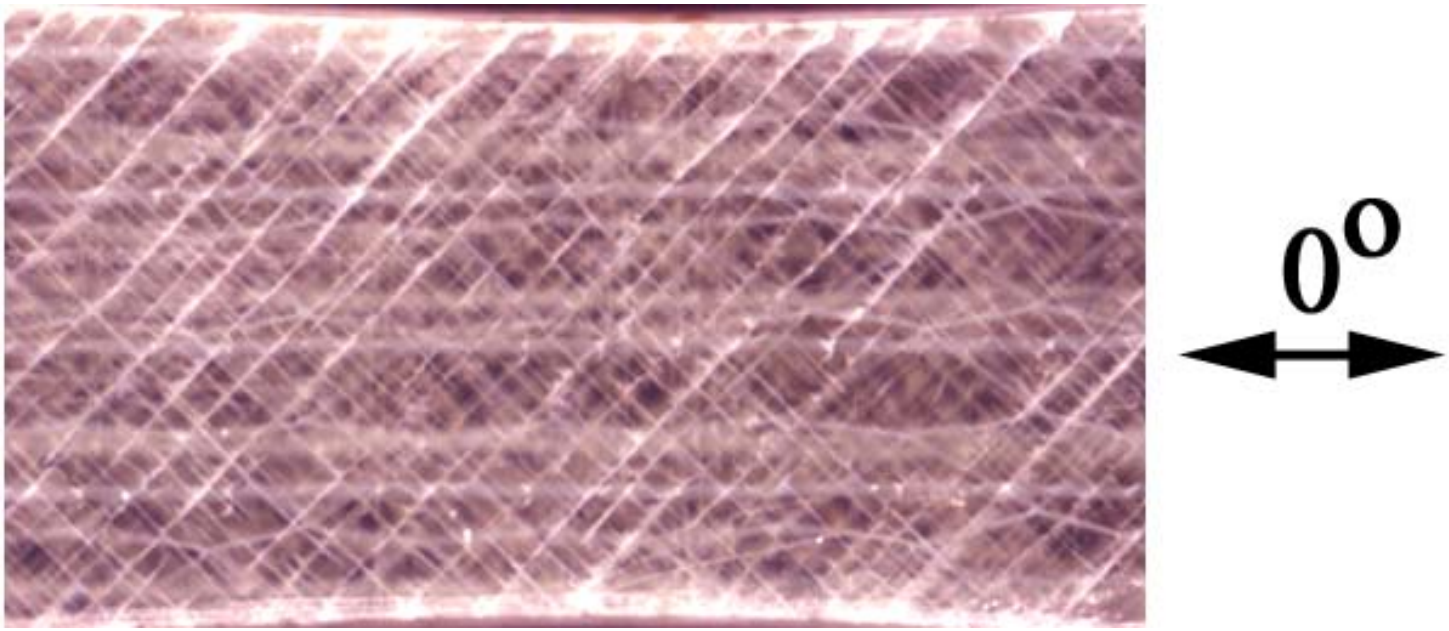
Fabric D

(0's - 1728 g/m^2, 90's - 114 g/m^2, total = 1842 g/m^2)

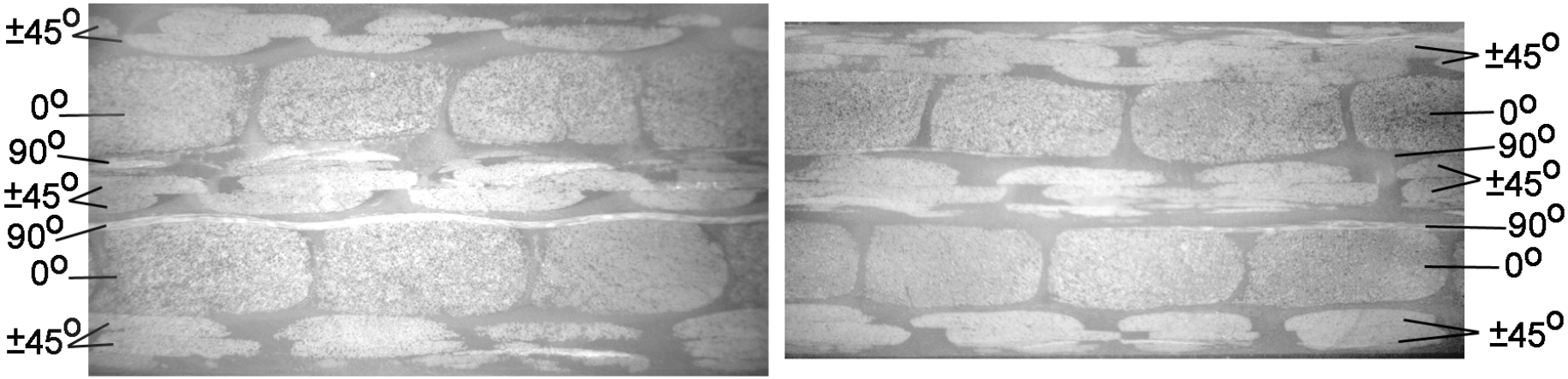

Comparison, E-Glass Fabrics B (QQ1), C (QQ4) and D (E-LT-5500 EP), R = 0.1
Maximum Tensile Strain, %
2.5
2
1.5
1
0.5
0
1E3
1E4
1E5
1E6
1E7
1E8
Cycles to Failure
E-LT-5500-EP
QQ1
QQ4



Million cycle strain vs. fiber volume content for various infused materials showing transitions to reduced fatigue resistance as a function of 0° fabric, R = 0.1 (8).

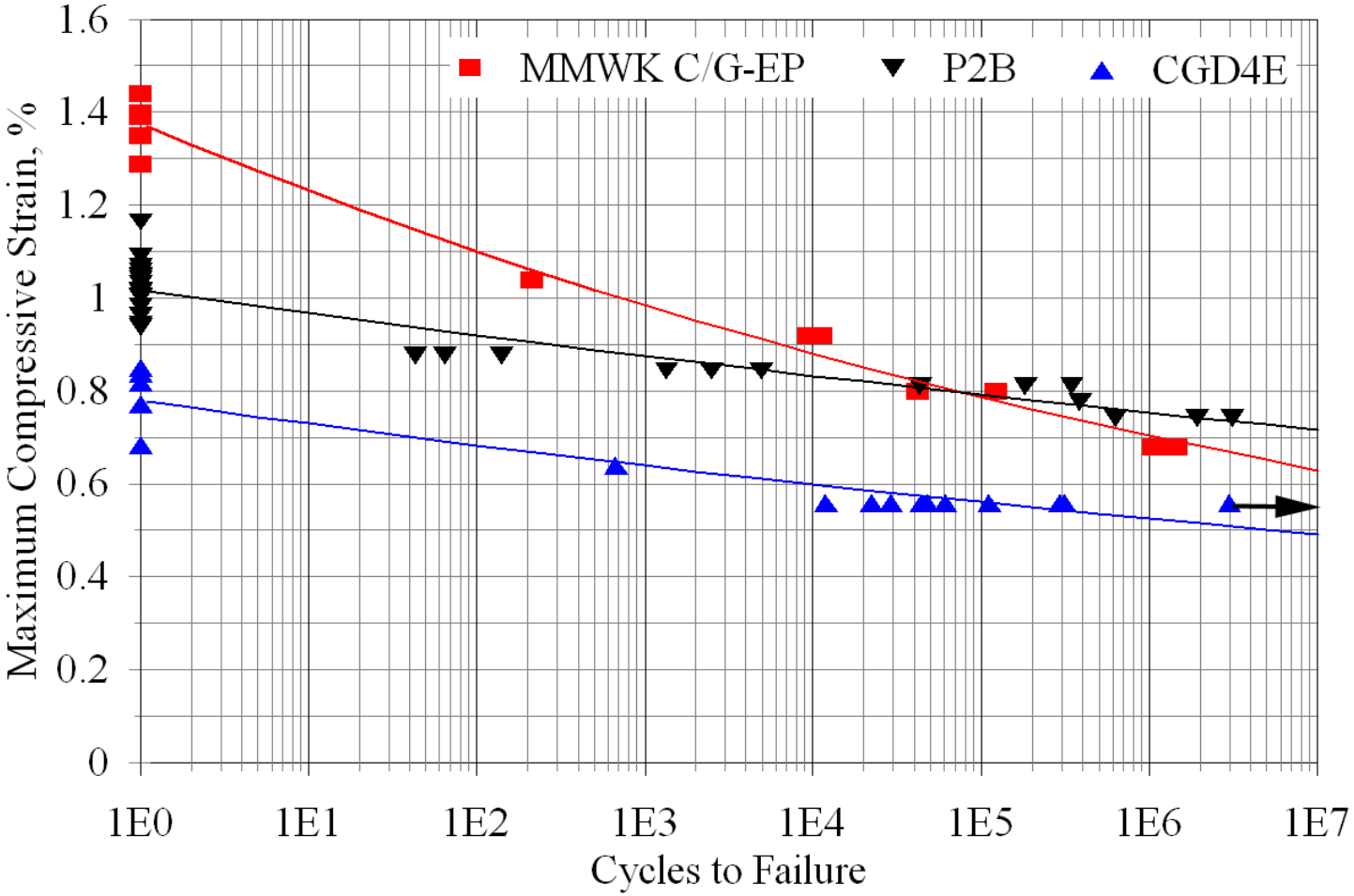


Cracking in ±45° plies of material QQ2 specimen prior to total failure (7).



Material QQ4 Material TT

Comparison of cross-section views of laminates QQ4 (fabric C), and TT (fabric D) (8).



Comparison of compressive fatigue resistance of hybrid laminates with carbon 0° plies and E-glass ±45° plies: materials P2B (prepreg); MMWK C/G-EP (infused stitched hybrid triaxial fabric); and CGD4E (VARTM stitched fabrics), R = 10.

Process-Property Interactions

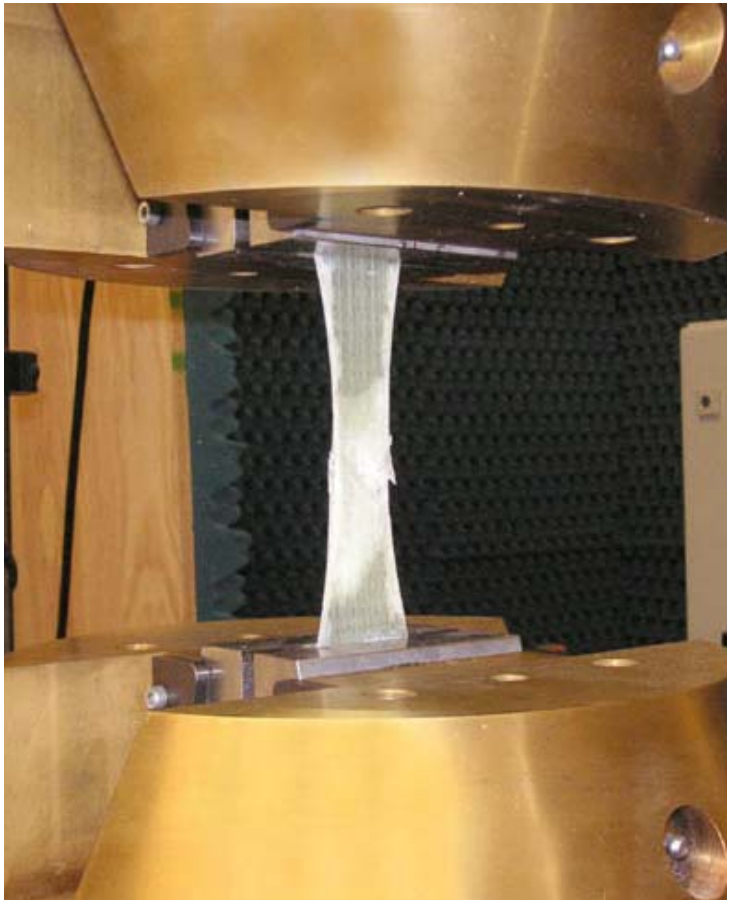
- PhD student Tiok Agastra/ Doug Cairns
- Process modeling based on ANSYS FLOTRAN and CFX, and 3-D fully coupled thermal/reaction kinetics/fluid infusion modeling based on COMSOL
- Application to current strength and fatigue issues
  - Wet-out and porosity, local and global fiber content, cure level, post curing, heat transfer interaction with mold, fabrics and epoxies of current interest
  - Local strand distortion and compaction/strand wet-out modeling, in-plane vs. through-thickness flow
  - Residual stresses and cure shrinkage including local effects at ply drops, etc.

Summary

Tensile Fatigue:
Carbon: very resistant in fiber direction
Glass: less resistant, depends on fabric details, processing

Compression:
Critical for carbon; fiber alignment, Waviness

Processing: Infused laminates approach prepreg for best glass and carbon fabrics



Ply Drops:
Thickness of material build-up; carbon more sensitive than glass