2004 SANDIA BLADE WORKSHOP

MATERIALS CHARACTERIZATION

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FATIGUE PROGRAM APPROACH

FATIGUE DATABASE: Characterize Static and Fatigue Properties

- Testing Equipment and Test Methodology
- Industry Materials and MSU fabricated materials
- Variation of Materials Parameters:
  - Fiber Type, Fabric, Resin, Manufacturing Method, etc.
- Effects of Flaws and Environment

SUBSTRUCTURE STUDIES: Demonstrate/Validate Materials Performance in Blade-Type Substructure

- Fabricate and Test Generic Substructure Geometries (Skins, Stiffeners, I-Beam, Sandwich Panels, Ply Drops, Flaws)
- Validate Finite Element Code Predictions
- Develop Methodologies for Delamination Resistant Designs
- Conducted in Coordination with Manufacturing Studies

DOE/MSU FATIGUE DATABASE

- Materials Properties (1989 to present)
  - 27 Commercial Materials
  - 150+ MSU Materials
  - European Materials
  - 9000+ Tests
- Updates (SNL Website)
  - Last update February 2003
  - Next update February 2004

NEW HIGHER FORCE CAPACITY TESTING MACHINE

INSTRON 8802

+/- 250 kN Capacity (+/- 50K Lbs)

+/- 75 mm stroke

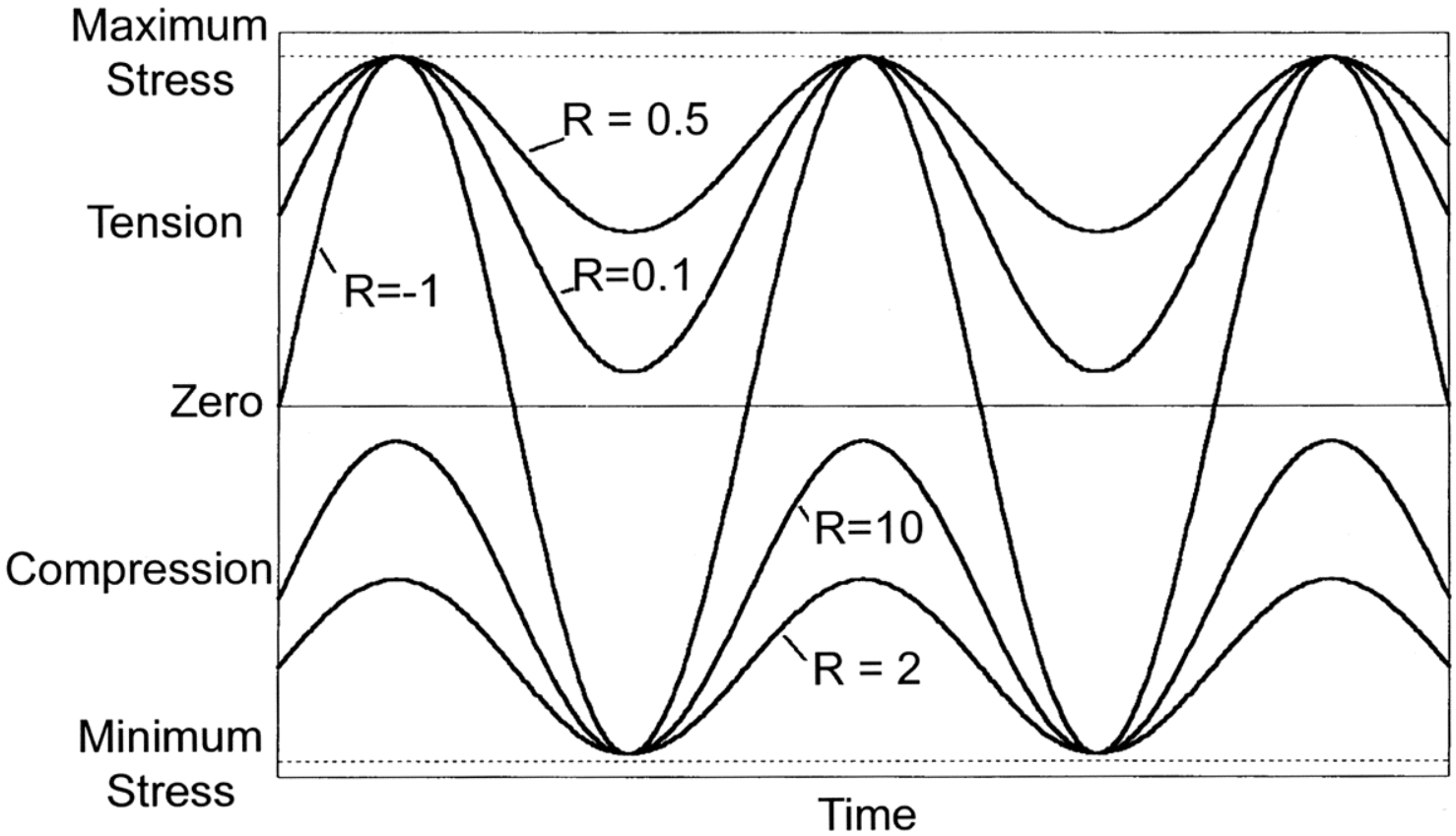
Spectrum Loading Capability

JUSTIFICATION: Needed for higher force levels typical of carbon fiber materials and thick laminates

Elastic Constants for Glass and Large Tow Carbon Unidirectional Fabrics

			Longitudinal Direction									Transverse Direction			
			Elastic Constants				Tension		Compression		Shear	Tension		Compression	
Fabric	lay-up	V_F %	E_L GPa	E_T GPa	υ_{LT}	G_{LT} GPa	UTS_L MPa	ϵ_U %	UCS_L MPa	ϵ_U %	τ_{TU} MPa	UTS_T MPa	ϵ_U %	UCS_T MPa	ϵ_U %
A130 Glass	$[0]_8$	45	36.3	8.76	0.32	3.48	858	2.53	-334	-0.92	85.3	33.8	0.39	-93.3	-1.05
D155	$[0]_6$	45	35.0	8.99	0.31	4.10	987	2.83	-746	-2.02	97.7	27.2	0.32	-123	-1.67
UNI25	[0]	45	89.7	6.80	0.27	----	1213	1.35	-535	-0.60	--	20.5	0.31	-100	-1.47

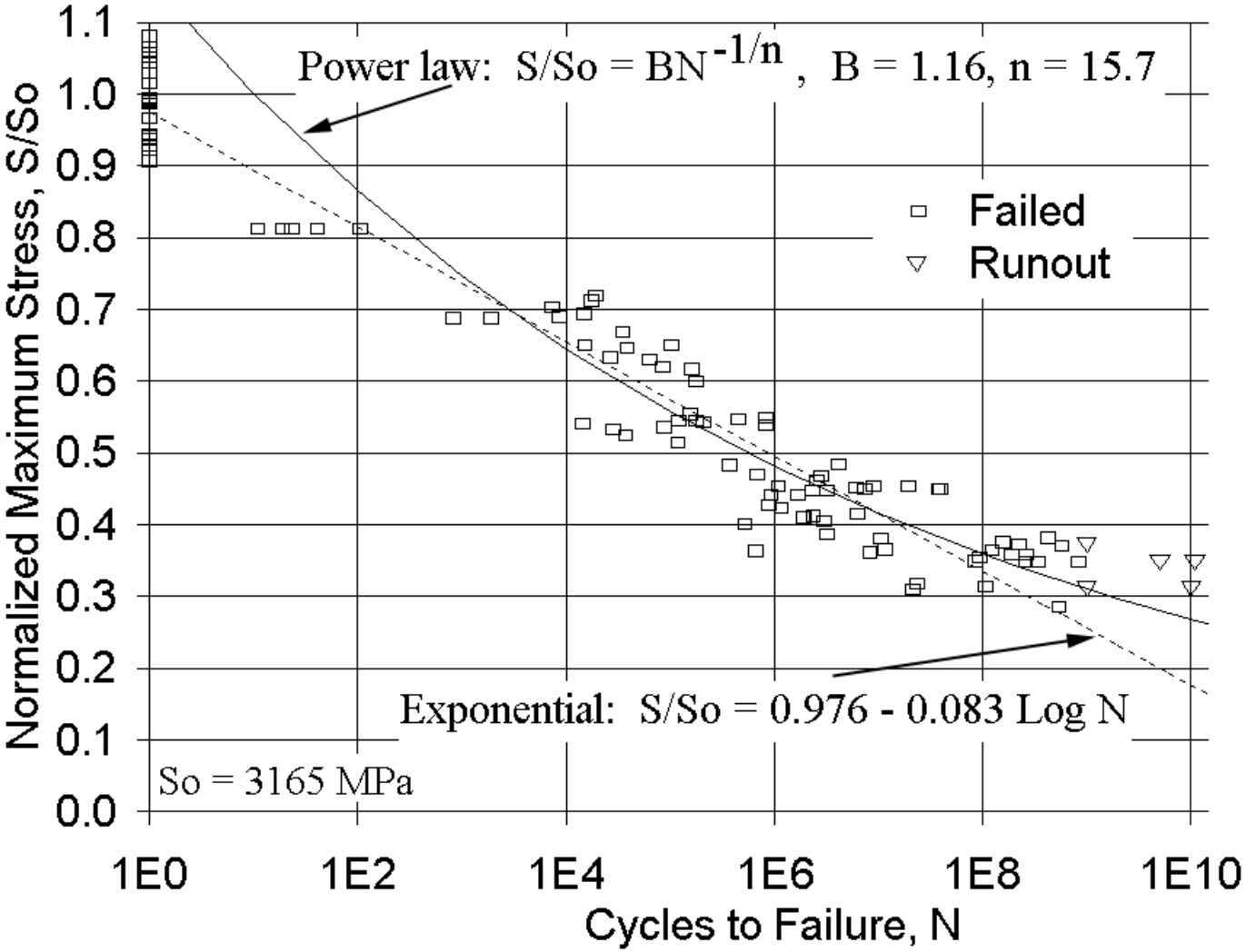
* See Database for testing details.

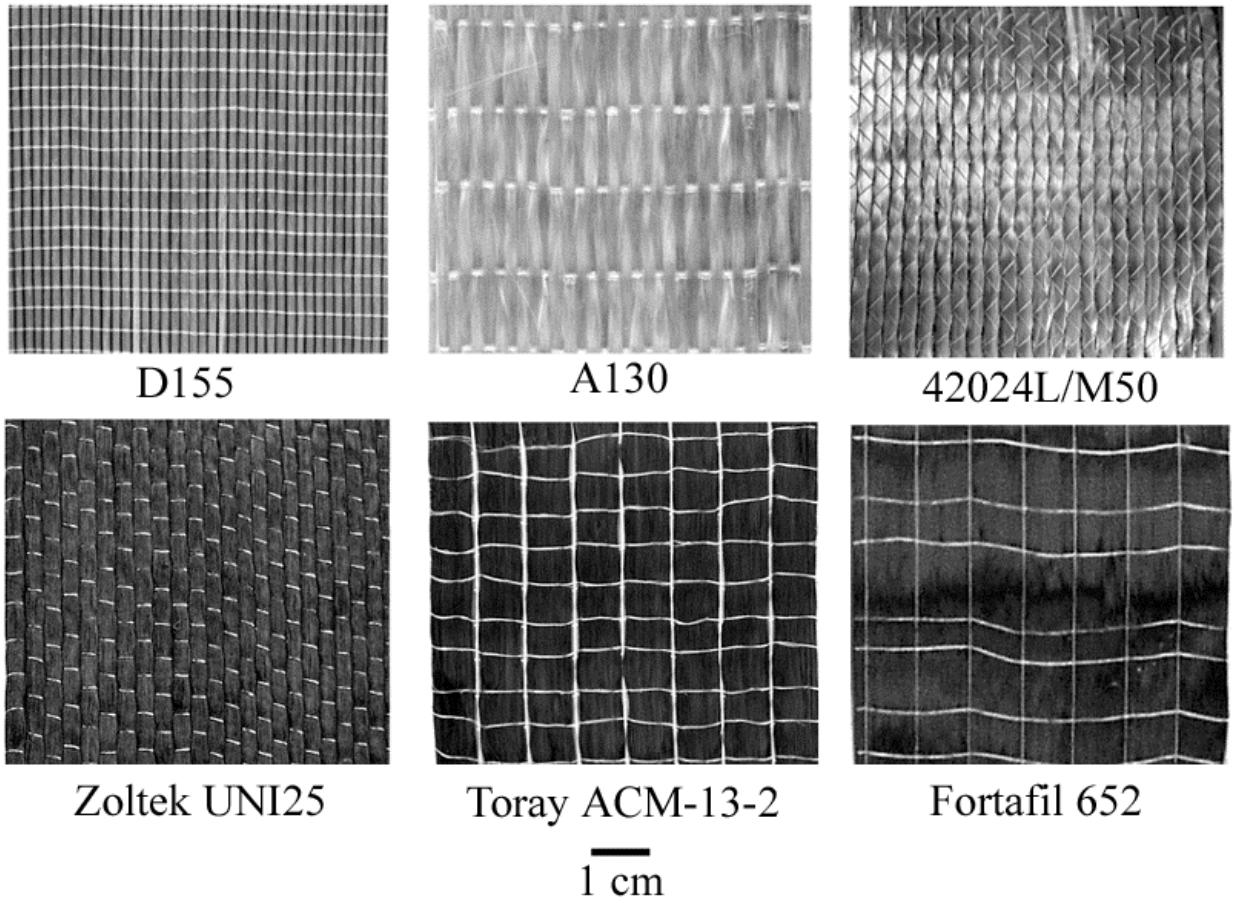


Constant Stress Amplitude Sine Waveforms for Different R-Values

R-Value = (Minimum Stress / Maximum Stress)

SPECIALIZED HIGH CYCLE STRAND TESTS TO VALIDATE HIGH CYCLE EXTRAPOLATION MODEL





Glass (top) and Carbon Fabrics Used in This Study.

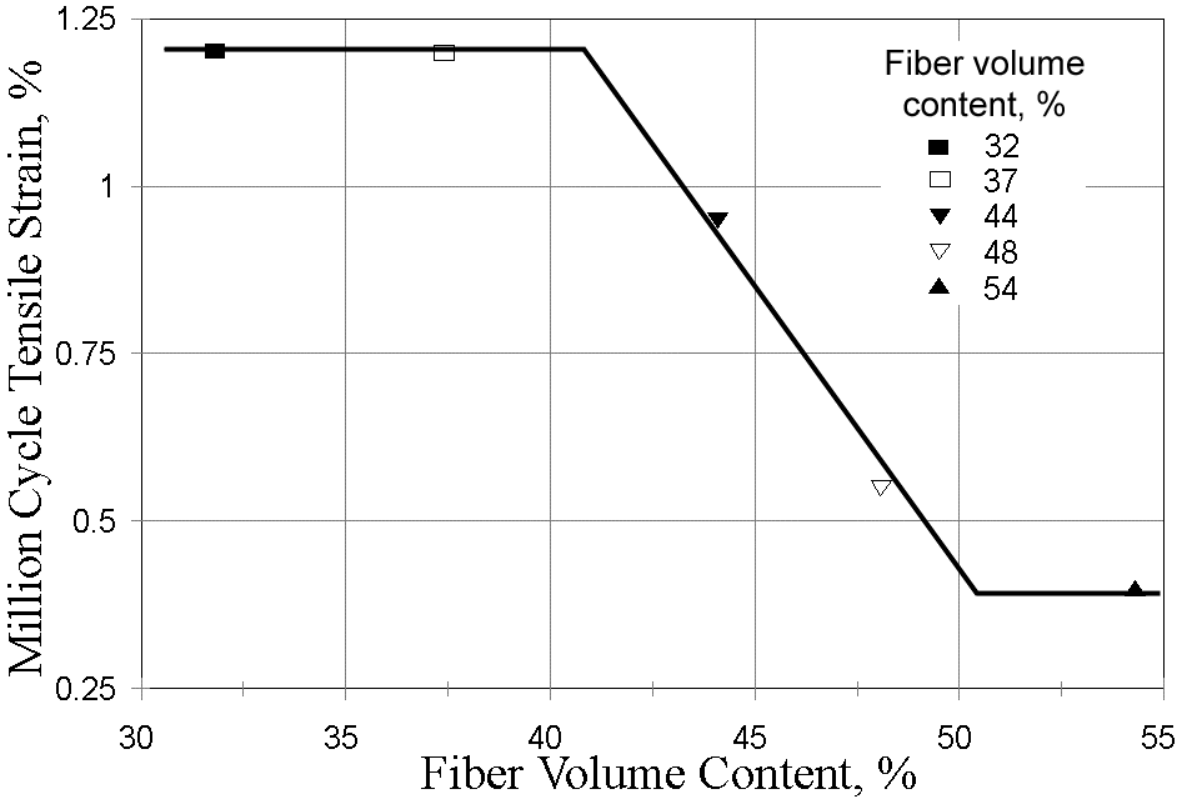
DATABASE TRENDS

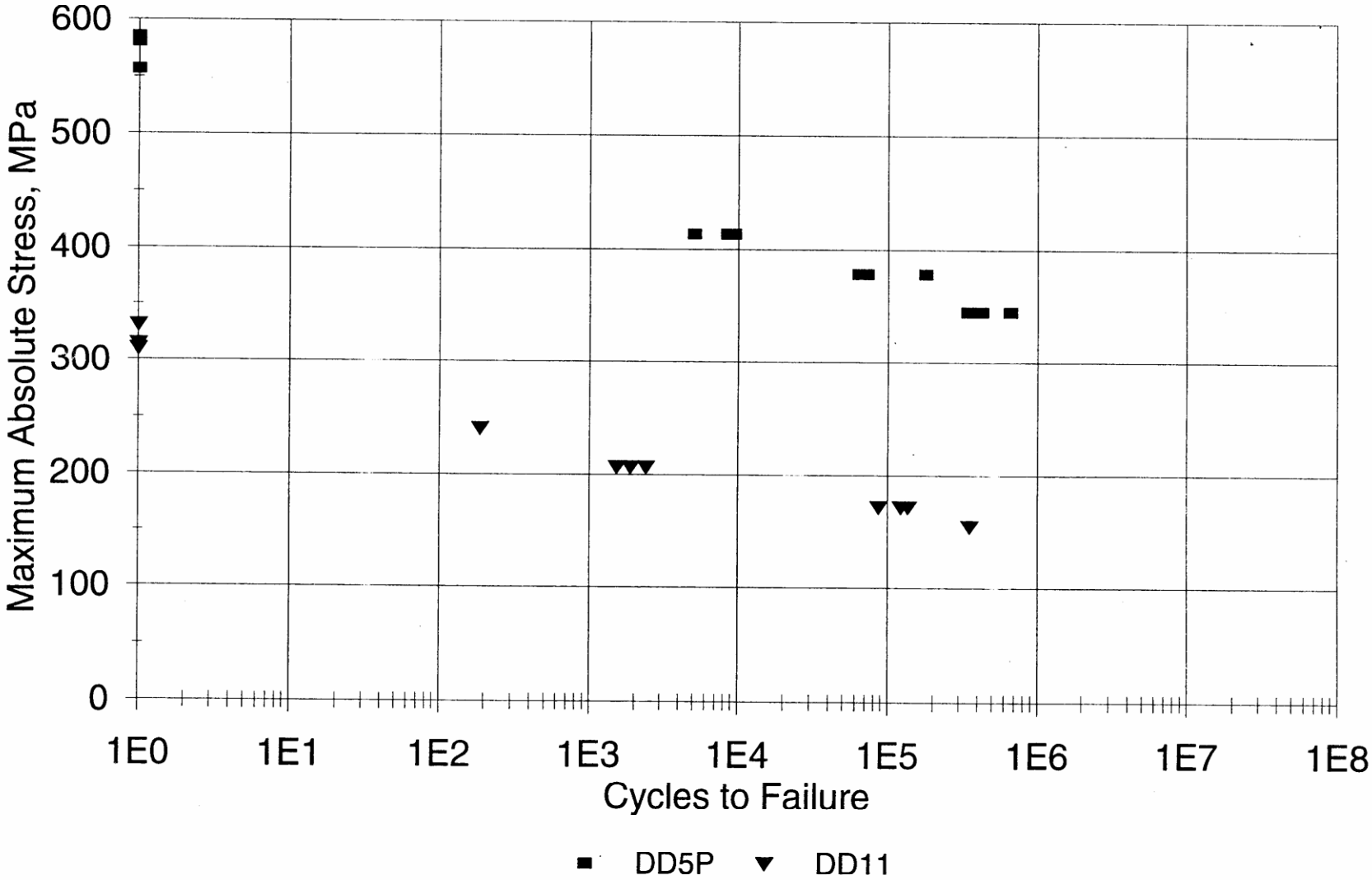
- Tension (with some 0° fibers)
  - UTS dominated by V_f, % 0° fibers
  - Fatigue
    - Carbon: excellent
    - Glass: fatigue sensitive, V_f and fabric details important
    - Resin, Environment: not very important

Database Trends

- Compression (with some 0° fibers)
  - Resin dominated, fiber straightness and porosity important
  - Static: Fabrics with fiber waviness and low modulus resins (hot/wet) reduce UCS
    - **Glass: Max ultimate strain 2.0-2.4% (prepreg and straight fiber fabrics)**
    - **Carbon: Max ultimate strain 1.0-1.2% (prepreg)**
  - Fatigue: Low to moderate sensitivity, dominated by static UCS effects. (Carbon may be better than glass due to lower strains)

Tensile Fatigue Sensitivity of Stranded Glass Fabric Laminates $[0/\pm45/0]_S$, 70% 0 - Degree





Compression Fatigue Data for Materials DD5P (D155 fabric, straight fibers) and DD11 (A130 fabric, woven strands)

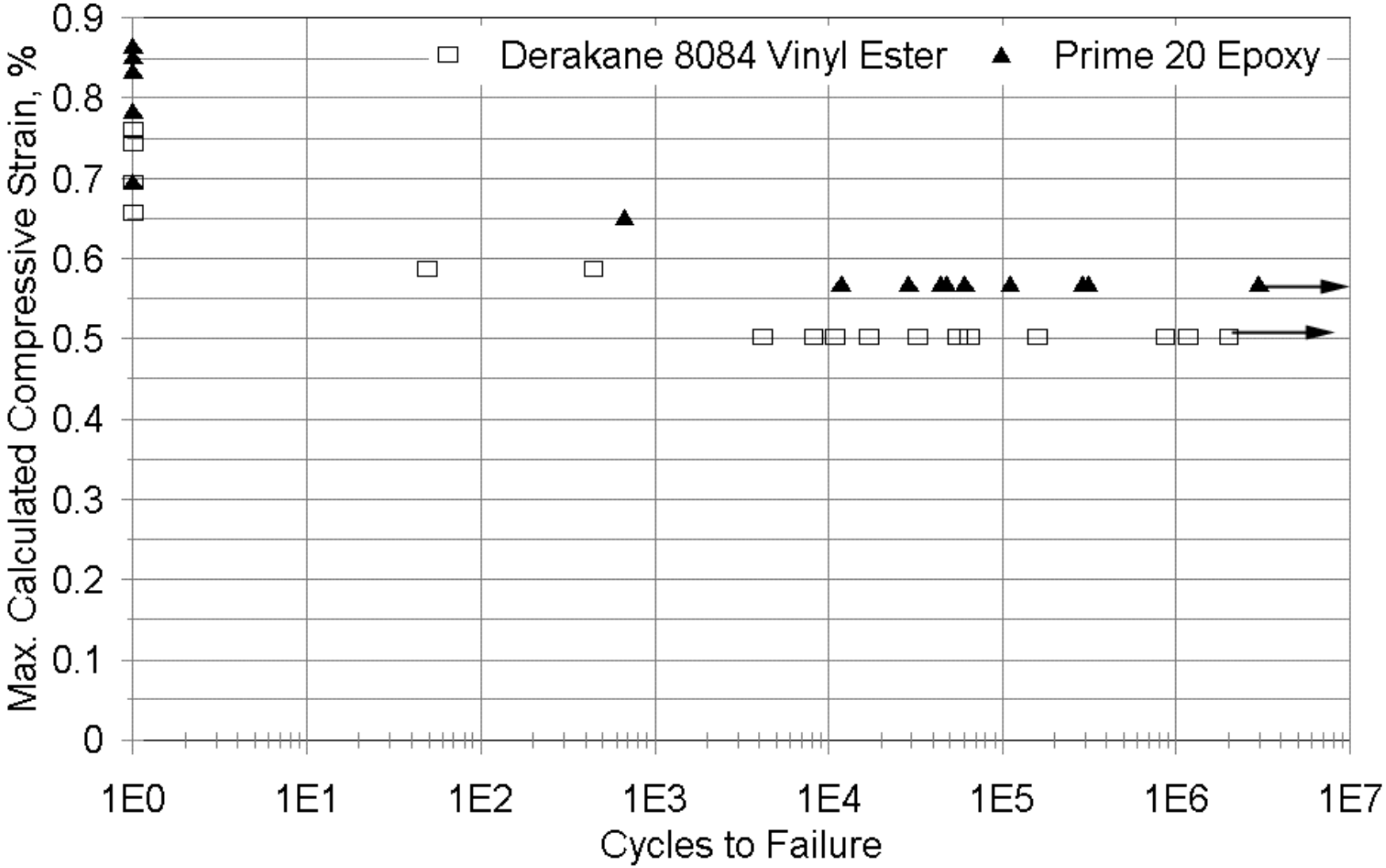
CARBON FIBER AND HYBRID LAMINATES

- Database static results for nine materials; prepreg, RTM, hand lay-up (Fatigue for three materials)

ISSUE: Compressive Strain to Failure

Current Research on Carbon Materials

- Test Methodologies
- Effect of resin
- Effect of fiber misalignment
- Effect of structural details and flaws (ply drops and joints)
- Starting major test series on fatigue
    - Constant amplitude, many R-values
    - Goodman Diagram
    - Spectrum loading



Hybrid Compression Fatigue Data for Vinyl Ester and Epoxy Matrices, Material CGD4 with a ply Configuration ($\pm45_G/0_{3C}/\pm45_G$), 0° Fabric is Toray ACM-13 Carbon and $\pm45^O$ Fabric is DB120 Glass, 76 Percent 0° Material by Volume, R = 10.

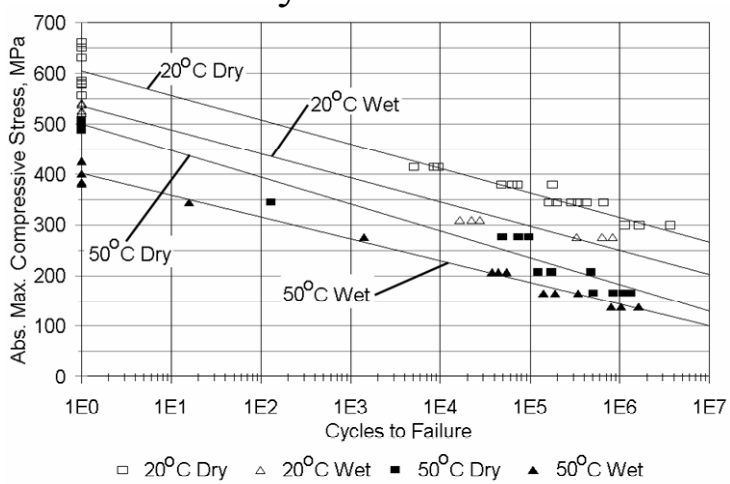
ENVIRONMENTAL EFFECTS

Hot/Wet Compressive Strength with Infusion Resins, Glass Fibers

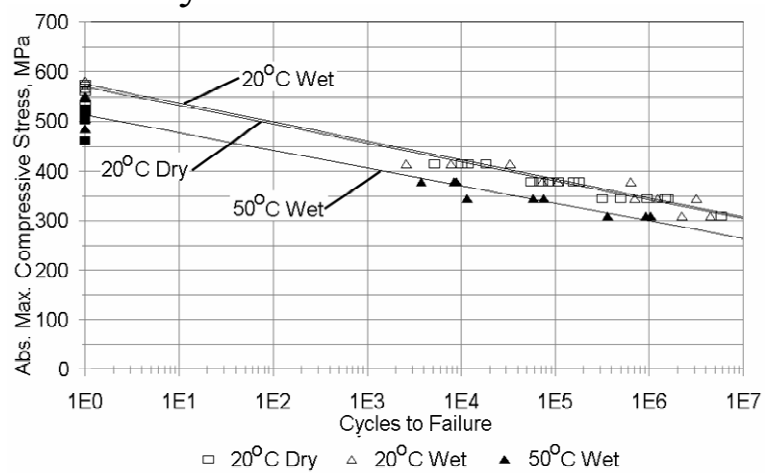
Resin system in $(0/\pm45/0)_S$ Lay-up	0° fabric	Moisture pick-up, %	20°C Dry	20°C Wet	60°C Dry	60°C Wet
Reichhold DION 9800 vinyl ester, 65°C post cure	D155	0.28	591 (42)	570 (27)	566 (34)	599 (22)
SP Systems Prime 20, STD Hardener, epoxy, 65°C post cure	D155	1.24	623 (25)	494 (21)	544 (22)	369 (24)
	A130	1.79	288 (19)	240 (33)	215 (7)	128 (12)
Jeffco 1401-12 resin, 4101-17 hardener, epoxy, 60°C post cure	D155	1.55	623 (44)	512 (32)	553 (14)	331 (48)
	A130	1.72	302 (10)	297 (40)	258 (23)	218 (46)
Specimens conditioned to saturation at 65 °C						

CONCERN:
Infusion Epoxies
at Hot/Wet
Conditions

Ortho Polyester Material DD5P

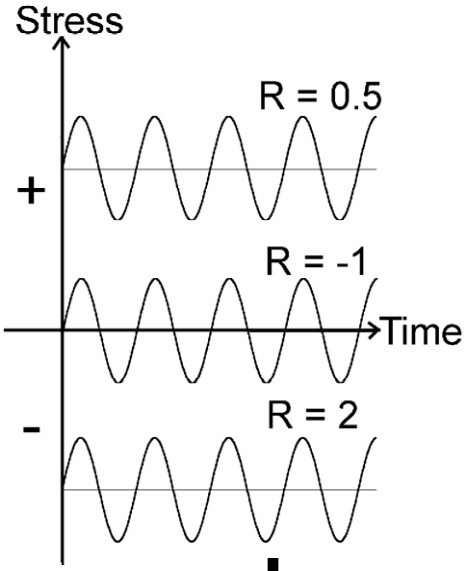


Vinyl ester Material DD5V



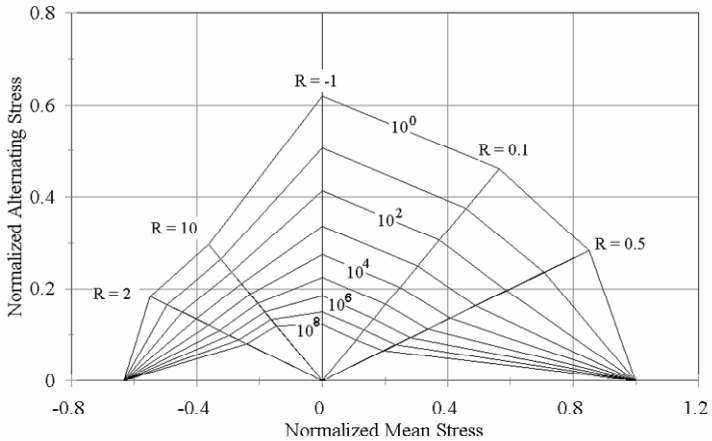
SPECTRUM LOADING APPROACH

CONSTANT AMPLITUDE DATABASE



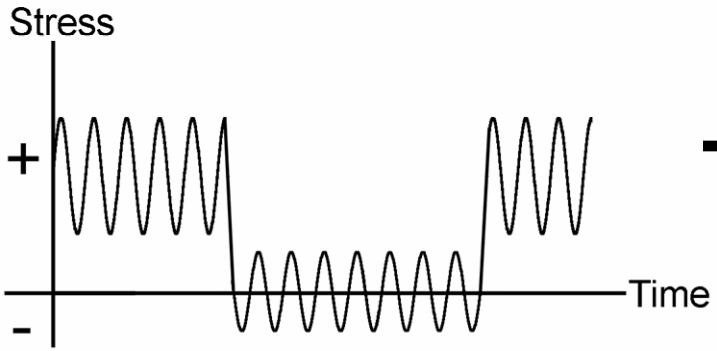
DESIGN/ANALYSIS

GOODMAN DIAGRAM

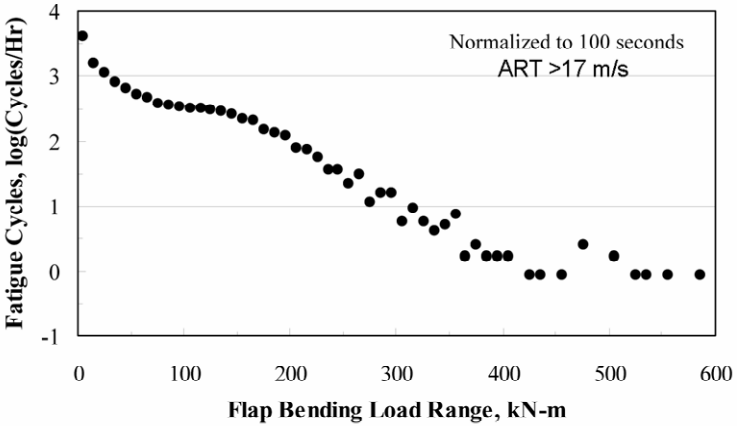


RESEARCH

SIMPLE SPECTRA



BLADE SPECTRUM



LIFETIME AND RESIDUAL STRENGTH DURING SERVICE

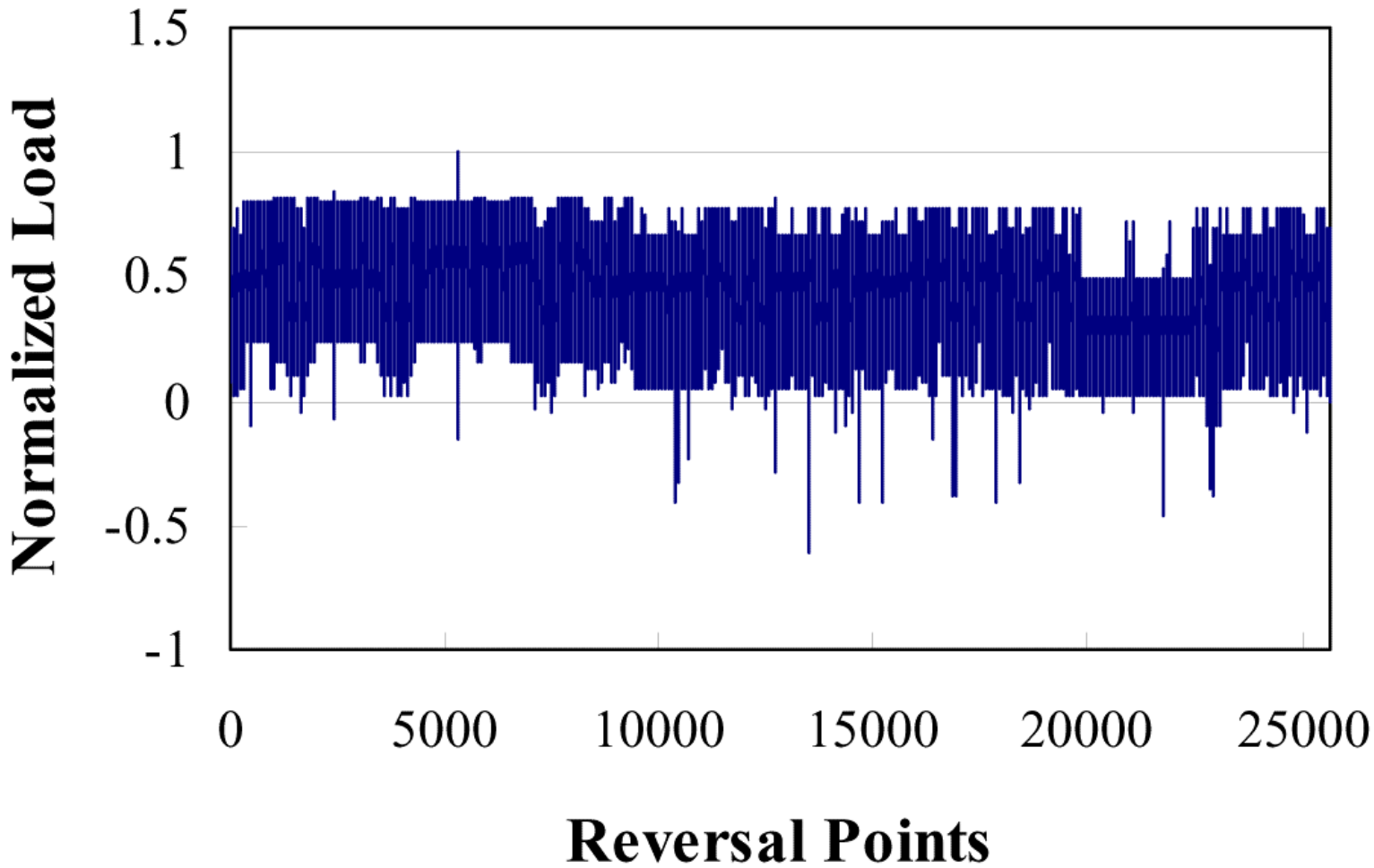
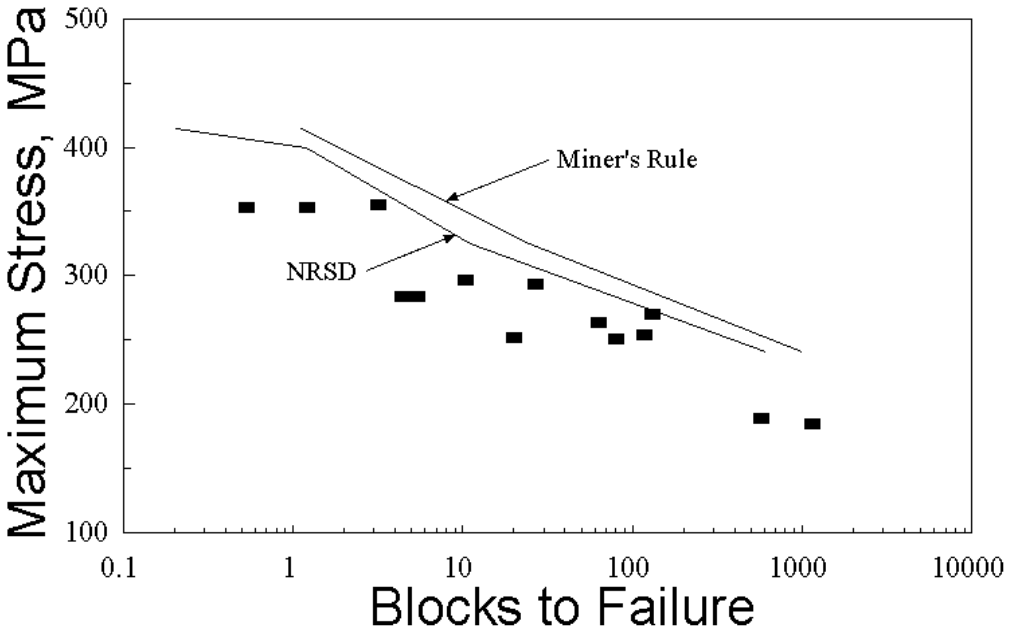


Fig. 6: Normalized WISPERX Specurum

SPECTRUM LOADING
2002 STATUS

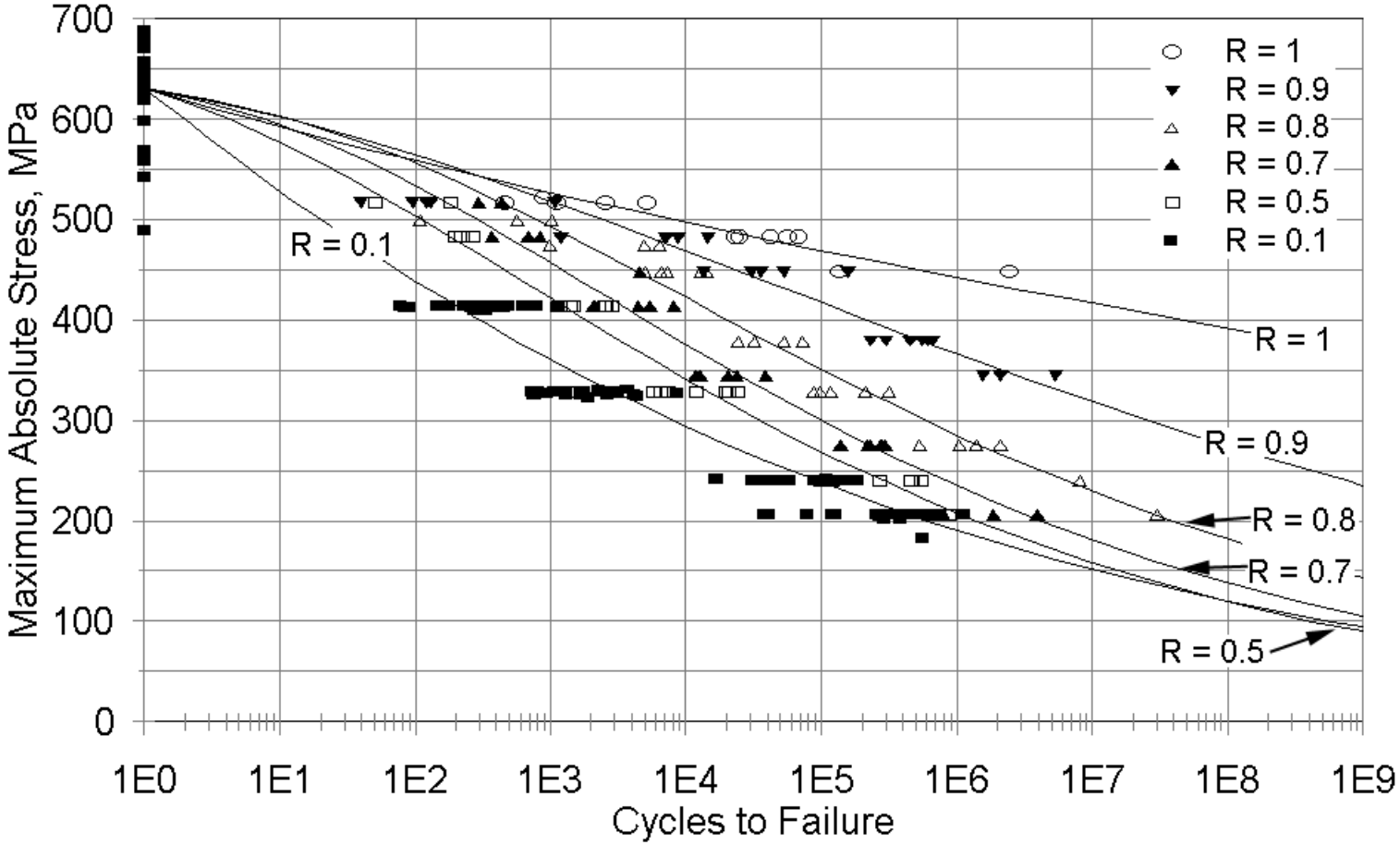
- MSU and European Lifetime Predictions often Non-Conservative by Factor of Ten for WISPER Testing

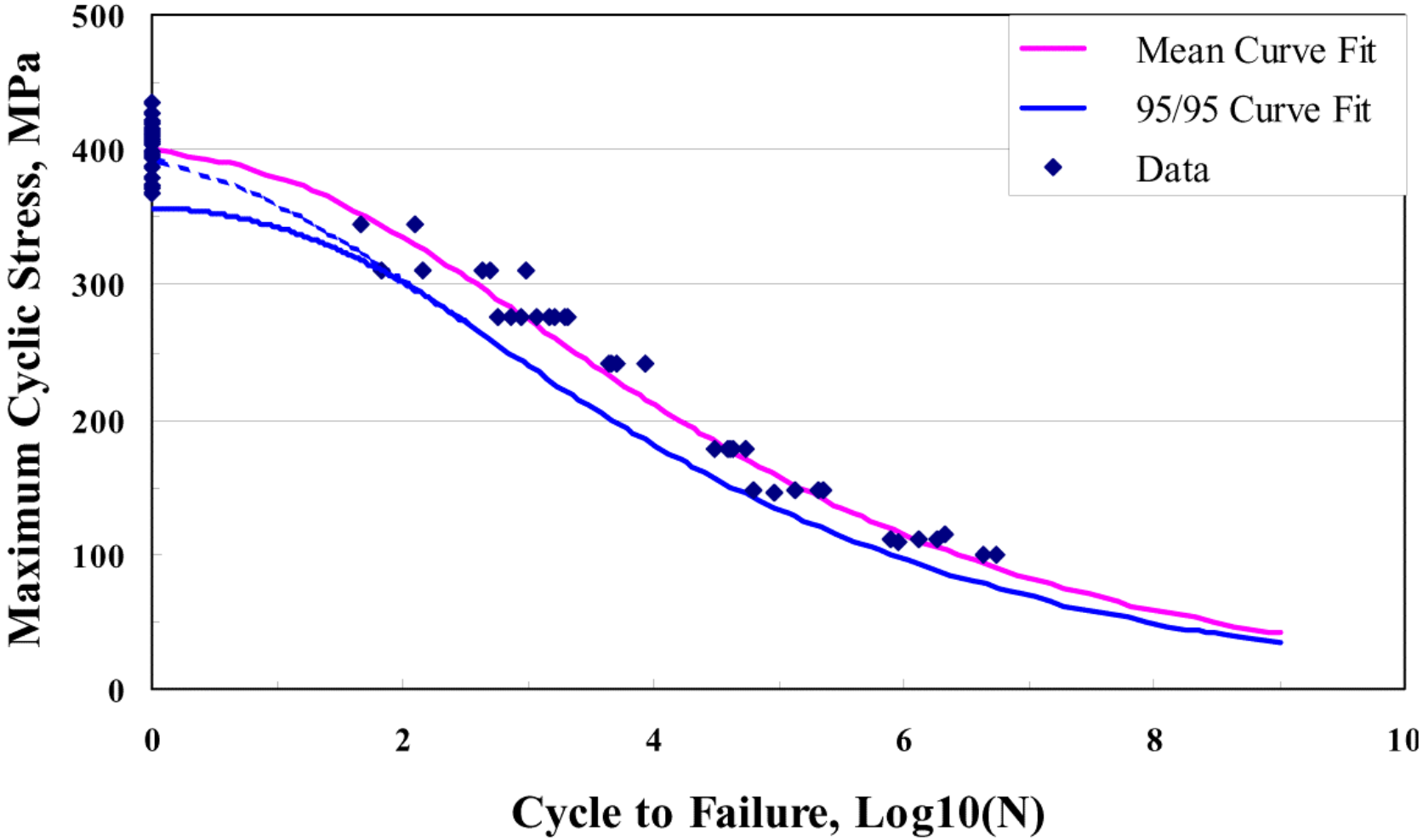


WISPERX Spectrum Lifetime Predictions vs. Experimental Data

TYPICAL STANDARD COUPON CONSTANT AMPLITUDE DATA TO 10^6 – 10^7 CYCLES

THREE – PARAMETER MODEL

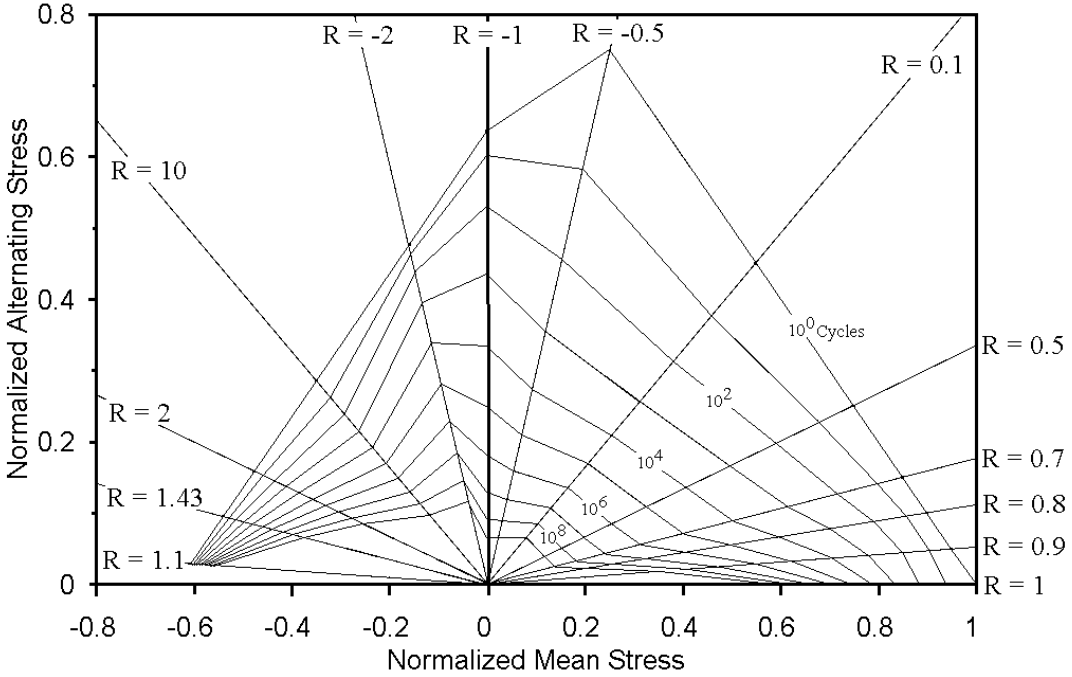




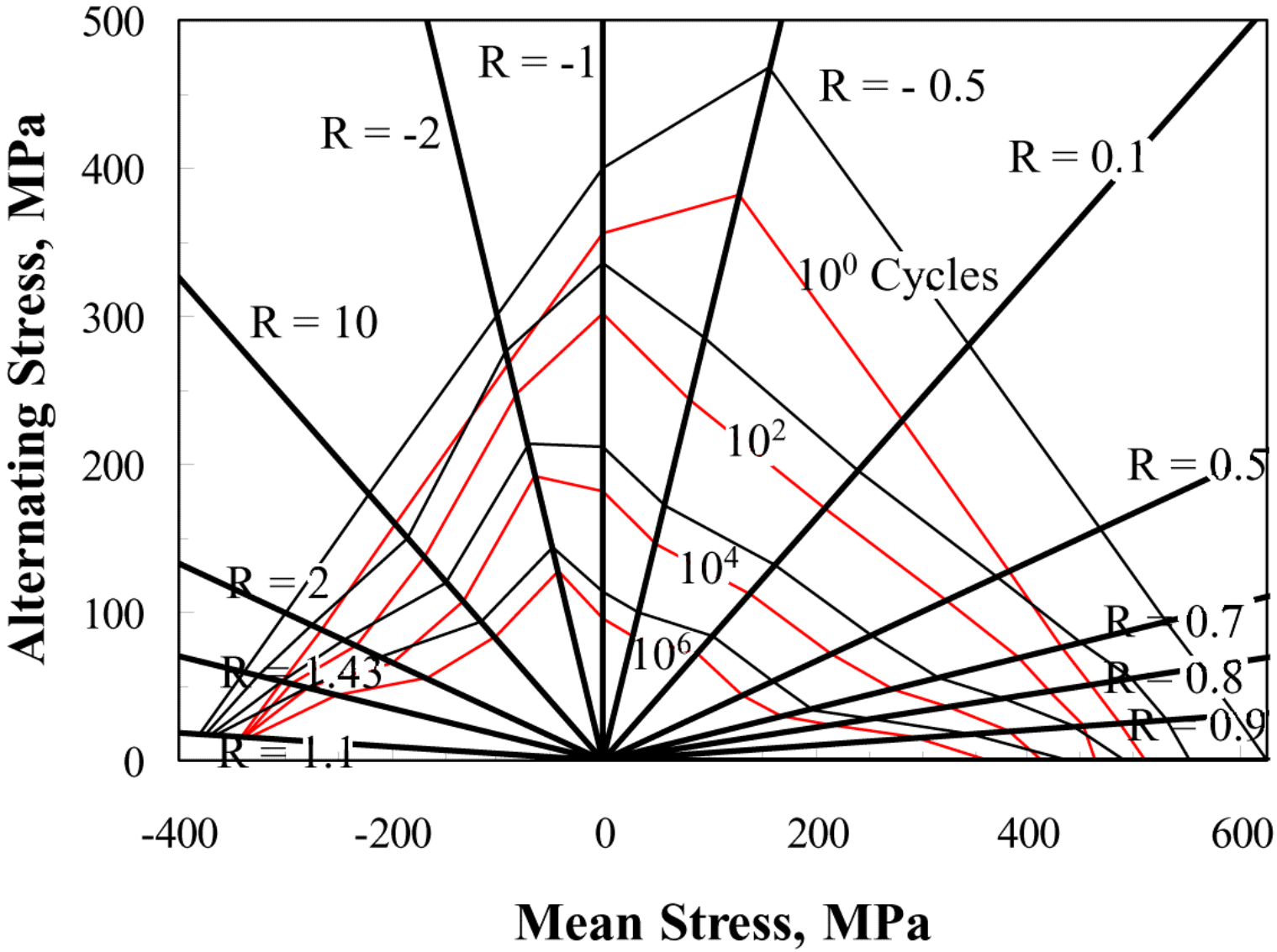
Data for Material DD16, R = -1

Current Applications of More Accurate Goodman Diagram with H. Sutherland

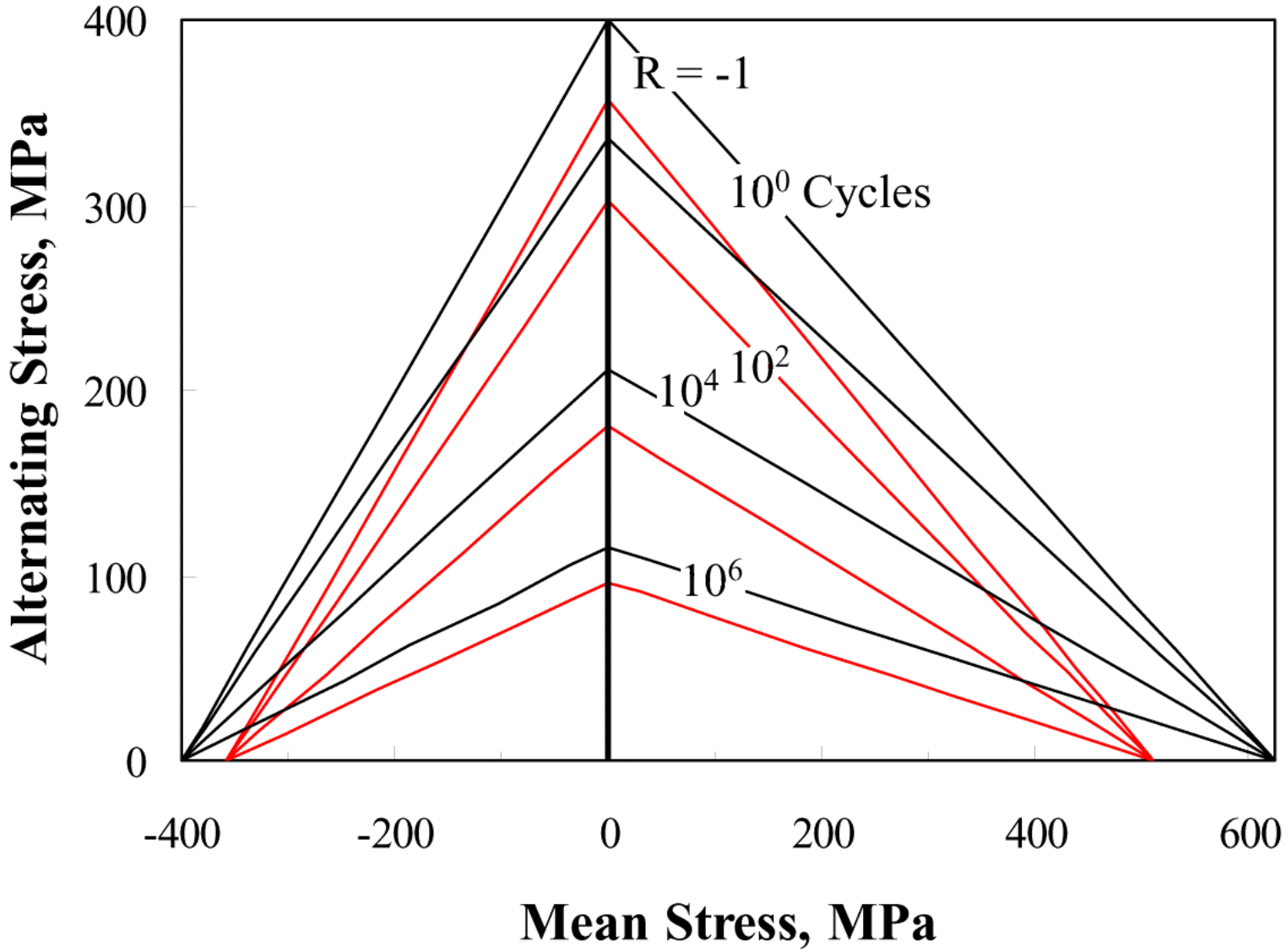
- Explore mean stress effects on lifetime prediction for LIST turbine data
- New prediction of WISPERX data
- Incorporate 95/95 statistics



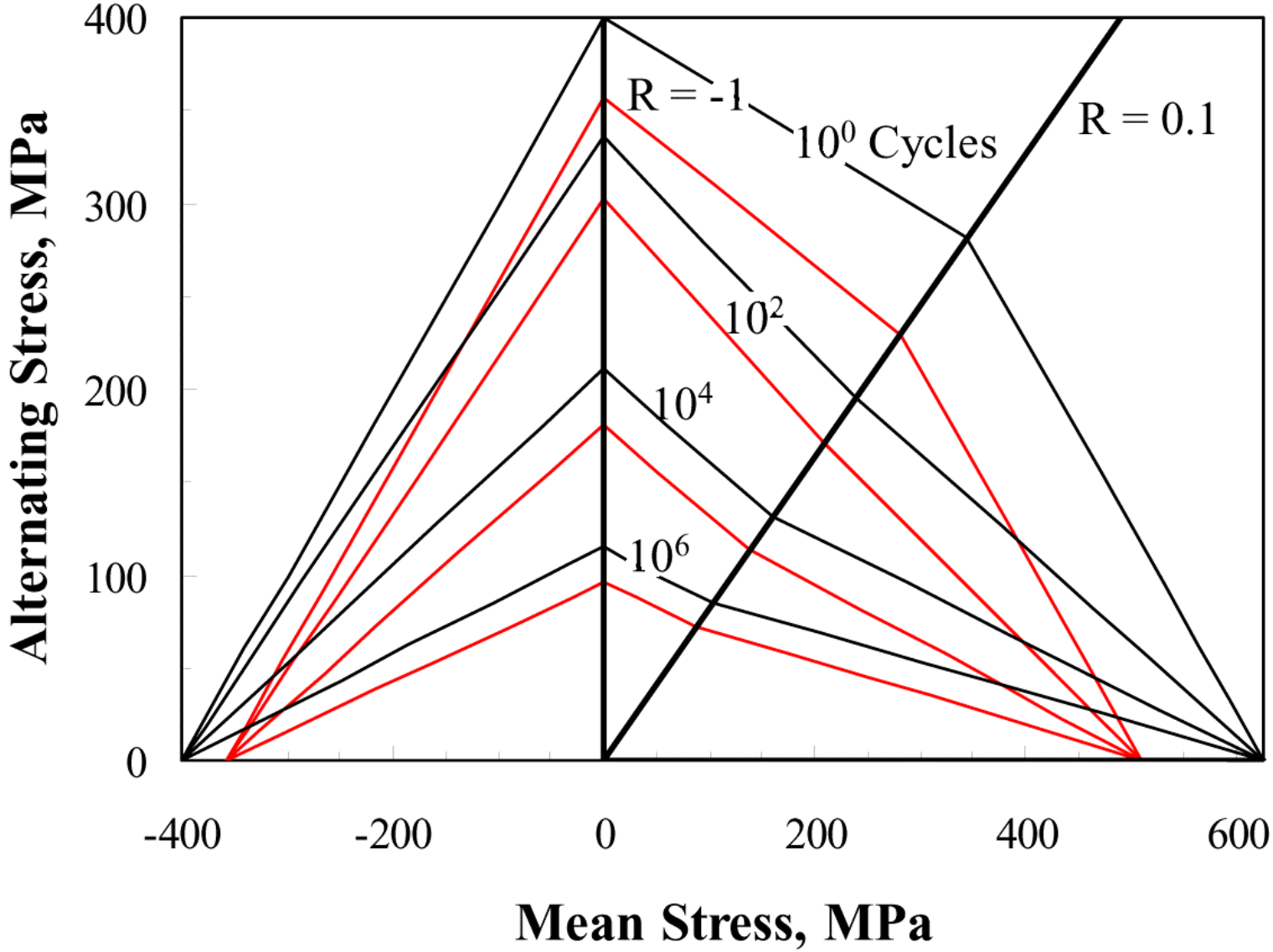
Goodman Diagram for Database Material DD16



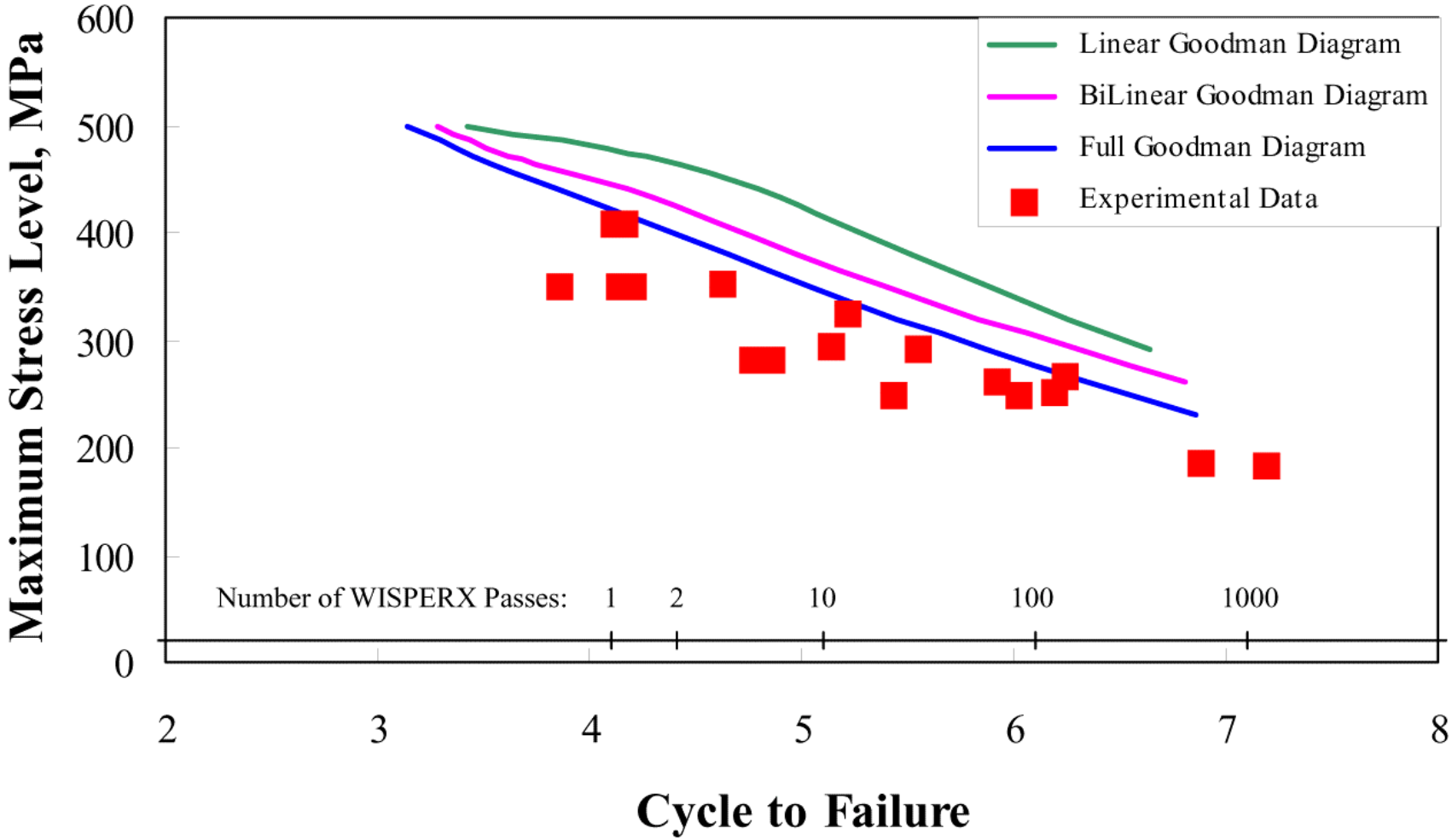
MSU/DoE Goodman Diagram for Thirteen R-Values
Comparison of Mean and 95/95 Goodman Diagrams



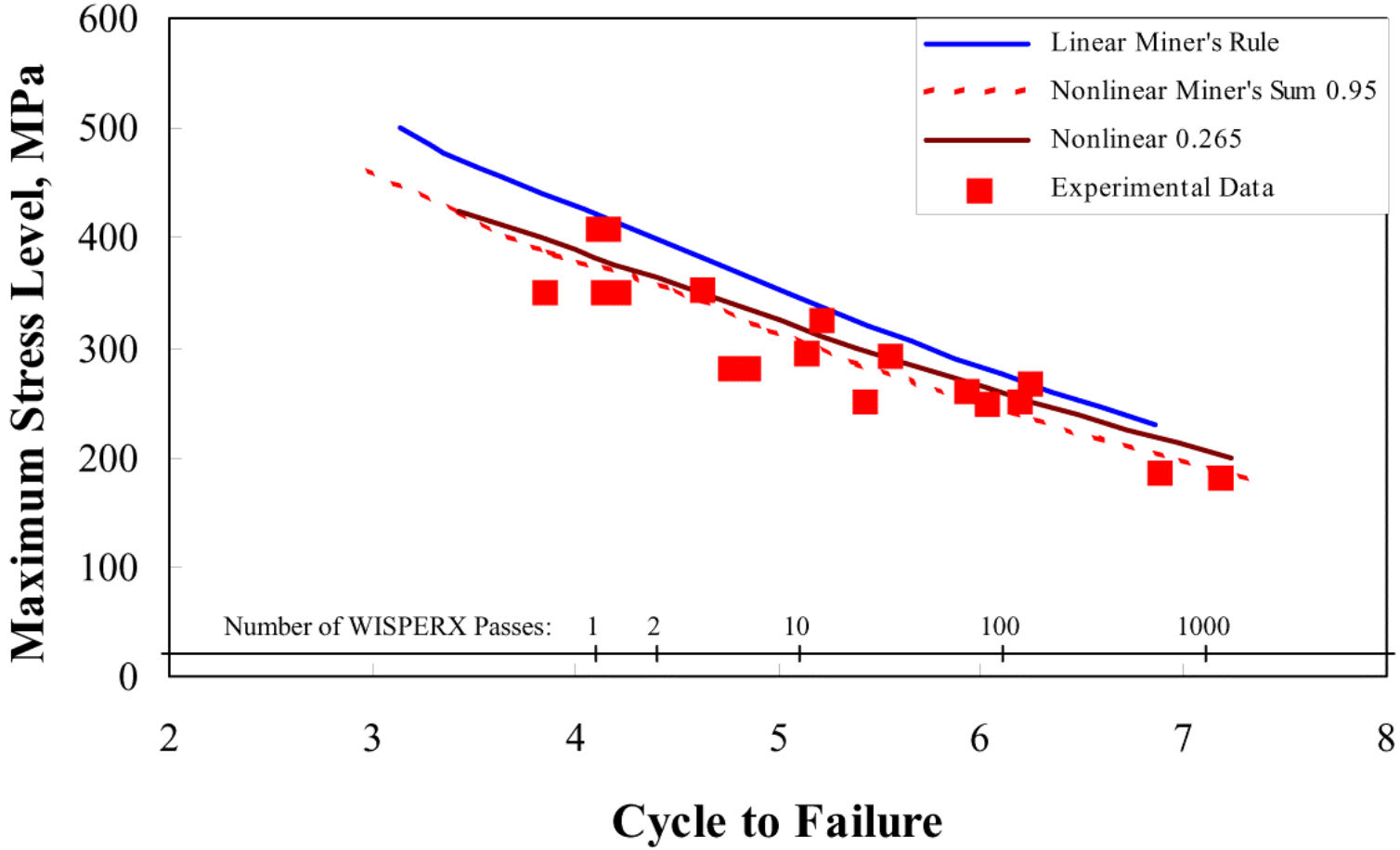
Linear Goodman Diagram



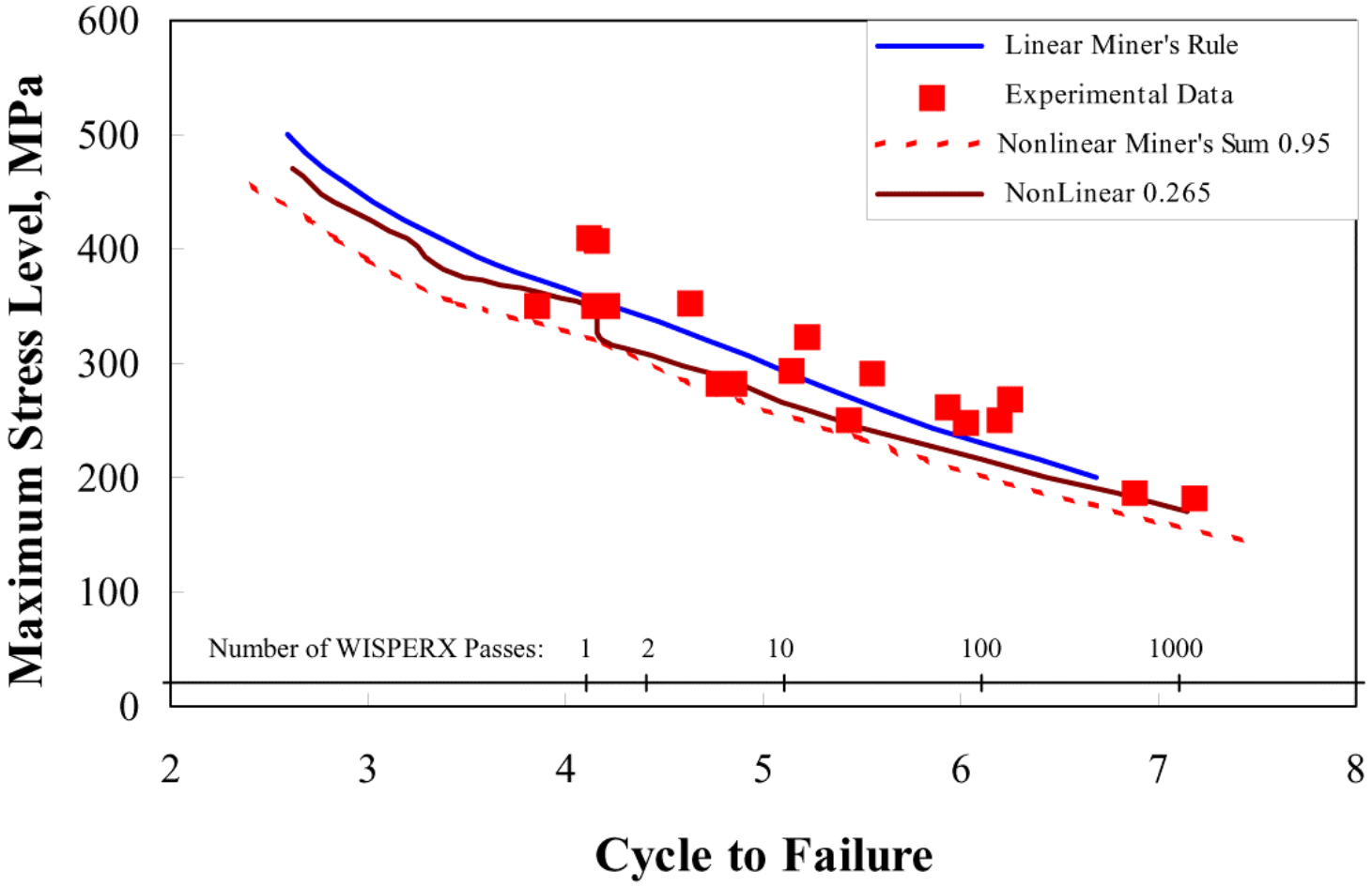
Bi-Linear Goodman Diagram



Prediction of WISPERX Data Using Mean Goodman Diagrams, Miner's Sum



Comparison of Experimental Data to Predicted Failure using Non-Linear Miner's Sum and Residual Strength Models



95/95 Goodman Diagram Predictions

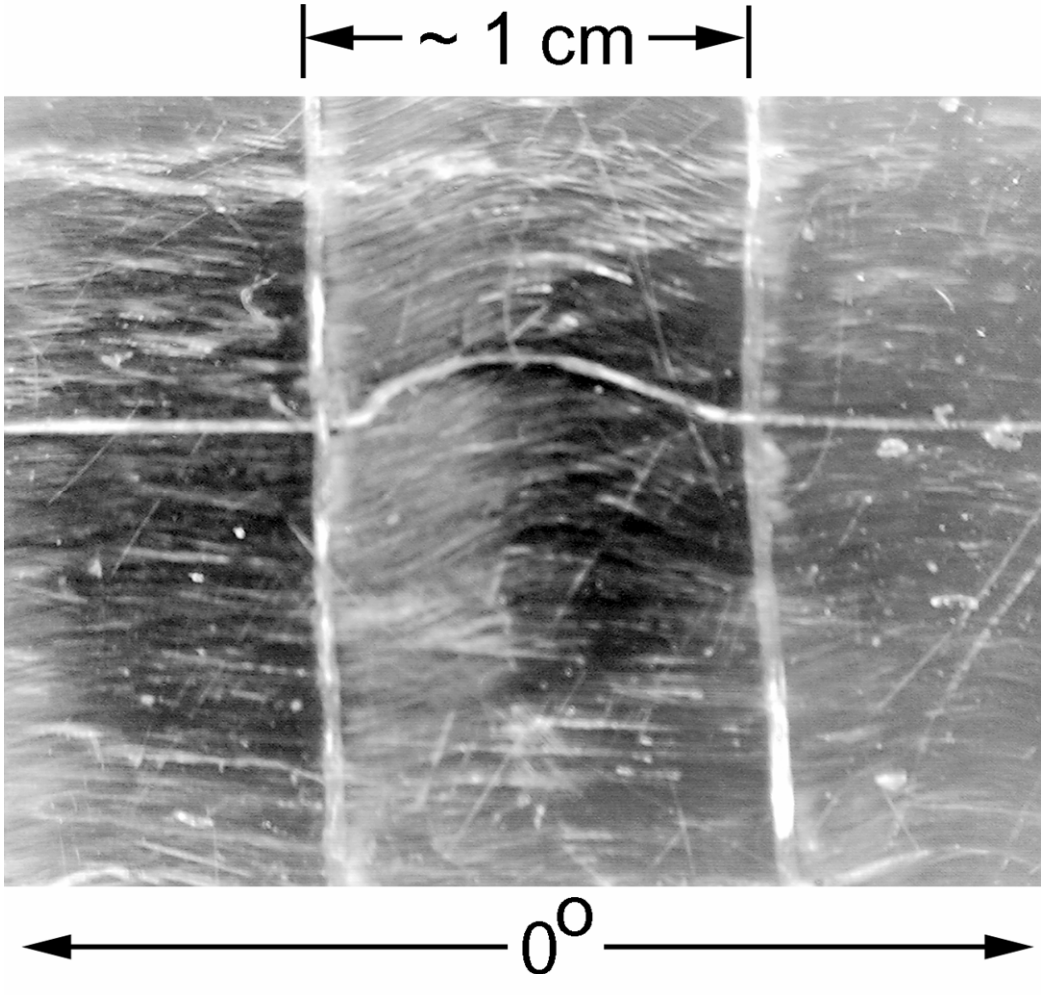
Effects of Fiber Waviness on Compression Strength and Compression Fatigue

Typical Blade Materials: Thick, Heterogeneous Layers

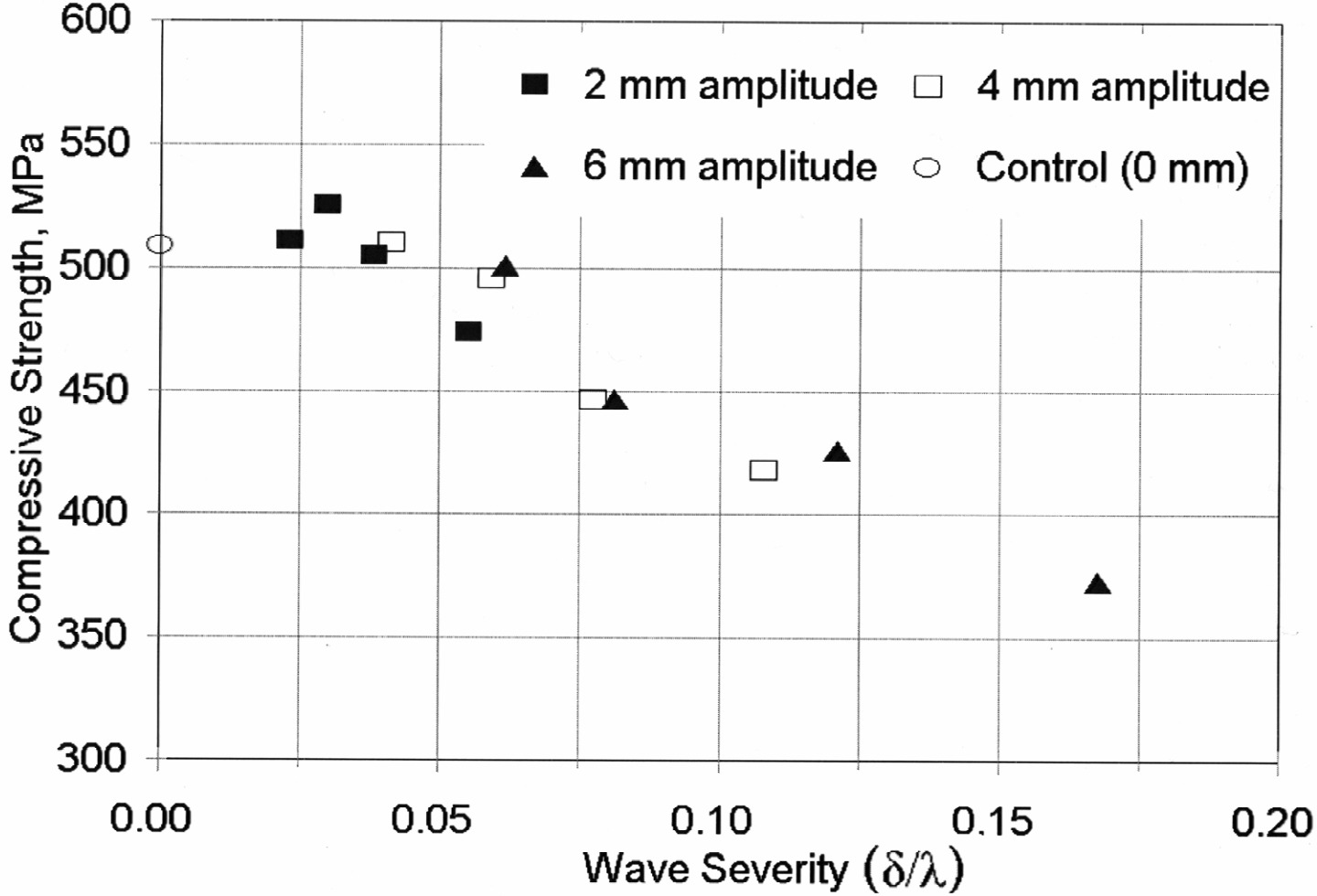
Waviness

In-Plane: Resin Flow, Geometry Changes

Through-Thickness: Fabric Weaves, Ply Drops
and Joints, Flaws, Compaction



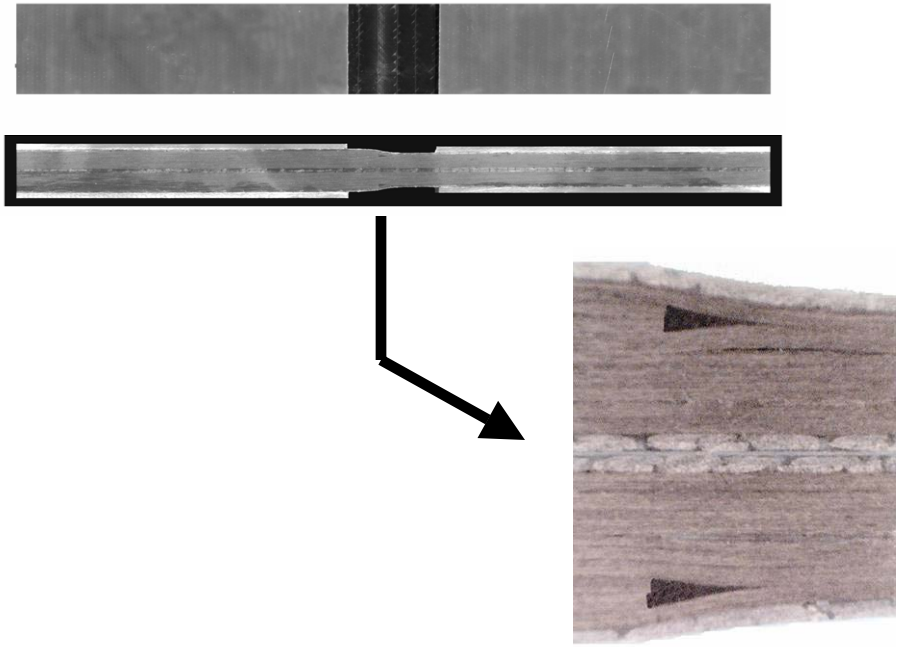
In-Plane Waviness in a Single-Ply Laminate of Fortafil 652 Carbon Fiber/Epoxy Processed by RTM.



Effects of Wave Severity on Compressive Strength; Waviness in a Single Surface Ply of a $[0/\pm45/0]_S$ Laminate.

CARBON FIBER HYBRID LAMINATES WITH PLY DROPS
CARBON FIBER 0'S; GLASS +/- 45'S

Static Compressive Strain to Failure



PREPREG

Control: 0.86%

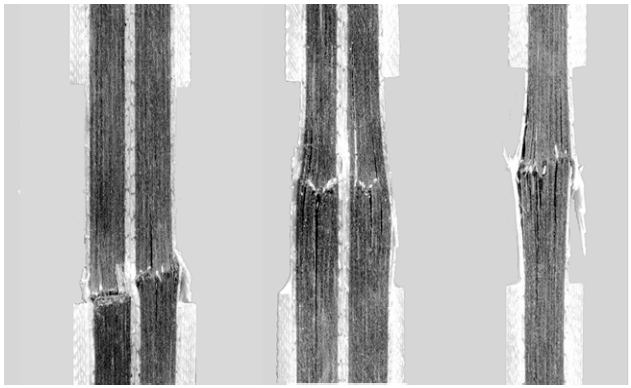
Single ply drop: 0.62, 0.71, 0.72%
(depending upon position)

Double ply drop: 0.44, 0.55%
(depending upon position)

HAND LAY-UP, WOVEN FABRIC (Zoltek UNI25)

Control: 0.78% (epoxy resin),
0.61% (vinyl ester resin)

Single ply drop: 0.67, 0.69%
depending on position (epoxy resin)



- Woven Fabric Architectures Reduce Average Ultimate Compressive Strain by as Much as 50% Compared to Straight Fiber Composites.

- Carbon Fiber Laminate Baseline (Straight Fiber) Compressive Ultimate Strain About Half That for Glass; Waviness is a More Critical Issue.

- Prepreg Carbon with Ply Drops and Joints May Have Acceptable Performance in Compression if Carefully Designed and Fabricated.

- In-Plane Waviness with Glass Fiber laminates Reduces Compressive Properties to a Similar Extent as Off-Axis Laminates at the Same Misorientation Angle.

Size Effects on Properties and Testing

- Generally good correlation between standard coupon properties and substructural elements like beams, and small blades.
- Strain levels much lower in tension for coupons than for strands. Size and testing effects difficult to separate.
- Recent compression data lower for larger test specimens

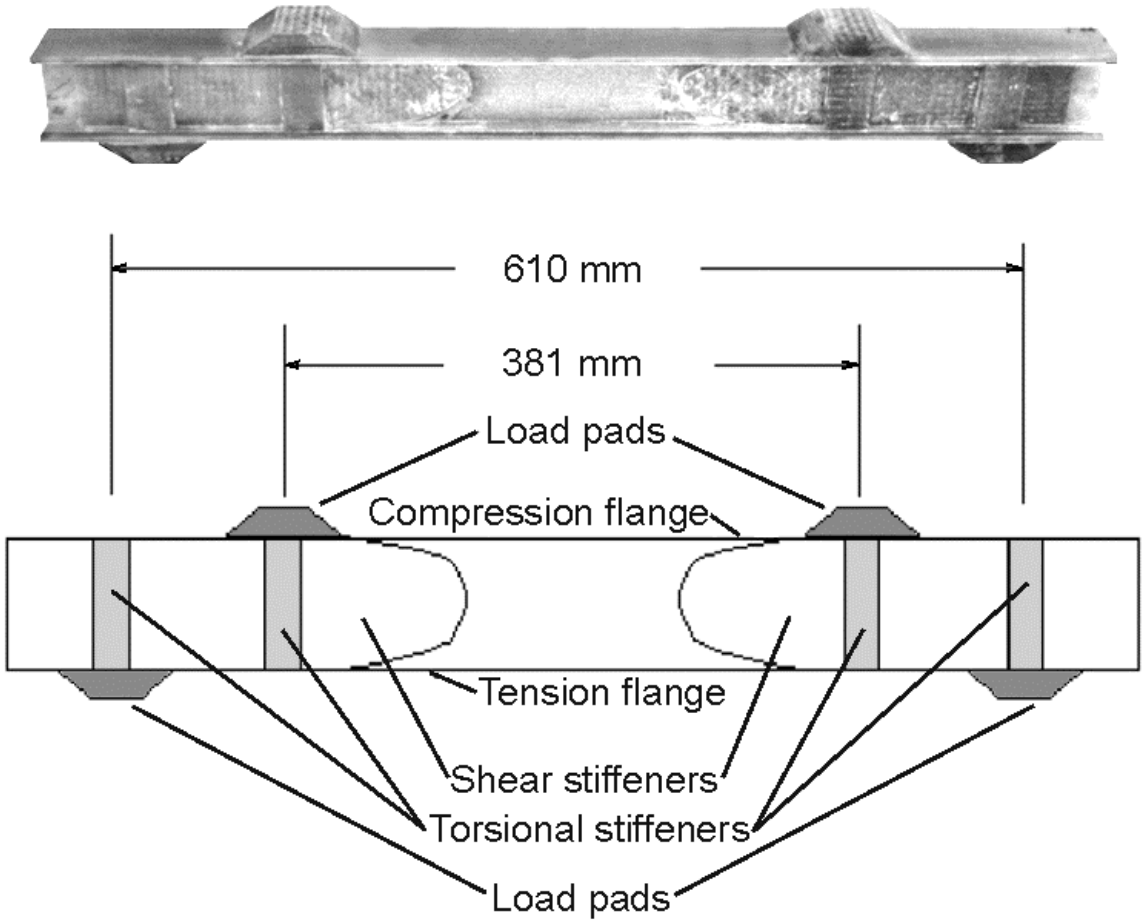
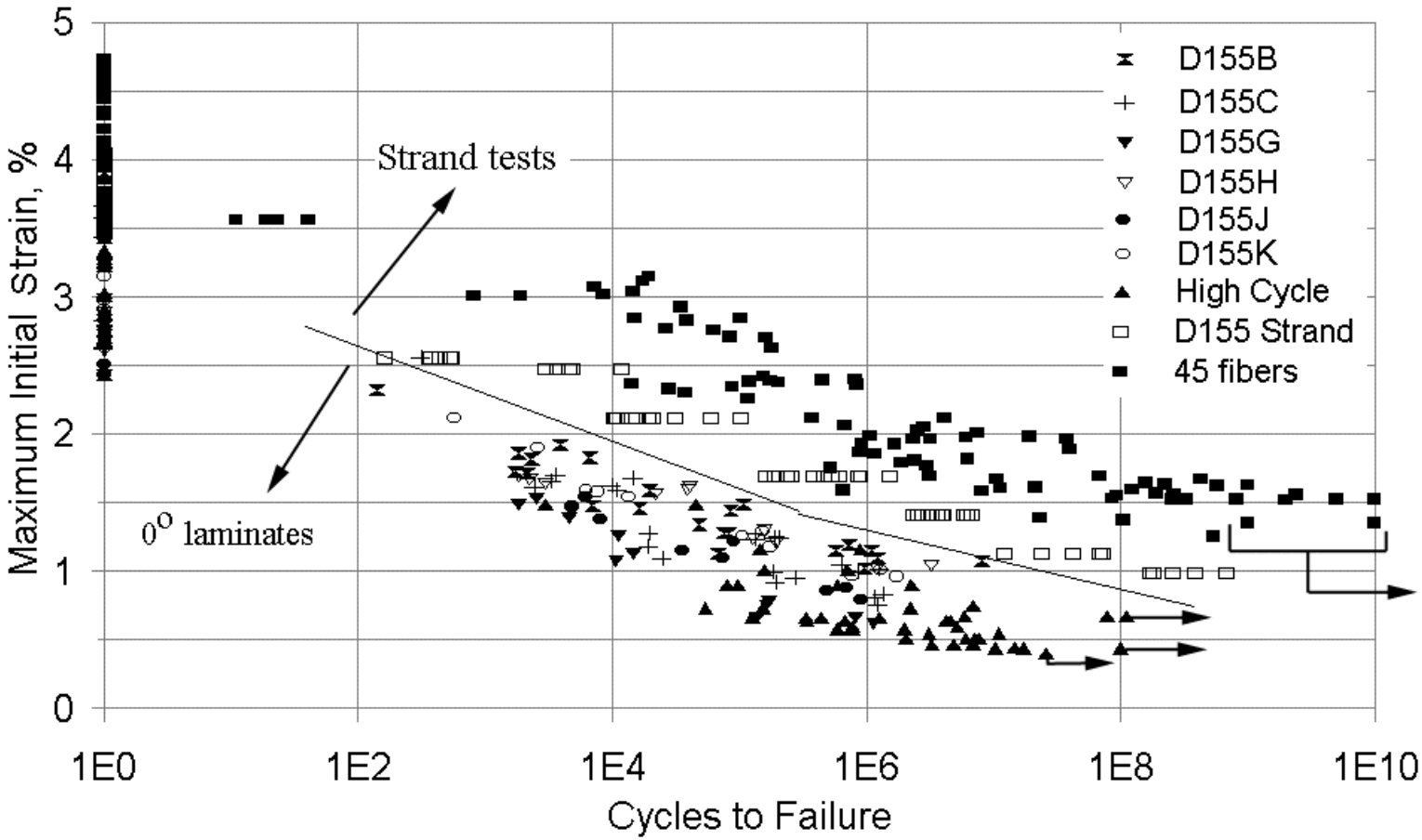


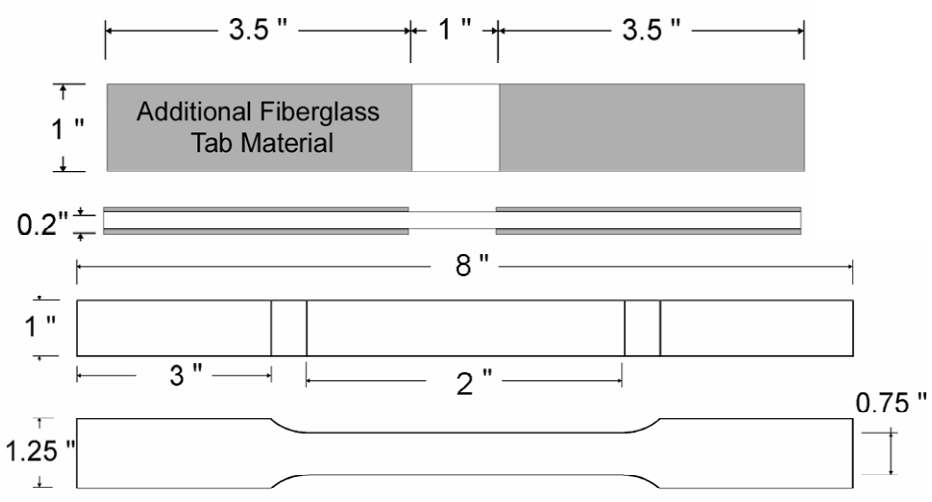
Photo and Schematic of the Composite I-Beam Section.



Maximum Initial Tensile Strain for MSU Laminates and Small Strands, R = 0.1

Size Effects on Compression Tests of U.D. Fiberglass Coupons From Spar Caps

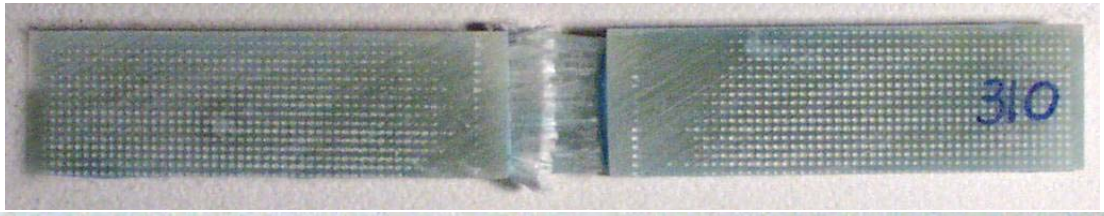
Specimen Geometry



Ultimate Compressive Strain

Average = 1.62%

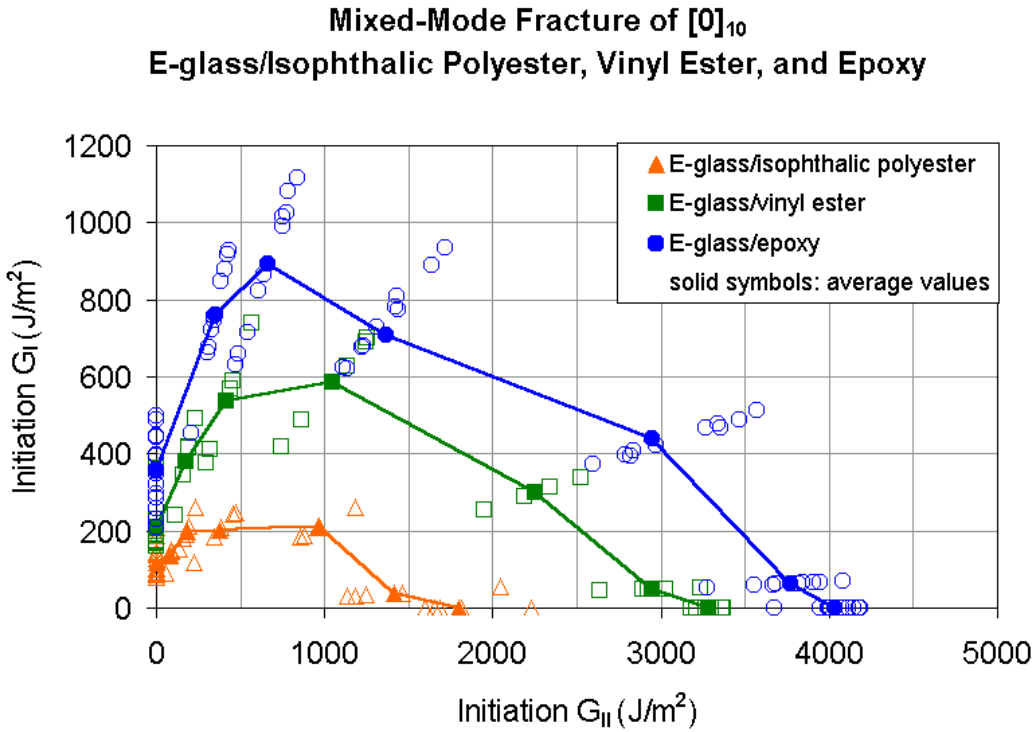
Average = 1.26%

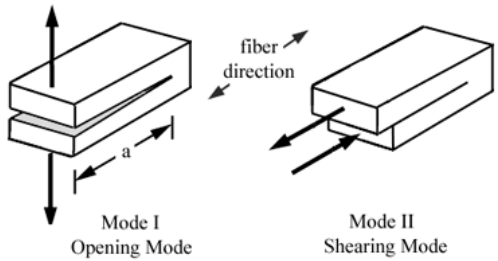


DELAMINATION BETWEEN PLIES

(Structural Integrity at Trailing Edges, Skin-Stiffener Intersections, Ply-Drops)

- DATABASE for G_{IC} and G_{IIC} (and Mode Interaction) for Various Resins, Environmental Conditions.
- DESIGN METHODOLOGY for Avoiding Delamination in Structural Details
- MATERIALS SELECTION for increased structural integrity





PRIORITIES FOR FUTURE STUDIES

- Carbon fiber materials and hybrids
- Industrial materials
- Spectrum loading
- New resins: mostly epoxies for carbon fibers and epoxy compatible glass fibers; environmental effects
- Effects of flaws and structural details
- Delamination of carbon laminates

CONCERNS

- Testing of thick composites
- Effects of complex stress states