



Methodology for Composite Durability Assessment

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- 7. Conclusions**



Objectives



AIM-C : Accelerated Insertion of Materials – Composites

(Funded by DARPA and managed by NavAir)

The goal of the AIM-C program

- (1) Accelerate the insertion of new materials and processes
- (2) Evaluate the effects of material, processing, and design on the performance of composite structures

Our objective is to analyze

- **Environmental effects** (temperature, moisture)
- **Durability** (creep and fatigue life, residual strength)



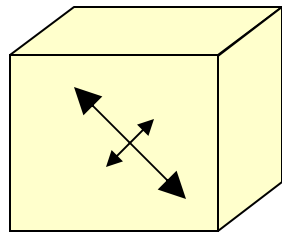
State of the Art in Composite Analysis



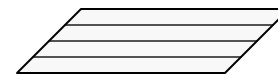
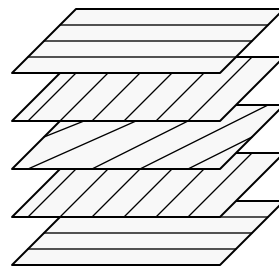
No principal stresses or strains

- Composites are highly orthotropic and viscoelastic

Involves numerous parameters



isotropic materials



Ply failure



Laminate failure

$$\begin{aligned} &E_x, E_y, E_z, G_{xy}, G_{xz}, G_{yz} \\ &\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz} \\ &X, X', Y, Y', S \end{aligned}$$

Composite materials

Smallest level of imperfection is at the fiber / matrix level

Infinite combinations of parameters must be tested



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Analytical Models

Strain Invariant Failure Theory (SIFT)

- Predicts initial and final failure of composite structures

Micromechanics

- Predicts 3-D ply properties and strain magnification factors

Accelerated Testing Methodology (ATM)

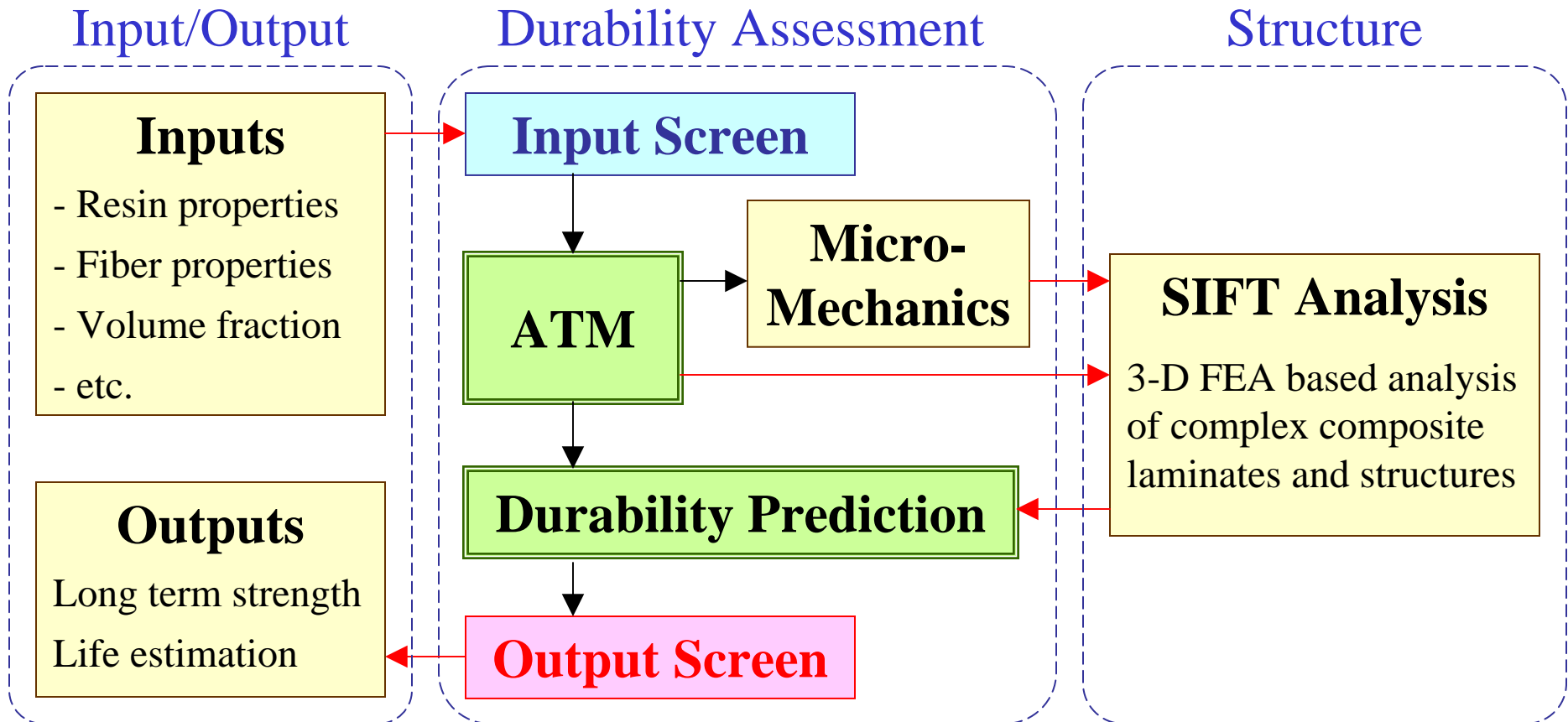
- Rapid generation of durability database as master curves

Linear Cumulative Damage Law (LCD)

- Life estimation under combined fatigue/creep loads
- Residual strength prediction



Analysis Architecture





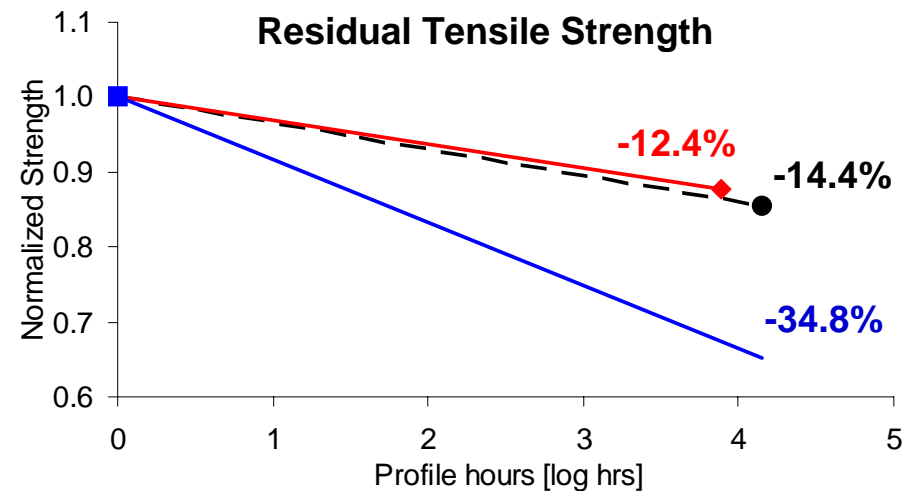
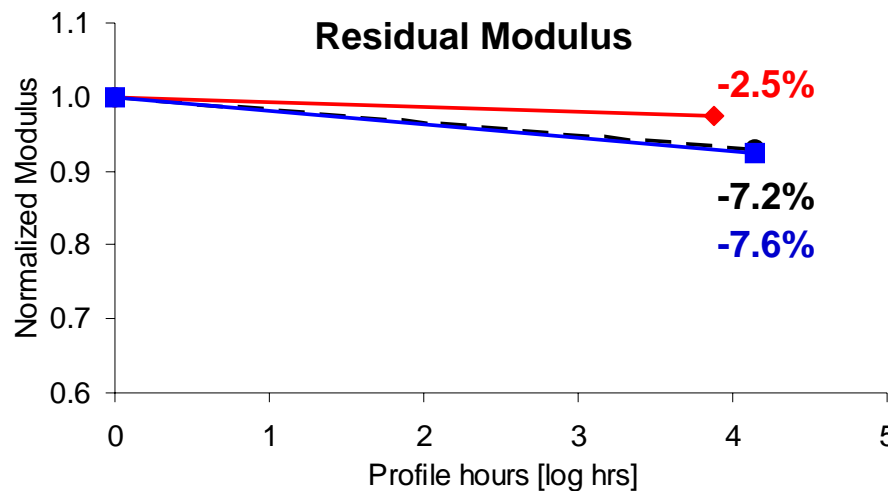
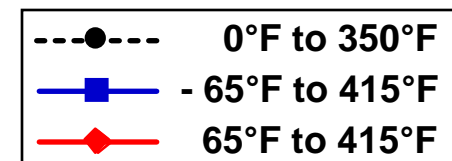
Verification Process



Evaluation of NASA HSR Data

- Mainly residual modulus and strength after thermal and mechanical load cycles
- IM7/5250-4 and IM7/K3B

IM7/K3B quasi-isotropic laminates after 3 types of thermal and mechanical load cycles (Gates, 2003)



Use for the verification of the durability assessment methodology



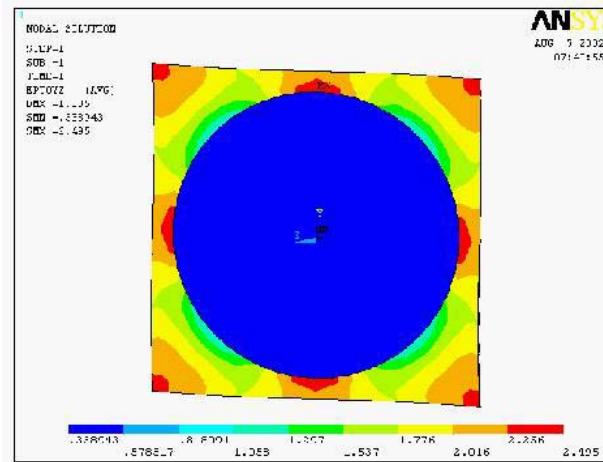
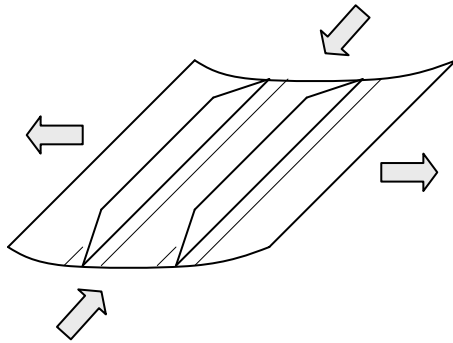
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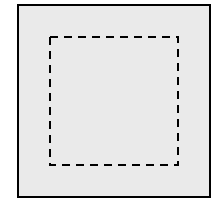


Strain Invariant Failure Theory (SIFT)



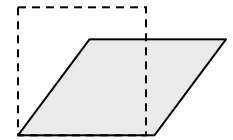
dilatational

$$J_1 = \epsilon_1 + \epsilon_2 + \epsilon_3$$

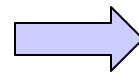


distortional

$$\epsilon_{vM} = [\{ (\epsilon_2 - \epsilon_3)^2 + (\epsilon_1 - \epsilon_3)^2 + (\epsilon_1 - \epsilon_2)^2 \} / 2]^{1/2}$$



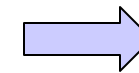
3-D macro strains
due to mechanical
and thermal loads



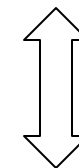
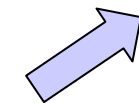
3-D micro strains
at various locations
in the fiber and resin

+

Micro thermal strains
due to CTE mismatch
of fiber and resin



Strain invariants
in the resin
and in the fiber



compare

Critical invariants

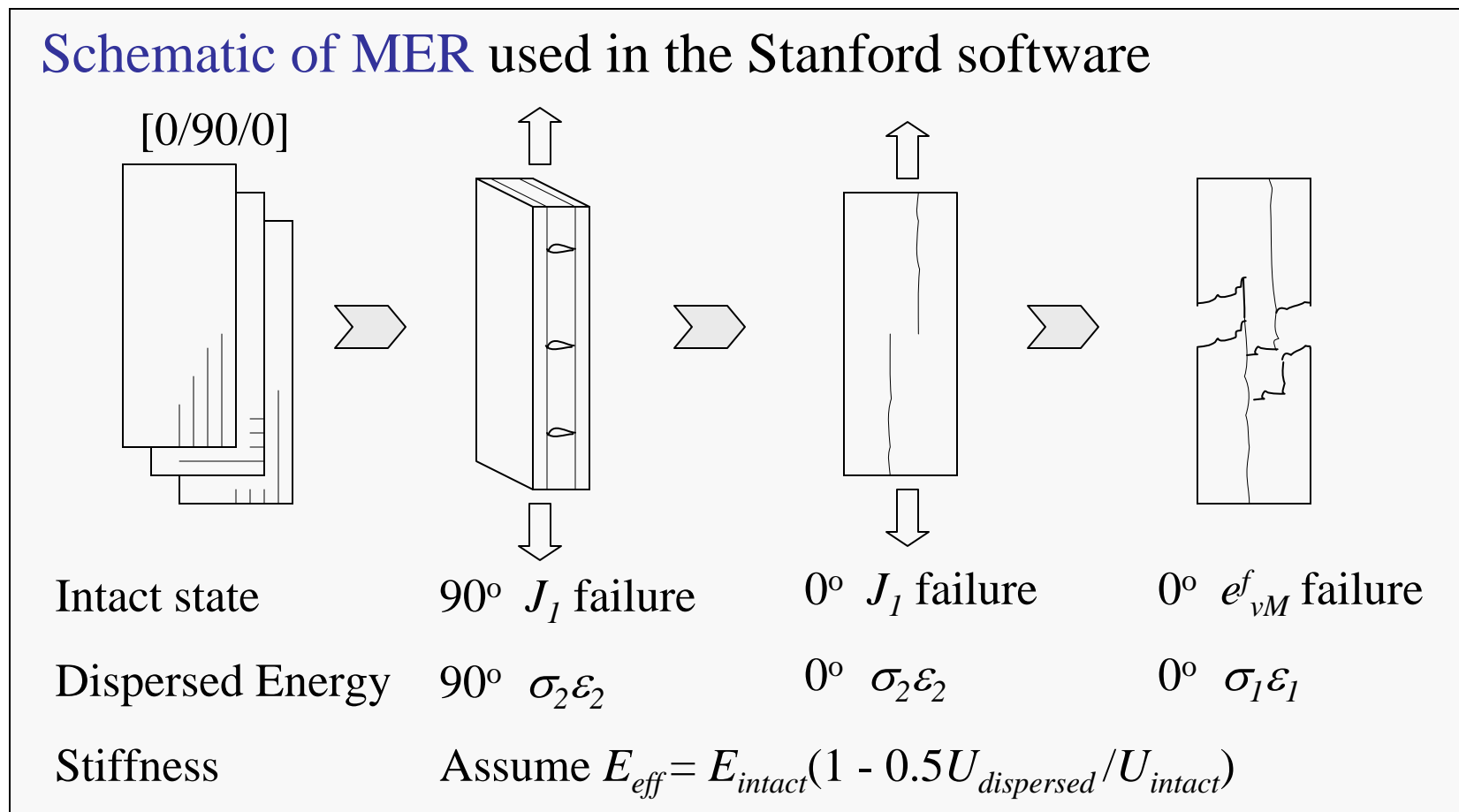


Final Failure Prediction Using MER



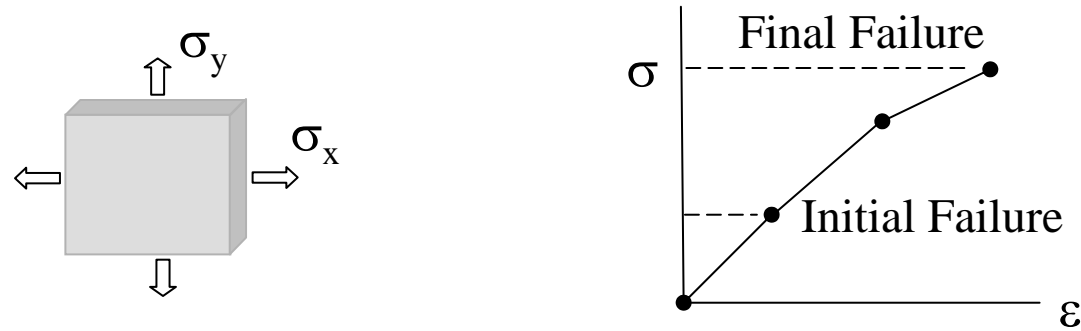
Maximum Energy Retention (MER) monitors retained and dispersed strain energies during the progressive damage to predict the final failure (2002, Gosse)

Schematic of MER used in the Stanford software

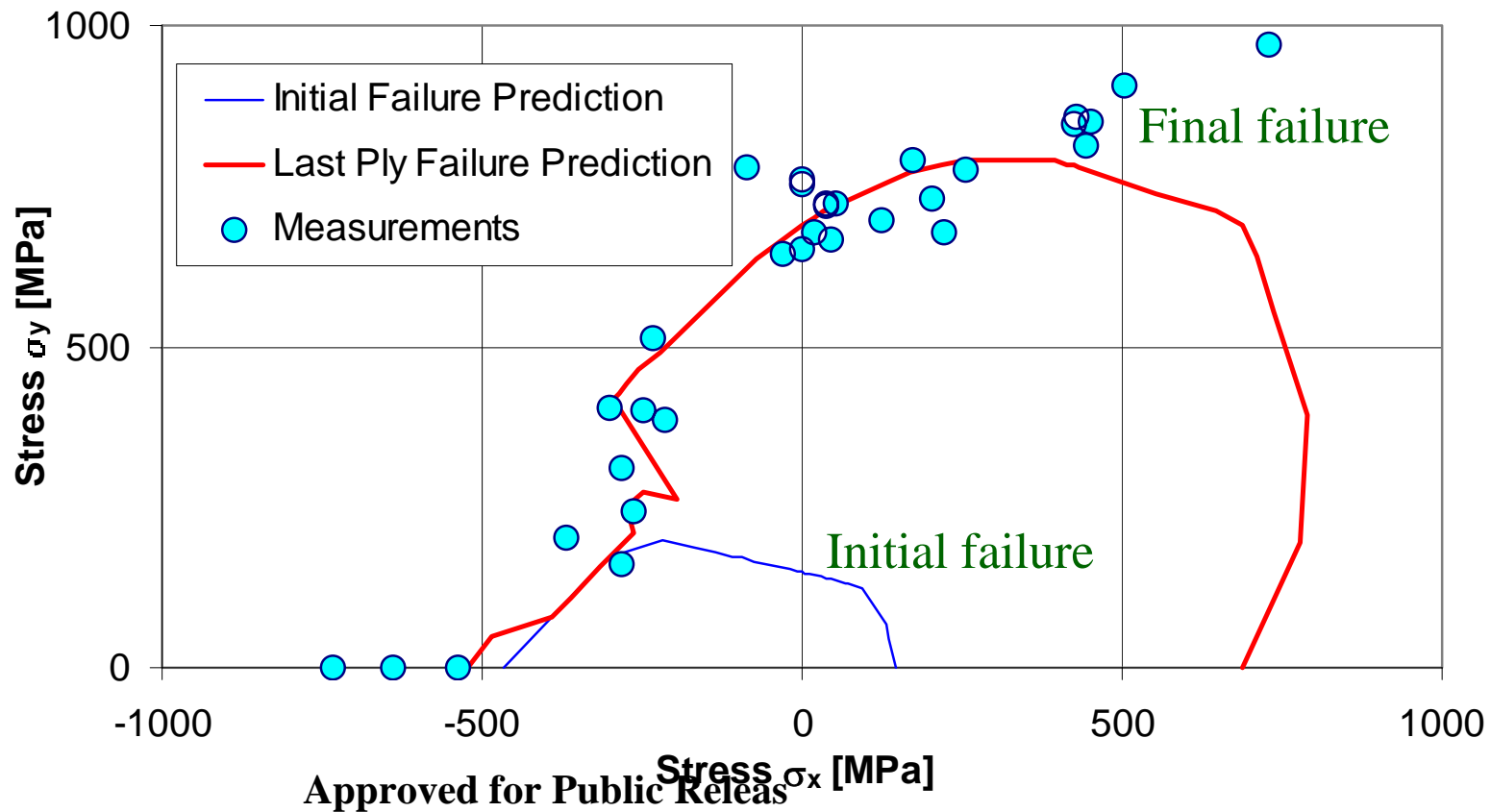




Examples of Failure Envelopes



AS4/3501-6 [0/90/45/-45] Bi-axial Failure Envelope





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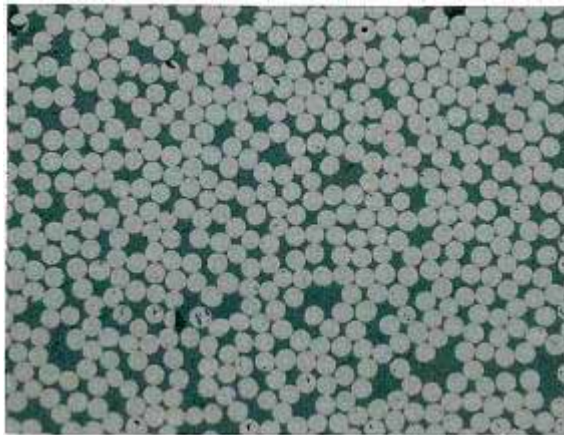
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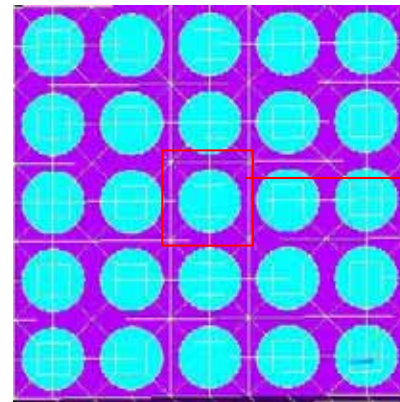
Micromechanics Finite Element Models



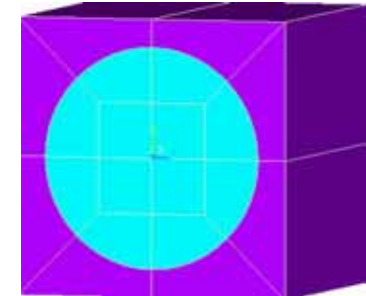
Cross-sectional view of continuous fiber composites



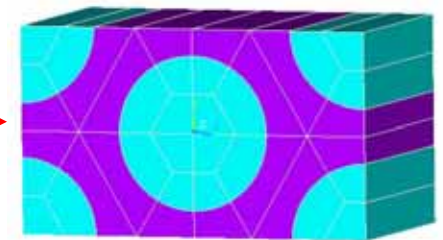
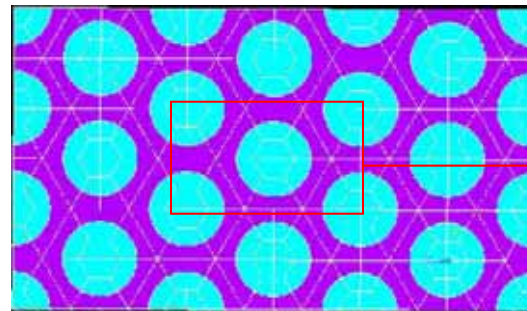
Square Array Model



Unit Cells



Hexagonal Array Model



Predicts 3-D ply properties and strain magnification factors as functions of V_f , E_f , and E_m .

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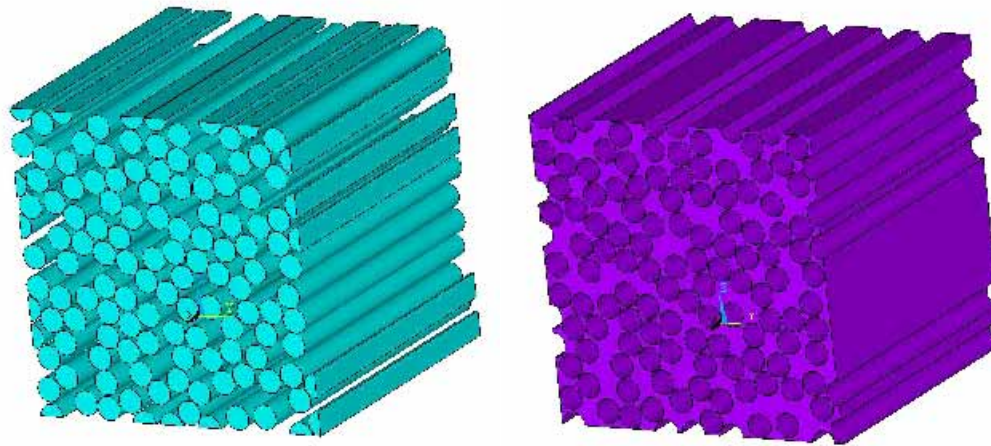


Evaluation of Random Fiber Array

Finite element model (Ha, 2003)

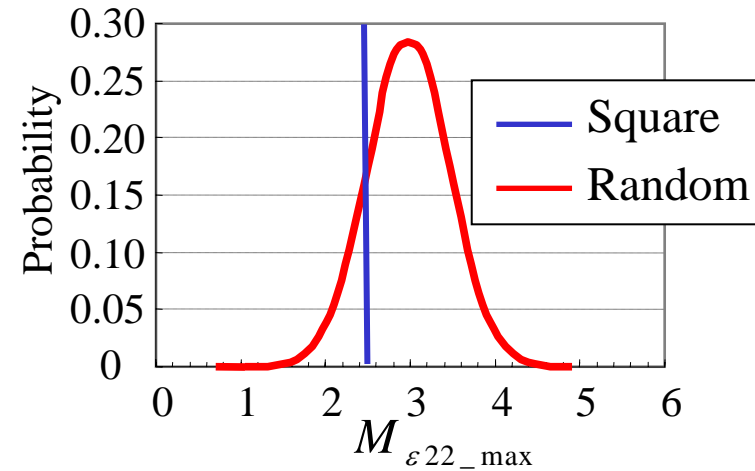
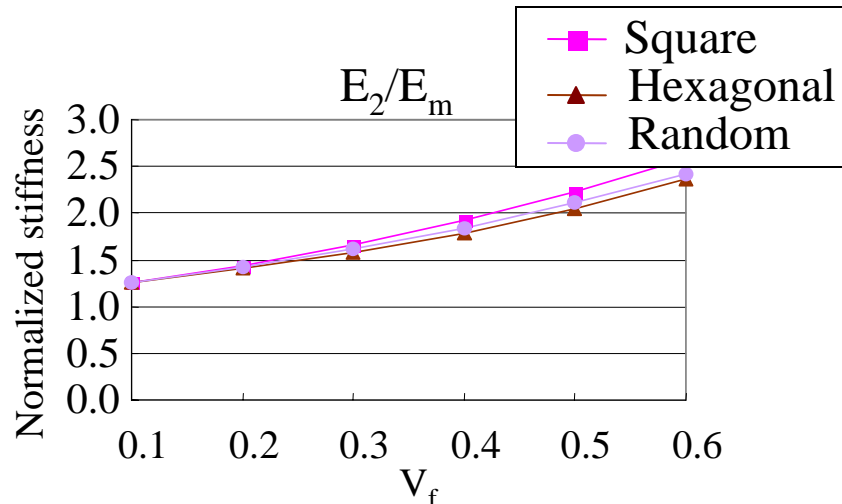
* $V_f = 0.60$

* Number of fibers = 120



Magnification

Modulus



Identical to idealized array

Distribution of microscopic failures



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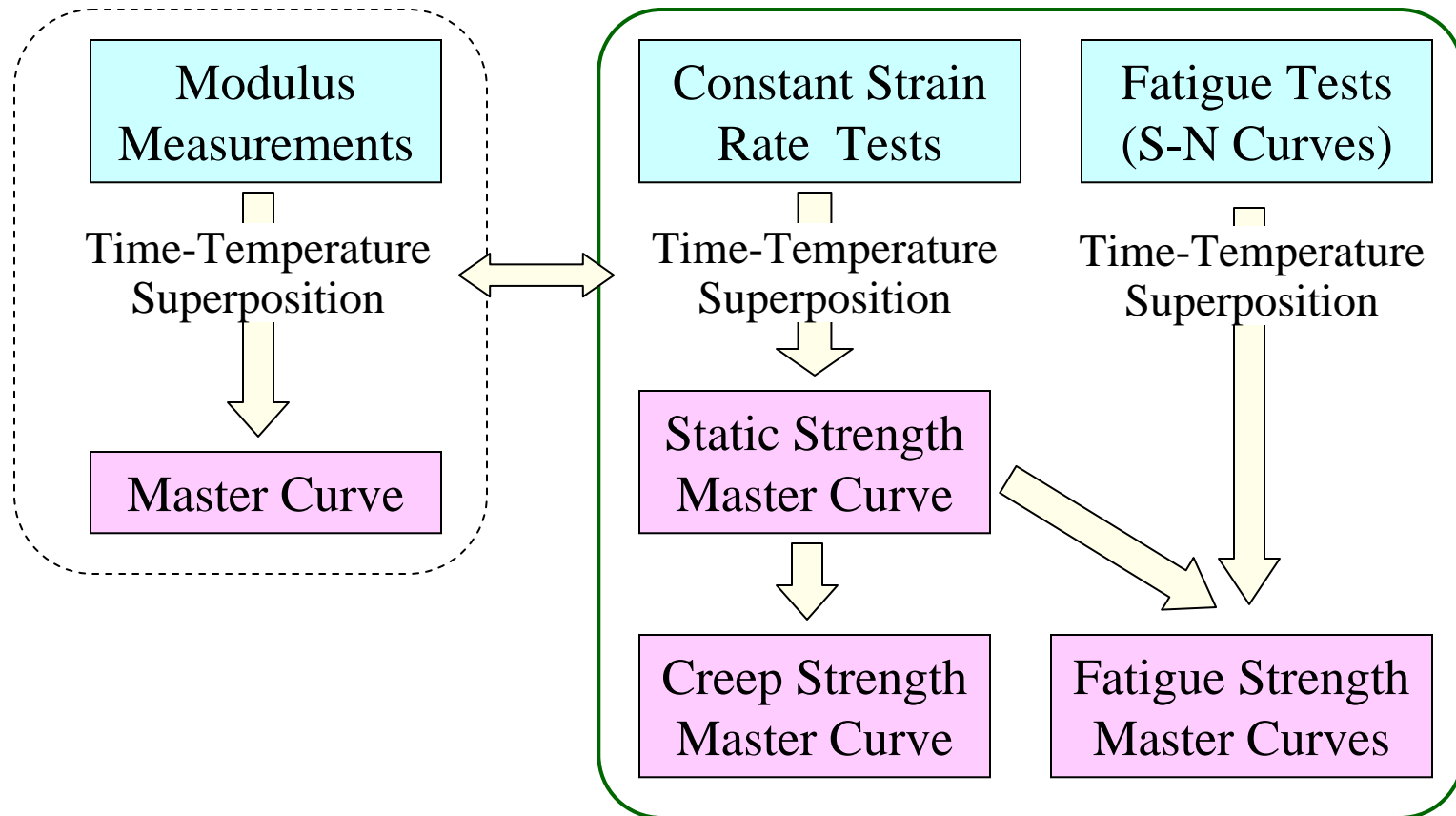
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Accelerated Testing Methodology



Series of tests at elevated temperature



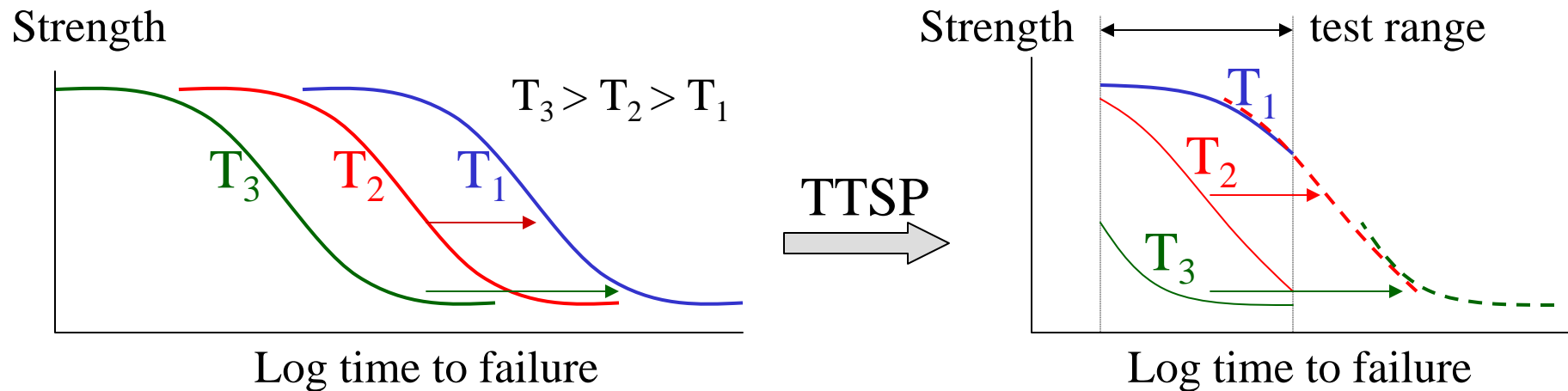
Predictions for wide ranges of temperature and time to failure



Time-Temperature Superposition (TTSP)



Assumption: Same shape for any temperature = Master Curve

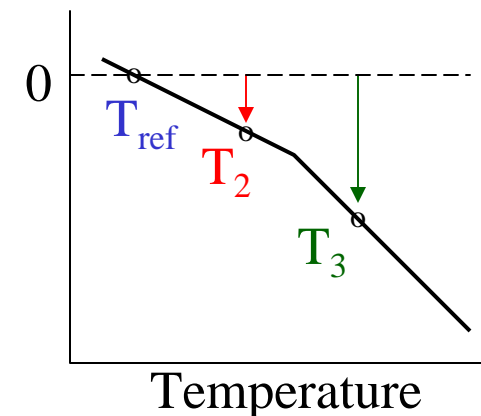


Curves can be superposed by horizontal shifts

⇒ **Master curve** can be generated from the fragments of curves at different temperatures

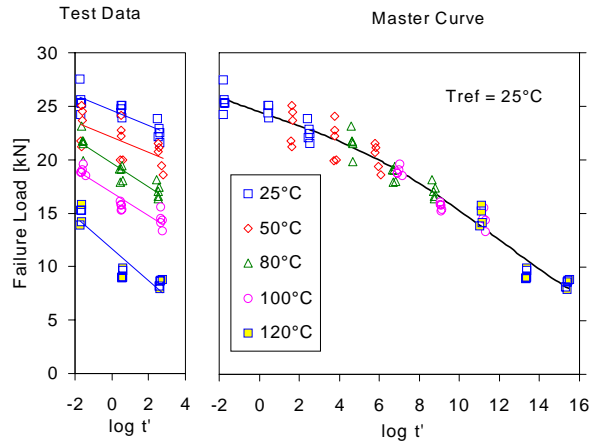
⇒ **Accelerated evaluation of long term performance**

Shift factors





Time-Temperature Shift Factors

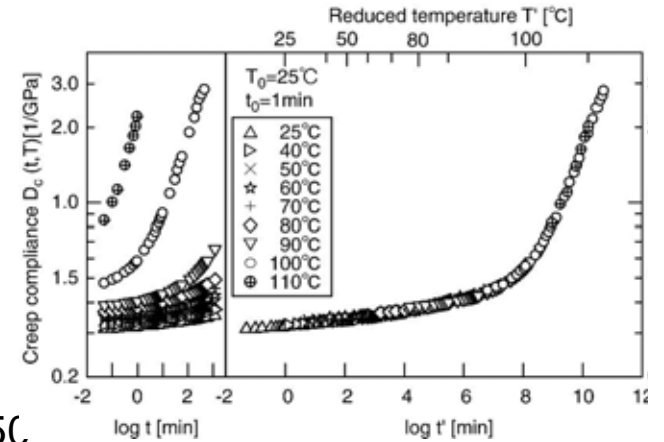


CFRP Bolted Joint Strength

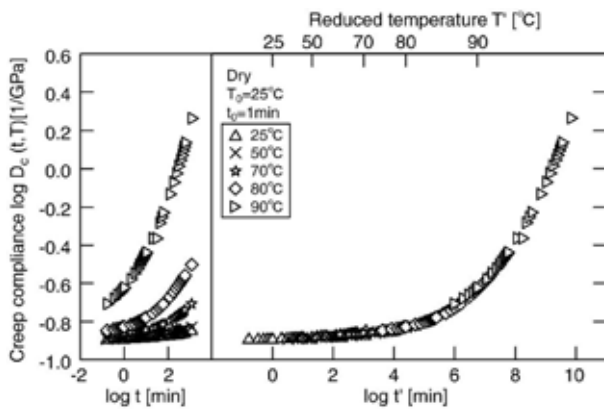
- CFRP Bolted Joint Strength
- Creep Compliance of CFRP
- △ Creep Compliance of Resin
- × Storage Modulus of Resin

Temperature [°C]

0 50 100 150

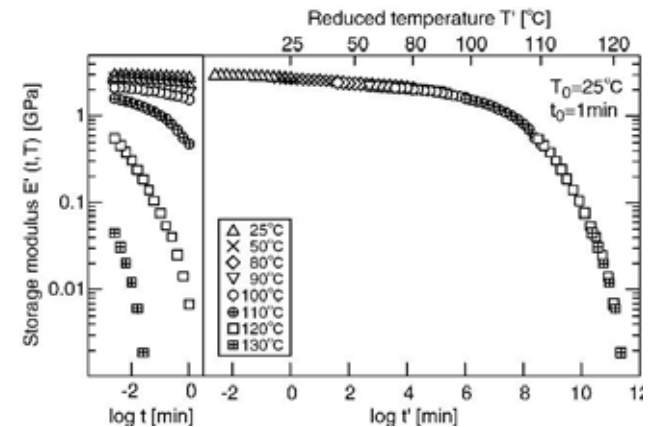
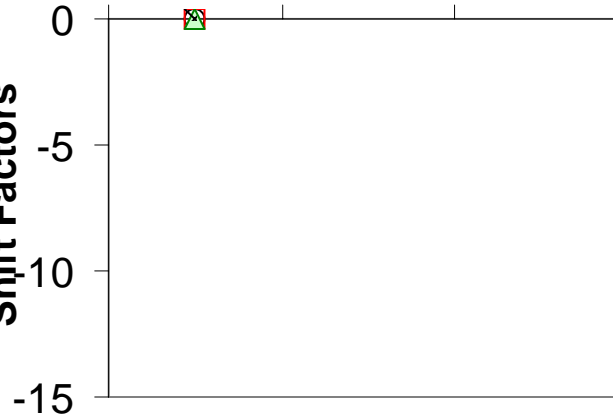


Creep Compliance of Resin



Creep Compliance of CFRP

Shift Factors



Storage Modulus of Resin

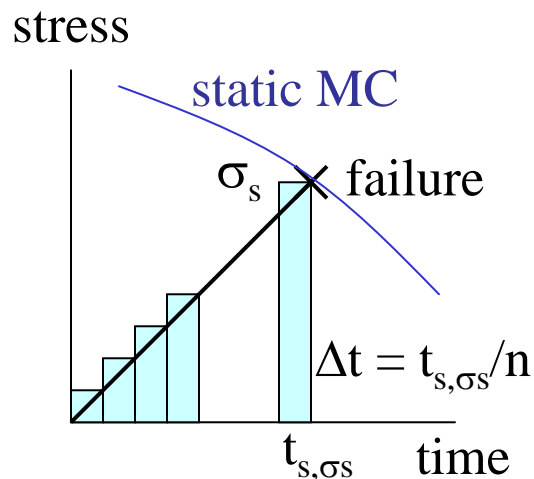
Same shift factors for various cases with common resin system



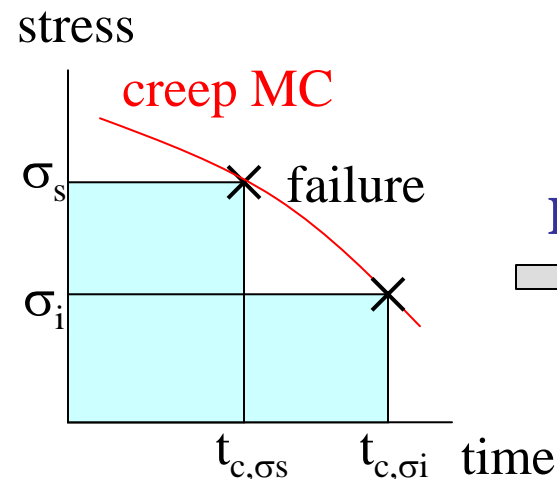
Creep Life Prediction

Linear Cumulative Damage Law (LCD) relates static and creep failures

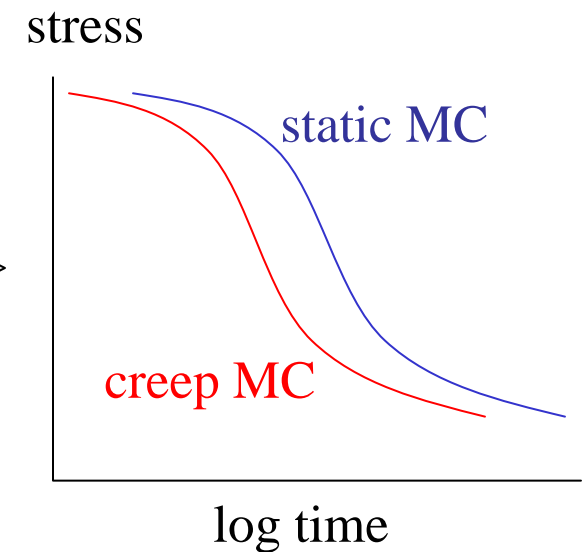
Static loading



Creep loading



LCD
→



Static (constant strain rate) loading considered as series of creep loads with increasing stress level.

Using LCD,

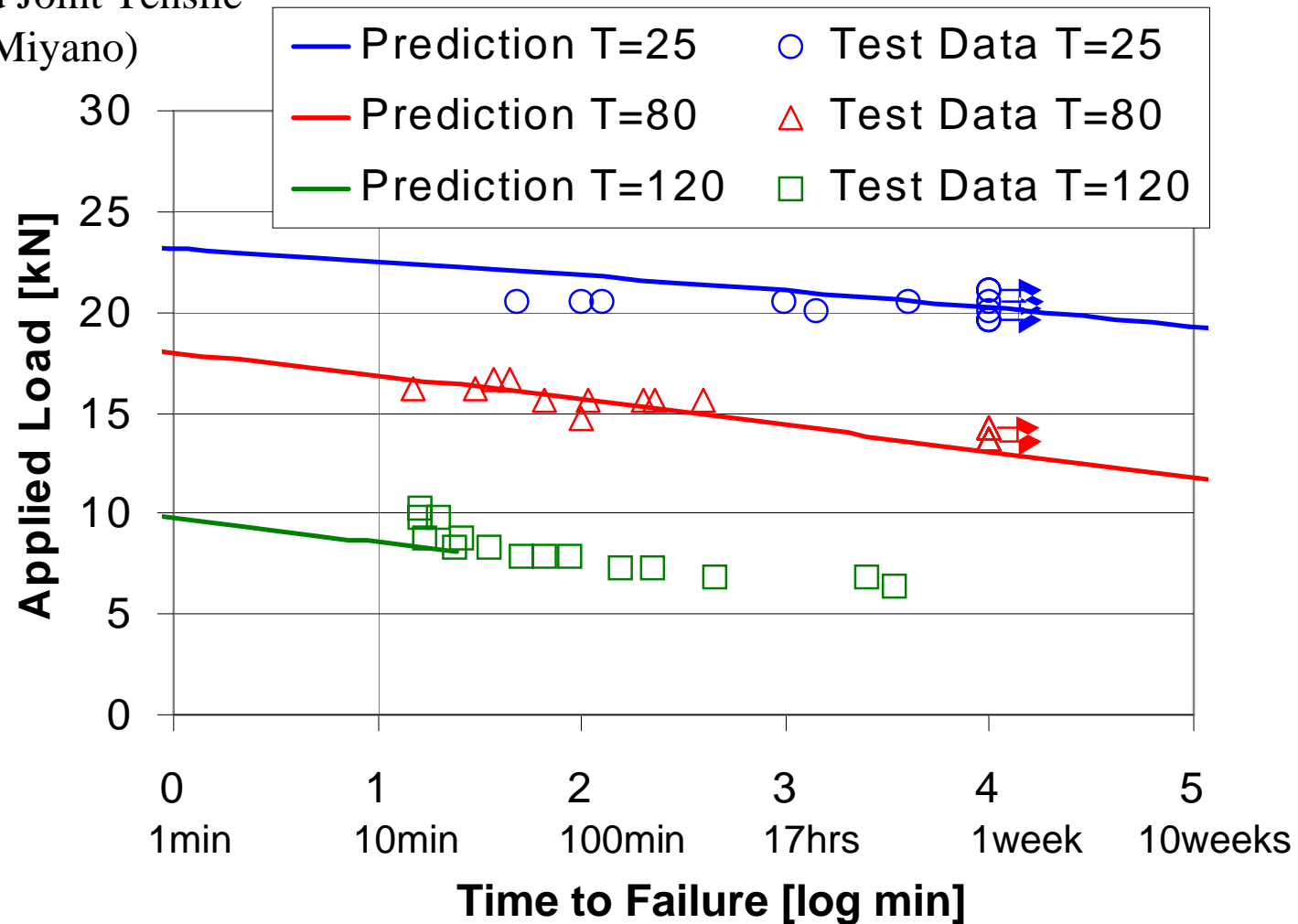
$$\frac{\Delta t}{t_{c, \sigma_1}} + \frac{\Delta t}{t_{c, \sigma_2}} + \frac{\Delta t}{t_{c, \sigma_3}} + \frac{\Delta t}{t_{c, \sigma_4}} + \dots = 1 \Rightarrow t_{c, \sigma} = f(t_{s, \sigma})$$



Creep Life Predictions and Measurements



CFRP Bolted Joint Tensile
Creep Test (Miyano)



Creep life predictions agree with the creep test measurements

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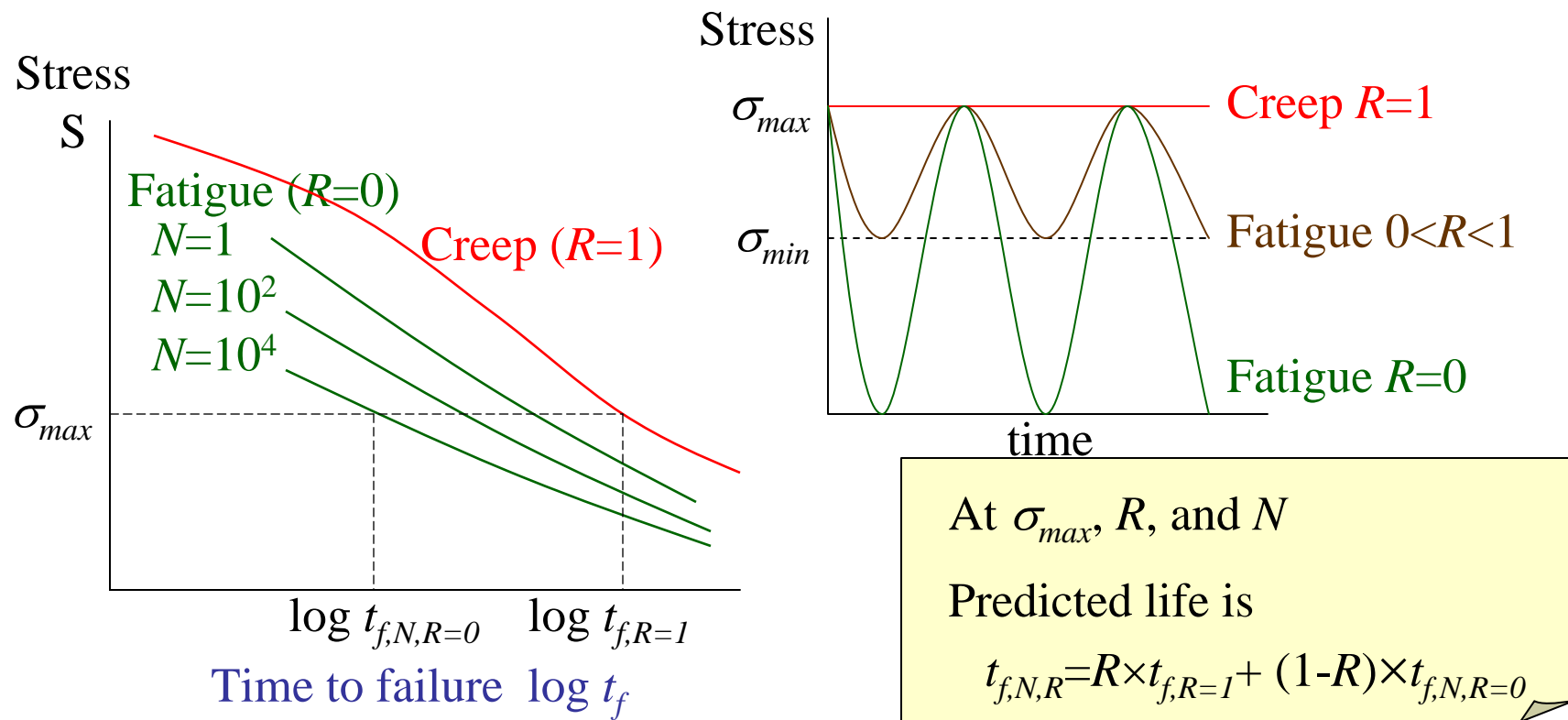


Fatigue / Creep Life Prediction

Creep and fatigue are related when rate dependence is considered

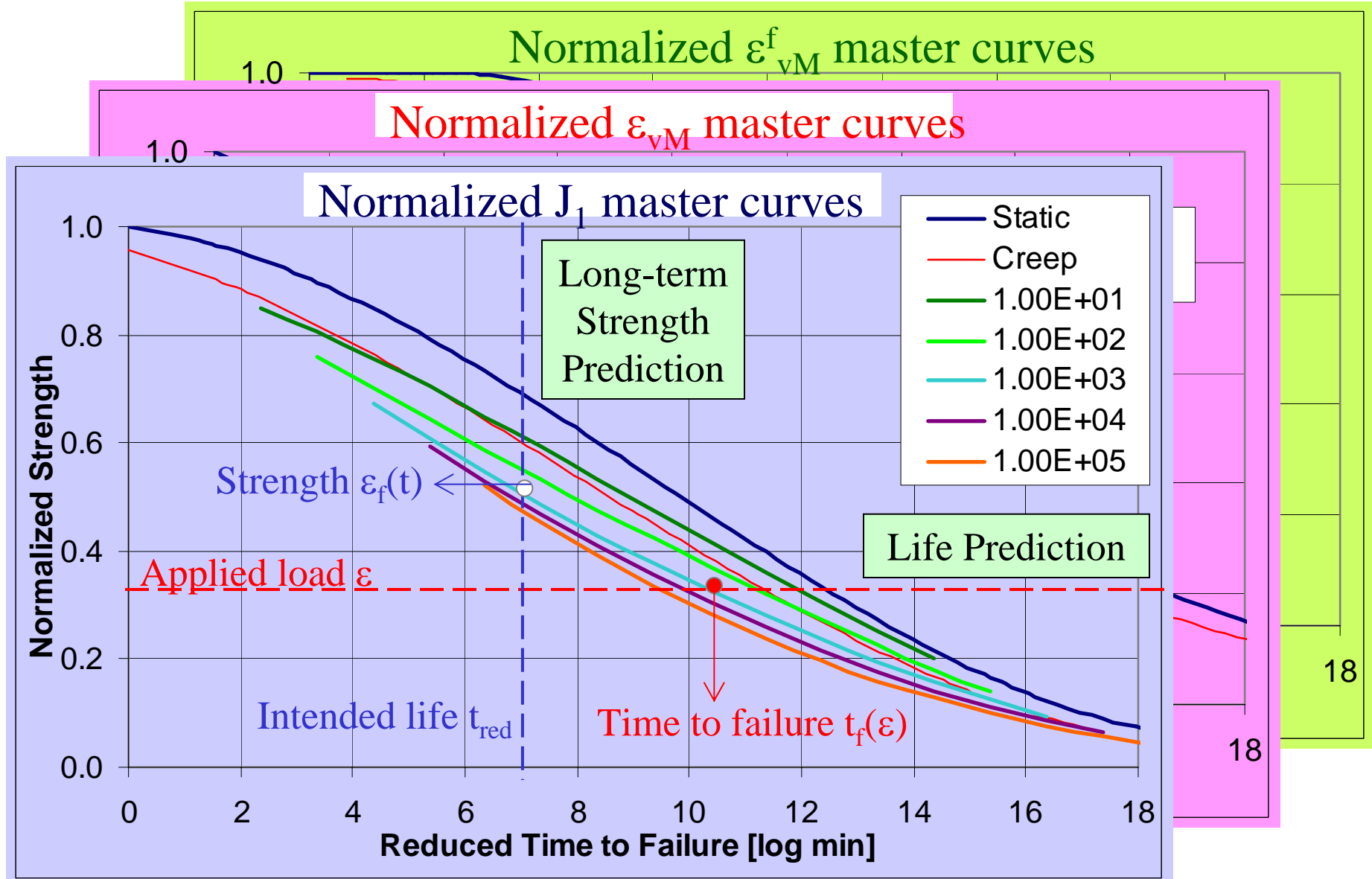
This allows

- Linear interpolation for arbitrary stress ratio ($R = \sigma_{min} / \sigma_{max}$)
- Life prediction for combination of creep and fatigue loads using LCD





Prediction based on Master Curves



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Fatigue / Creep Combined Load

Linear Cumulative Damage (LCD) = Miner's Rule

with respect to time

only if correct frequencies are used

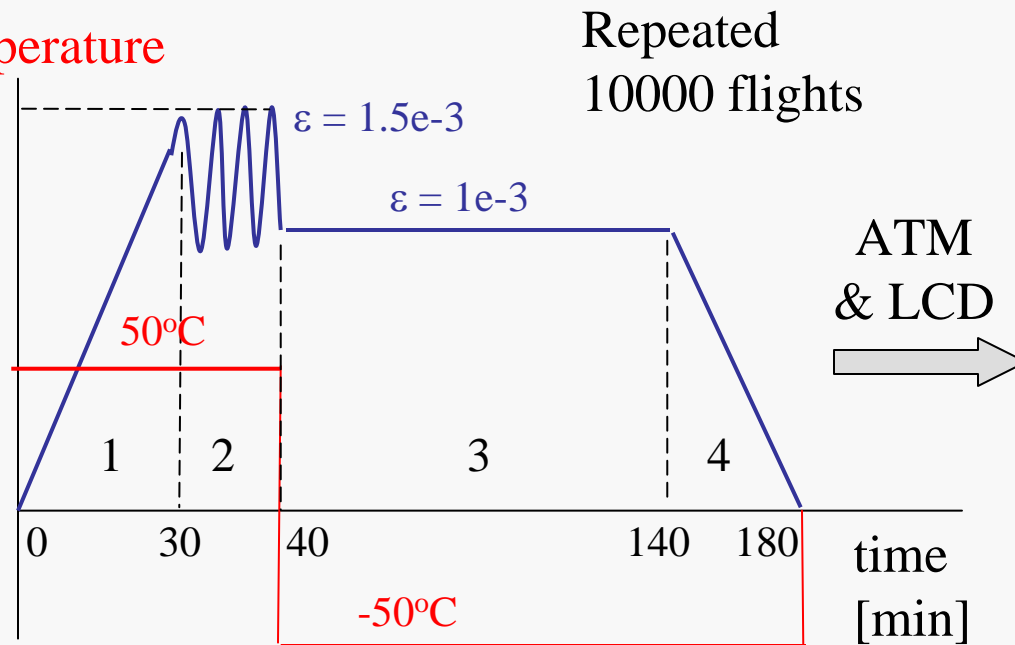
$$\frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \frac{t_4}{t_{f,4}} + \dots = 1$$

⇒ Require ATM

Example: Simplified flight load

Applied strain

Temperature



i	t _i	t _{f,i}	Δ _i
1	10 ^{5.5}	10 ^{6.4}	0.11
2	10 ^{5.0}	10 ^{5.2}	0.57
3	10 ^{6.0}	10 ²⁴	0.00
4	10 ^{5.6}	10 ²⁵	0.00
sum			0.68

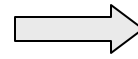
$$\text{Life} = 1 / 0.68 = 1.5$$



Residual Strength Prediction

Linear Cumulative Damage (LCD)

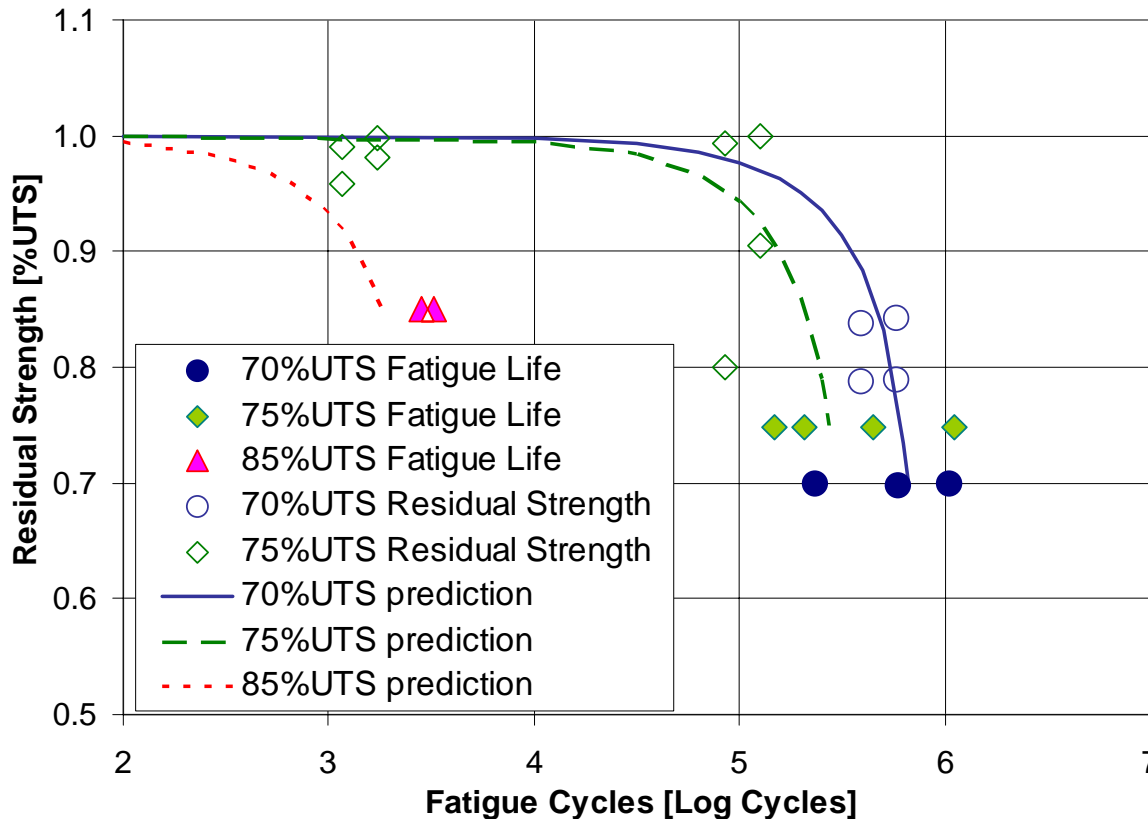
$$\frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \dots = 1$$



After a damage of λ

$$\lambda + \frac{t_1}{t_{f,1}} + \frac{t_2}{t_{f,2}} + \frac{t_3}{t_{f,3}} + \dots = 1$$

Residual strength at time to failure t_f = CSR strength at $t_f/(1-\lambda)$



Residual strength of graphite/epoxy laminate (test data from Verghese et al, 2001)



Effects of Moisture

Reversible effects

- reduced modulus
- reduced strength
- lower T_g
- swelling of the resin

Temperature-Moisture Superposition

(2002, Miyano and Sekine)

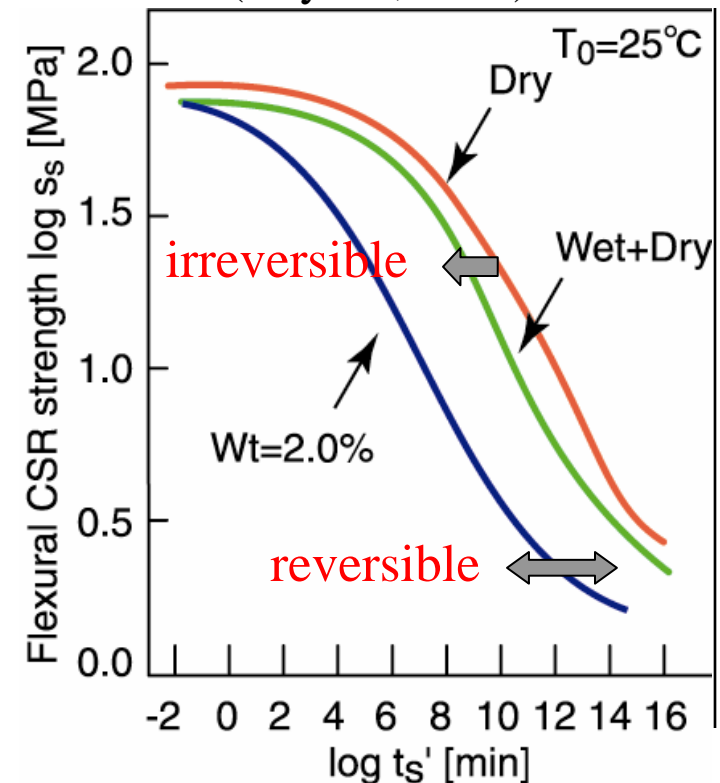
$$T_{eff} = T + a_M M, \text{ where } a_M = \text{Moisture shift factor}$$

Irreversible effects

- fiber/matrix interface failure
- ...

Micromechanics analysis
of interface failure

CFRP [0] flexural strength
(Miyano, 2001)





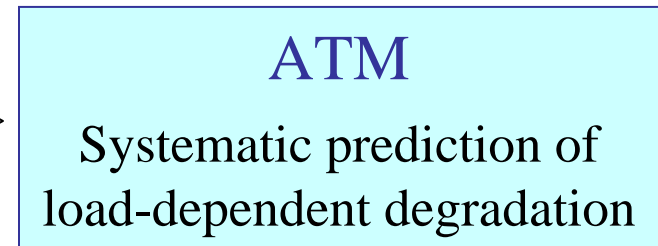
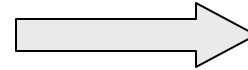
Load Independent Degradation



Separate the long-term degradation to

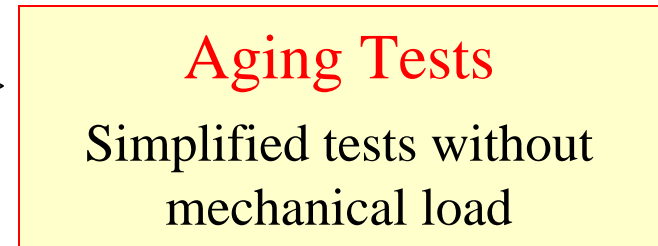
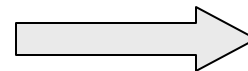
Load-dependent degradation

- Creep/fatigue failures
- Due to applied or hygro-thermally induced stress

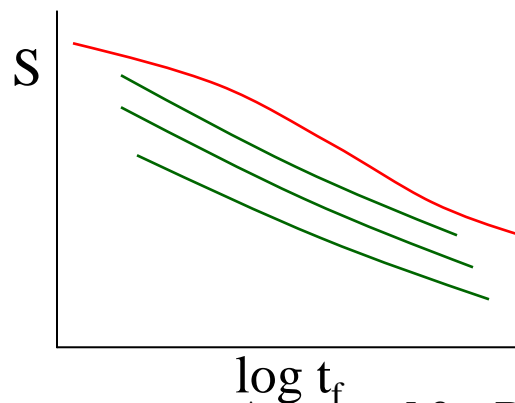


Load-independent degradation

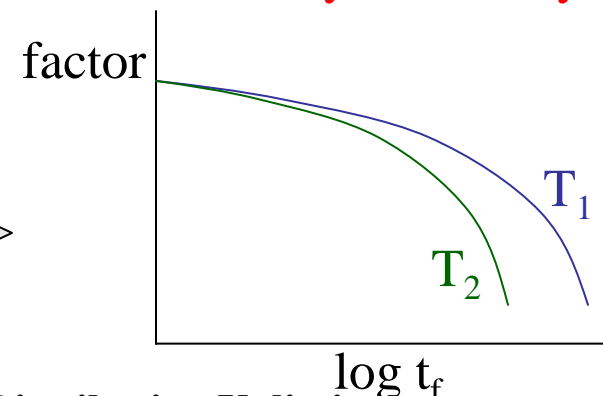
- Assume no effect of applied loads
- Chemical degradation due to oxidization, UV, etc.



Master curves from ATM



Degradation factors from aging tests
(Thermal stability models by Boeing)



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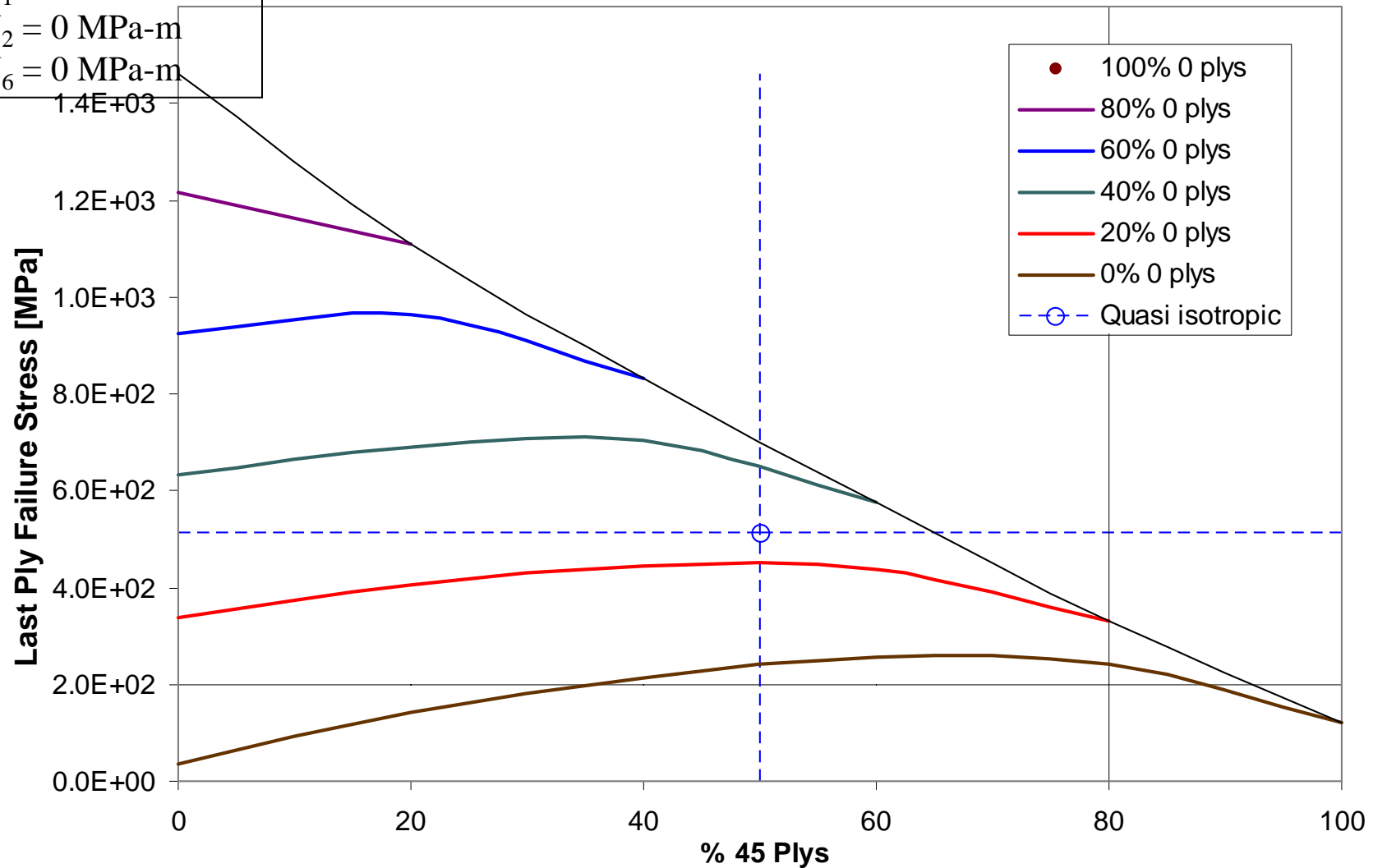
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Conventional Carpet Plot

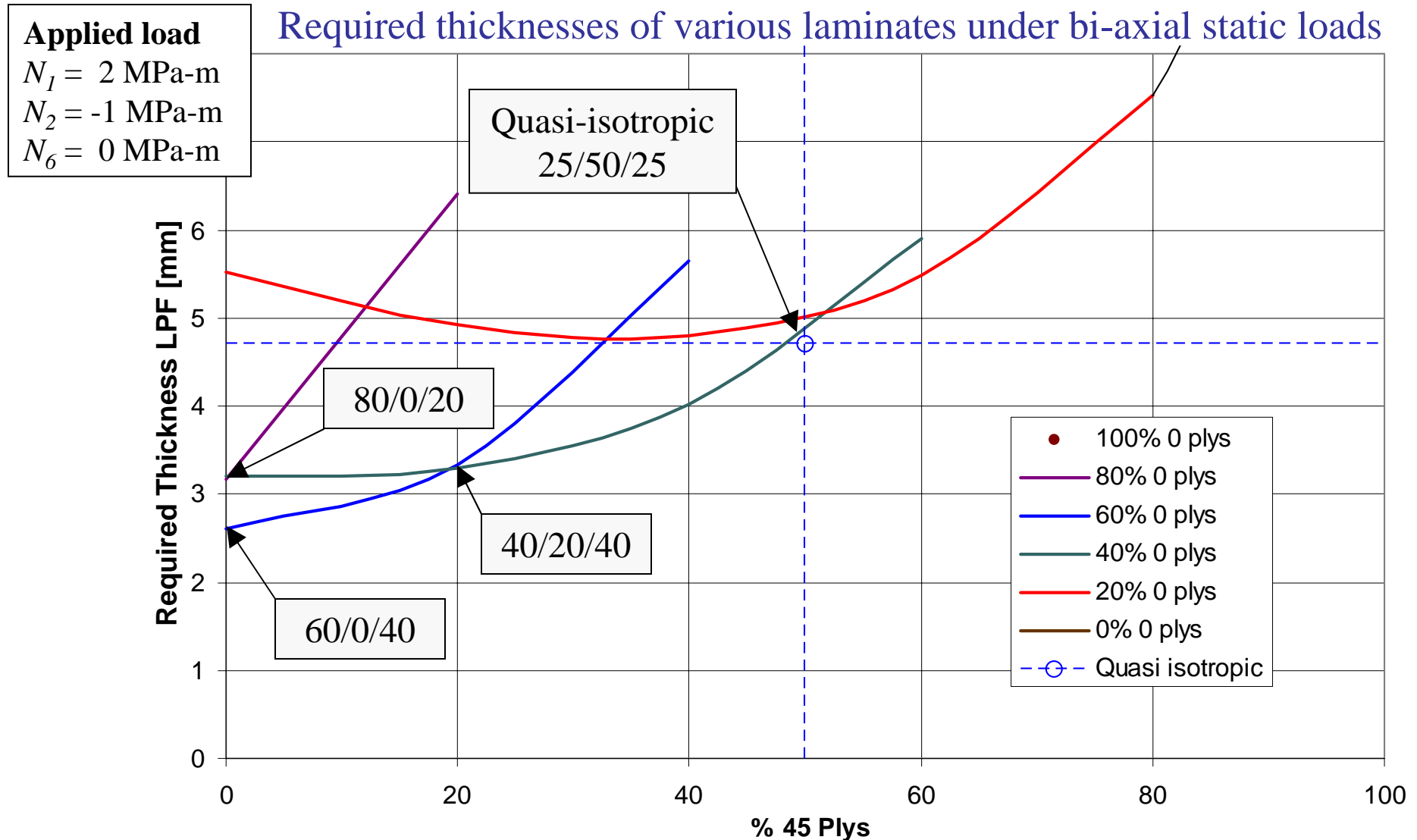
Applied load
 $N_1 = 1 \text{ MPa-m}$
 $N_2 = 0 \text{ MPa-m}$
 $N_6 = 0 \text{ MPa-m}$

Last ply failure stress for various laminates





Electronic Carpet Plot Output



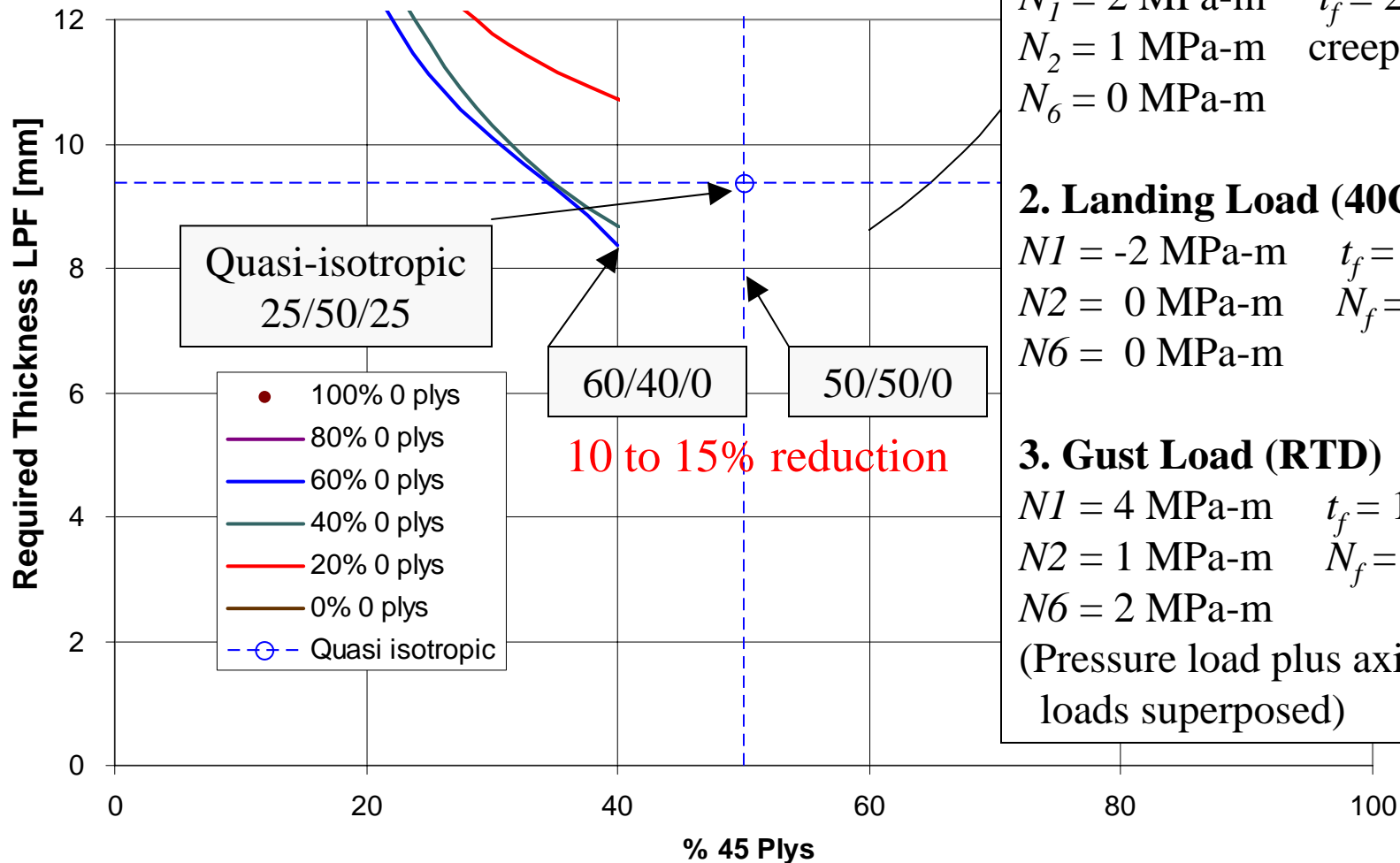
Up to 50% reduction in required thickness using wide ranges of ply orientations



Electronic Carpet Plot – Multiple Loads



Required thicknesses of various laminates under multiple fatigue/creep loads



1. Pressure Load (RTD)

$N_1 = 2$ MPa-m $t_f = 20$ years
 $N_2 = 1$ MPa-m creep load
 $N_6 = 0$ MPa-m

2. Landing Load (40C, 0.5%)

$N1 = -2$ MPa-m $t_f = 50000$ min
 $N2 = 0$ MPa-m $N_f = 50000$ cycles
 $N6 = 0$ MPa-m

3. Gust Load (RTD)

$N1 = 4$ MPa-m $t_f = 100$ min
 $N2 = 1$ MPa-m $N_f = 100$ cycles
 $N6 = 2$ MPa-m
(Pressure load plus axial and shear loads superposed)

Optimum layup for multiple loads are not obvious

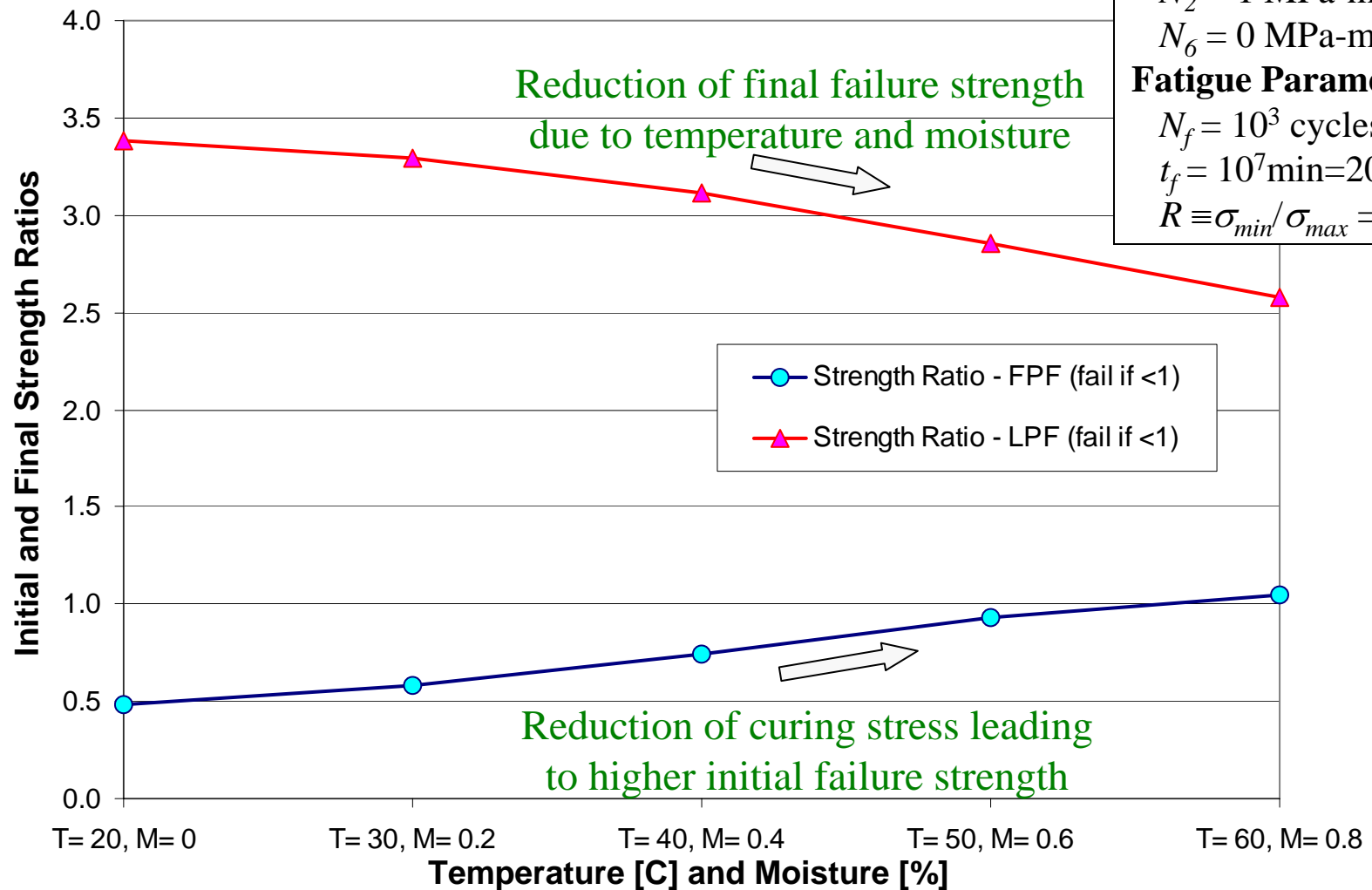
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Parameter Study



Initial and final fatigue strength ratios of quasi-isotropic laminate for RTD (room temperature dry) to HTW (hot wet) conditions



Applied load
 $N_1 = 2 \text{ MPa-m}$
 $N_2 = 1 \text{ MPa-m}$
 $N_6 = 0 \text{ MPa-m}$
Fatigue Parameters
 $N_f = 10^3 \text{ cycles}$
 $t_f = 10^7 \text{ min} = 20 \text{ years}$
 $R \equiv \sigma_{min} / \sigma_{max} = 0$



Conclusions



Accelerated Testing Methodology (ATM) allows rapid generation of durability database as master curves.

Strain Invariant Failure Theory (SIFT) relates basic material durability database to the durability of composite laminates and structures

ATM/SIFT combination provides framework for evaluating the effects of various parameters associated with material selection, processing, design, loads, and environmental conditions.



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