CompTest 2004

Analytical Models for Assessing Environmental Degradation of Unidirectional and Cross-Ply Laminates

W R Broughton and M J Lodeiro

National Physical Laboratory

Teddington, UK

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Contents

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Introduction

- Mechanistic/physics based models are the preferred approach for determining the effect of environmental degradation on mechanical properties of PMCs
- Analytical and semi-empirical models can be used to determine the degree of degradation of elastic and strength properties with the level of degrading agent, typically:
  - Moisture
  - Temperature
  - Moisture + Temperature
- Experimental evaluation carried out on unidirectional and cross-ply GRP and CFRP laminates
- Models include input data obtained from conditioned resin samples

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Laminate Property Predictive Analysis

- Layer or ply properties - micro-mechanics
- Laminate properties - classical laminate analysis
- Thermo-elastic and strength properties
- Moisture diffusion (Fickian diffusion)
- CoDA (Composite Design and Analysis) and PREDICT*
- Empirical relationships $\Rightarrow$ predict moisture/temperature effects

* NPL software packages

Materials

- Unidirectional and cross-ply (0°/90°) laminates
  - E-glass/913 and E-glass/F922
  - HTA/F922
  - T300/914, T300/924 and T300/976
  - APC-2 (carbon/peek)
  - T300B/R23
  - XAS/914

- Several cross-ply configurations were included in the assessment
  - $[0°/90°]_{4S}$
  - $[0°_2/90°_2]_S$
  - $[0°_2/90°_4]_S$
  - $[0°_2/90°_6]_S$
  - $[0°_2/90°_8]_S$

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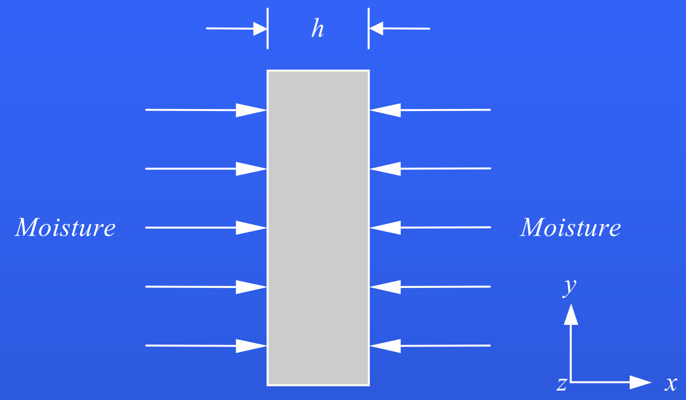
Moisture Diffusion



Diffusion coefficient D can be calculated using:

$$D = \frac{\pi}{16}\left(\frac{h(M_2 - M_1)}{M_\infty(\sqrt{t_2} - \sqrt{t_1})}\right)^2$$

M   Moisture content (wt%)

M_∞ Equilibrium moisture concentration

t   Time

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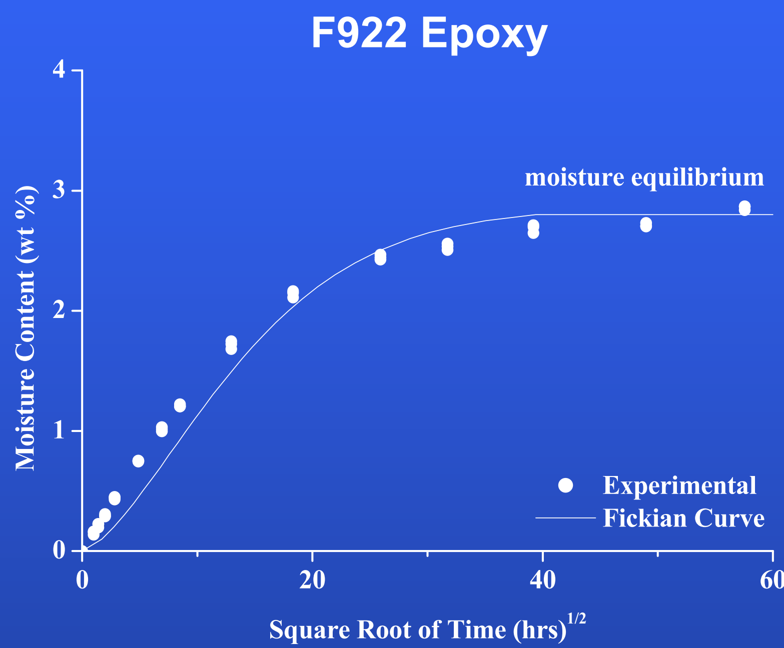
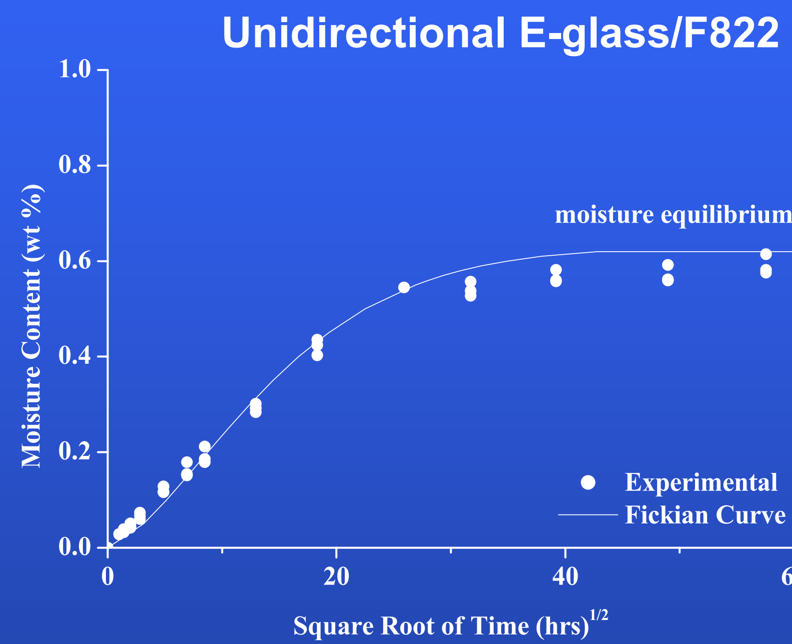
Fickian Diffusion





Diffusion Coefficients - Anisotropic Solids

Diffusion coefficients parallel and perpendicular to the fibres may be estimated using:

$$D_{11} = \left(1 - V_f\right) D_m \qquad D_{22} = \left(1 - 2\sqrt{\frac{V_f}{\pi}}\right) D_m$$

D_m diffusivity of the matrix

V_f fibre volume fraction

Unidirectional E-glass/F922

$$D_m = 8.3 \times 10^{-7}\ \mathrm{mm^2 s^{-1}}$$

$$D_{22} = 6.3 \times 10^{-8}\ \mathrm{mm^2 s^{-1}} \quad \text{(experimental)}$$

$$D_{22} = 7.3 \times 10^{-8}\ \mathrm{mm^2 s^{-1}} \quad \text{(predicted)}$$

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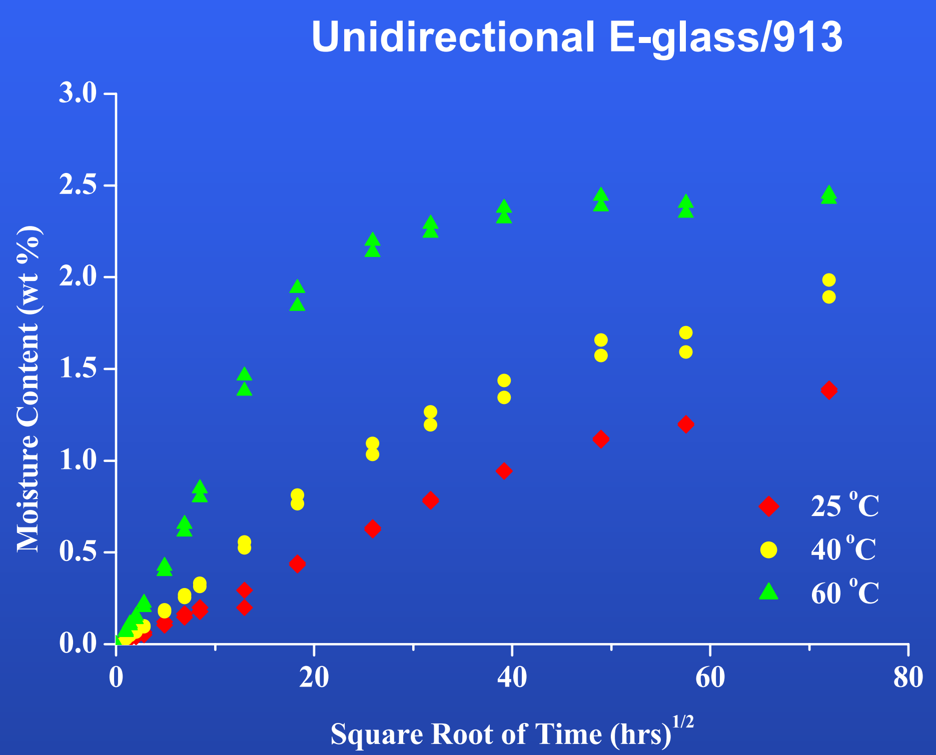
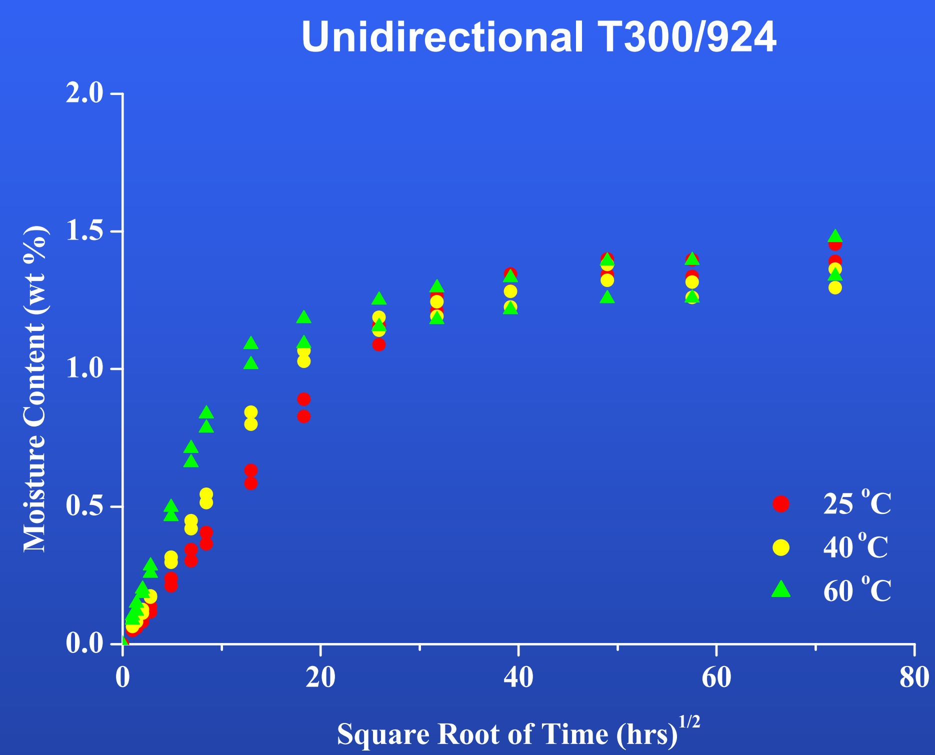
Diffusivity - Temperature Dependence





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Diffusivity - Temperature Dependence
Arrhenius Relationship

$$D = D_o \exp^{-E/RT}$$

D_o - constant

E - activation energy

R - ideal gas constant

T - absolute temperature

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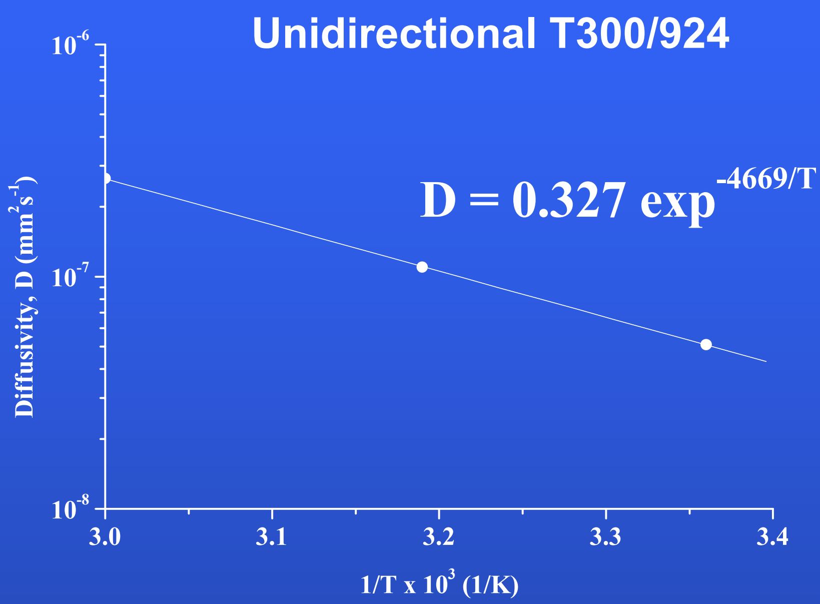
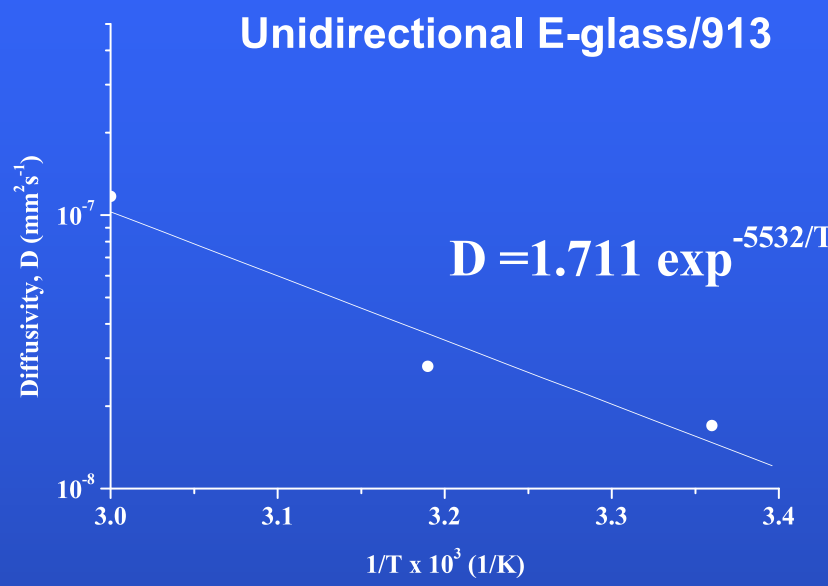
Transverse Diffusivity - Temperature Dependence





Arrhenius relationship:

$$D = D_o \exp^{-k/T}$$

Note: D_o and k are experimentally determined constants

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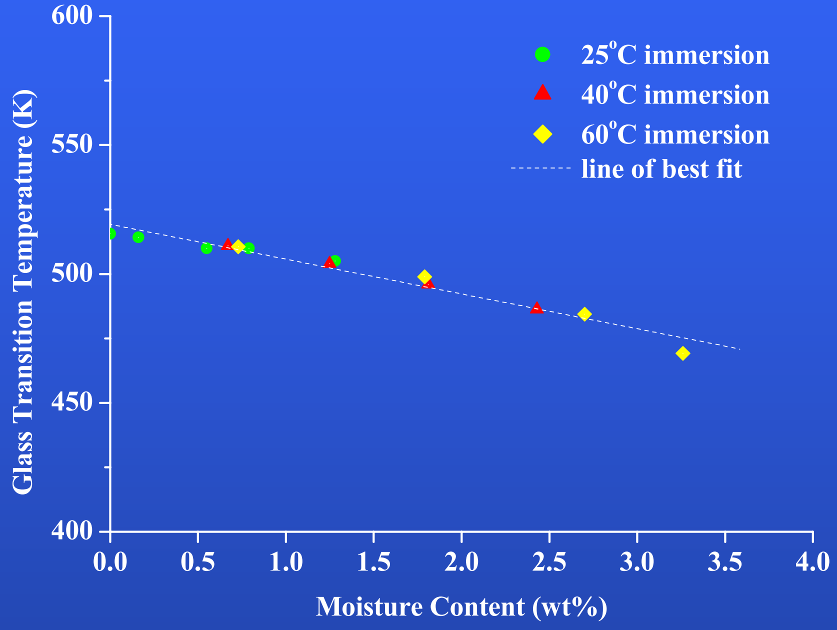
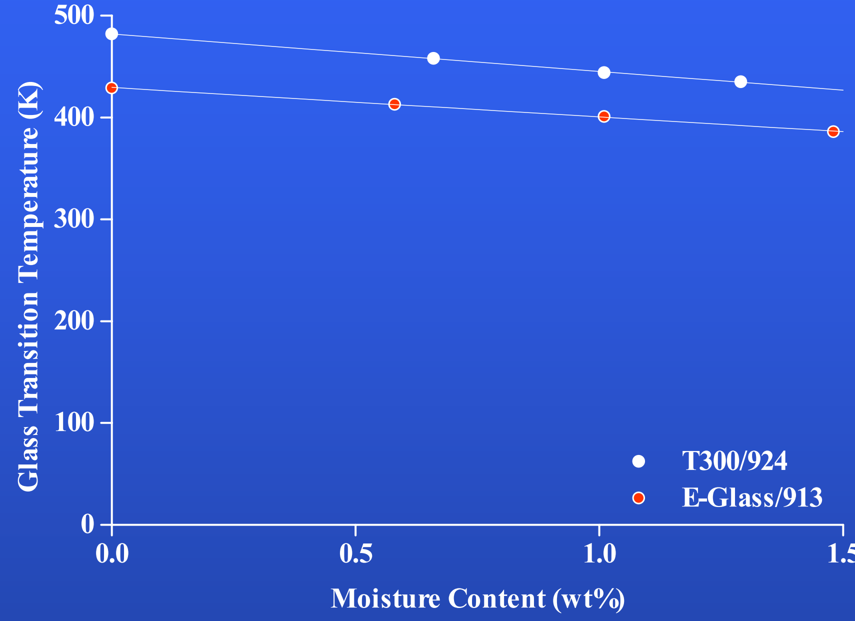
Glass Transition Temperature vs Moisture Content

F922 Epoxy



Unidirectional E-glass/913



$T_{gwet} = T_{gdry} - gM$

g   temperature shift (in K) per unit moisture absorbed

M   moisture content (wt %)

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Moisture Effects on Thermoset Resins

- Swelling, weight gain and cavity formation

- Plasticisation
  - Reduction in glass transition temperature
  - Lower operating temperatures
  - Reduction in stiffness and strength properties

- Chemical leaching
  - Loss of fillers, catalysts, hardeners, pigments or fire retardants

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Moisture Effects on E-Glass Fibres

- Leaching of alkali oxides (sodium + potassium) from the fibre surface
- Formation of surface micro-cracks $\Rightarrow$ stress concentrators
- Glass fibres slowly decompose/dissolve
- Permanent loss of strength (even after drying)
- Process accelerated with increasing temperature and stress

Moisture +Temperature Effects Unidirectional and Cross-Ply Laminates

- Conditioned at 70°C/85% RH (1,000 hrs)

- Micromechanics ⇒ lamina (layer) elastic and strength properties
  - Rule of mixtures, Halpin-Tsai, etc.

- Classical analysis ⇒ laminate elastic and strength property predictions
  - Loss of integrity (i.e. ply failure) - ply discount theory
  - All elastic properties (except E_{11}) of failed 90° plies set to zero

- CoDA ⇒ synthesise lamina and laminate properties

Tensile Properties for UD Laminates at Ambient (Measured/Predicted)

Material	Tensile Strength (MPa)	Tensile Modulus (GPa)	Poisson’s Ratio
E-glass/913 (dry)			
Longitudinal	1215/ 1178	43.0/ 36.6	0.30/ 0.33
Transverse	73.1/ 56.5	12.5/ 10.7	0.094/ 0.091
E-glass/F922 (dry)			
Longitudinal	1087/ 1479	43.0/ 46.0	0.31/ 0.33
Transverse	58.6/ 52.9	13.9/ 15.4	0.098/ 0.102
E-glass/F922 (wet)			
Longitudinal	797/ 1475	37.2/ 45.9	0.31/ 0.33
Transverse	64.1/ 36.5	14.3/ 14.5	0.108/ 0.096
T300/924 (dry)			
Longitudinal	1723/ 2193	133 ± 2/ 136	0.34/ 0.29
Transverse	92.7/ 56.1	8.5/ 8.7	0.020/ 0.021
HTA/F922 (dry)			
Longitudinal	1684/ 2016	126/ 134	0.32/ 0.34
Transverse	46.2/ 53.0	9.9/ 8.3	0.023/ 0.020
HTA/F922 (wet)			
Longitudinal	1728/ 2014	130/ 134	0.33/ 0.34
Transverse	48.6/ 36.4	8.9/ 7.9	0.022/ 0.022

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Strength of E-glass/F922 and HTA/F922 Cross-Ply Laminates (Ambient Test Conditions)

Material	First Ply Failure Stress (MPa)		Tensile Strength (MPa)	
	Measured	Predicted	Measured	Predicted
E-glass/F922 (dry)				
$[0_2/ 90_2]_S$	150	110	486	431
$[0_2/ 90_4]_S$	99	91	316	253
$[0_2/ 90_8]_S$	65	76	170	135
E-glass/F922 (wet)				
$[0_2/ 90_2]_S$	178	80	340	312
$[0_2/ 90_4]_S$	134	65	282	181
$[0_2/ 90_8]_S$	98	54	159	98
HTA/F922 (dry)				
$[0_2/ 90_2]_S$	360	455	814	972
$[0_2/ 90_4]_S$	135	322	516	649
$[0_2/ 90_6]_S$	149	255	407	484
HTA/F922 (wet)				
$[0_2/ 90_2]_S$	399	455	864	972
$[0_2/ 90_4]_S$	267	322	569	649
$[0_2/ 90_6]_S$	189	182	413	454

Longitudinal Moduli of E-glass/F922 and HTA/F922 Cross-Ply Laminates (Ambient Test Conditions)

Material	Initial Modulus (GPa) Measured	Initial Modulus (GPa) Predicted	Final Modulus (GPa) Measured	Final Modulus (GPa) Predicted
E-glass/F922 (dry)				
$[0_2/ 90_2]_S$	29.4	28.6	23.5	22.1
$[0_2/ 90_4]_S$	26.2	23.1	16.1	14.5
$[0_2/ 90_8]_S$	20.2	16.8	9.4	8.5
E-glass/F922 (wet)				
$[0_2/ 90_2]_S$	25.3	28.1	21.4	22.0
$[0_2/ 90_4]_S$	26.8	22.5	16.7	14.5
$[0_2/ 90_8]_S$	19.2	16.1	9.5	8.5
HTA/F922 (dry)				
$[0_2/ 90_2]_S$	64.4	70.2	60.7	66.3
$[0_2/ 90_4]_S$	46.7	49.8	41.9	44.4
$[0_2/ 90_6]_S$	37.6	39.1	31.8	32.3
HTA/F922 (wet)				
$[0_2/ 90_2]_S$	66.4	70.0	61.0	66.2
$[0_2/ 90_4]_S$	47.0	49.8	42.1	44.4
$[0_2/ 90_6]_S$	38.1	38.9	31.7	31.8

Poisson's Ratios of E-glass/F922 and HTA/F922 Cross-Ply Laminates (Ambient Test Conditions)

Material	Initial Poisson's Ratio		Final Poisson's Ratio	
	Measured	Predicted	Measured	Predicted
E-glass/F922 (dry)				
$[0_2/90_2]_S$	0.159	0.162	0.084	0.084
$[0_2/90_4]_S$	0.134	0.138	0.067	0.047
$[0_2/90_8]_S$	0.128	0.122	0.056	0.027
E-glass/F922 (wet)				
$[0_2/90_2]_S$	0.155	0.154	0.105	0.080
$[0_2/90_4]_S$	0.133	0.130	0.060	0.044
$[0_2/90_8]_S$	0.119	0.115	0.038	0.026
HTA/F922 (dry)				
$[0_2/90_2]_S$	0.042	0.040	0.040	0.019
$[0_2/90_4]_S$	0.042	0.031	0.027	0.010
$[0_2/90_6]_S$	0.041	0.028	0.022	0.007
HTA/F922 (wet)				
$[0_2/90_2]_S$	0.049	0.038	0.038	0.019
$[0_2/90_4]_S$	0.042	0.031	0.028	0.010
$[0_2/90_6]_S$	0.039	0.027	0.021	0.007

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Temperature Dependence - Unidirectional T300/924

Property	Temperature (°C)		
	-40	20	120
Longitudinal tensile modulus, E_{11}^{T} (GPa)			
Measured	133	135	139
Predicted	144	143	142
Transverse tensile modulus, E_{22}^{T} (GPa)			
Measured	10.8	10.5	8.2
Predicted	13.3	10.5	8.4
Longitudinal shear modulus, G_{12} (GPa)			
Measured	5.9	5.1	3.5
Predicted	7.7	5.1	4.5
Longitudinal Poisson's ratio, ν_{12}			
Measured	0.37	0.40	0.39
Predicted	0.40	0.40	0.39
Longitudinal tensile strength, S_{11}^{T} (MPa)			
Measured	1,750	1,683	1,550
Predicted	2,211	2,195	2,186
Transverse tensile strength, S_{22}^{T} (MPa)			
Measured	63.6	60.8	56.1
Predicted	48.9	44.1	24.7

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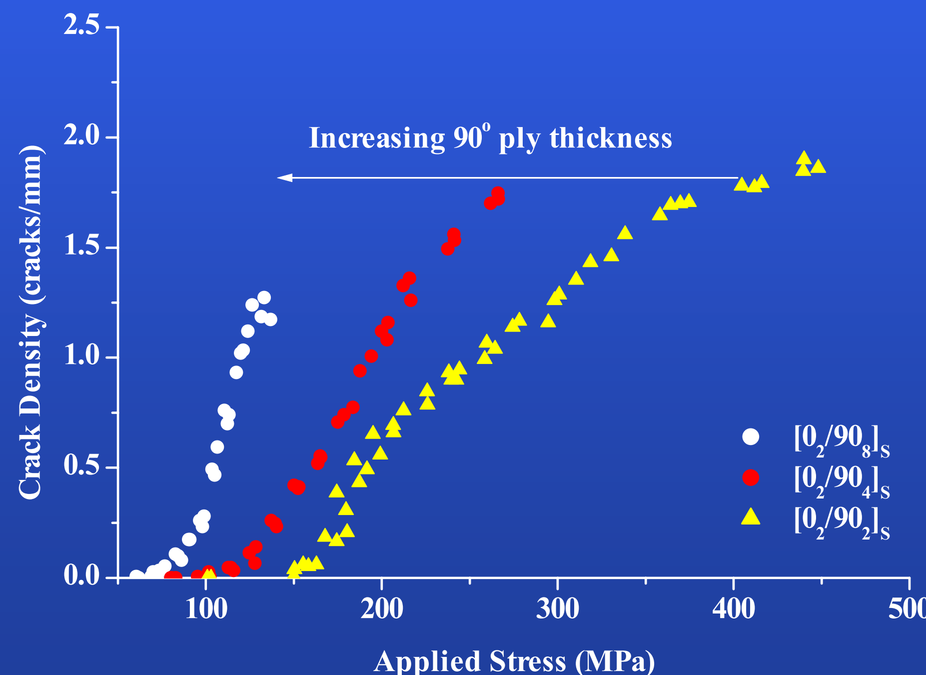
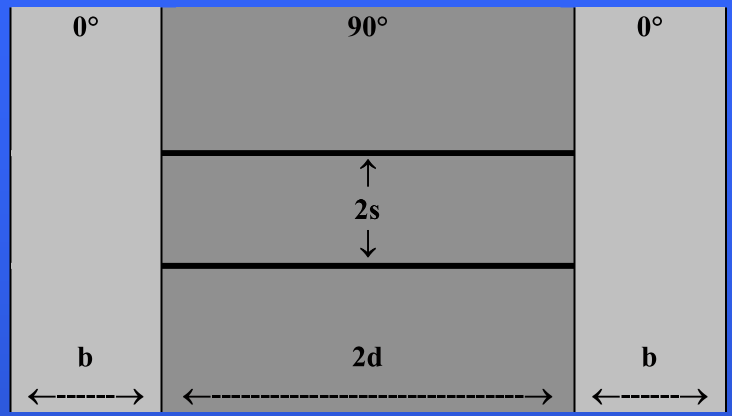
Transverse Cracking
E-glass/F922 Cross-Ply Laminates



Shear Lag Theory



- Reduction in E_{xx} as a function of average crack spacing, 2s, is given by:

$$\frac{E_{xx}}{E_{xx0}} = \frac{1}{1 + \frac{E_{xx0}}{E_{11}}\left(\frac{b+d}{b} - \frac{E_{11}}{E_{xx0}}\right)\frac{\tanh(\lambda s)}{\lambda s}}; \quad \lambda^2 = \frac{3G_{12}(b+d)E_{xxo}}{d^3 b E_{22} E_{11}}$$

- E_{xx}, E_{xx0}, E_{11} and E_{22} are the longitudinal moduli of the cracked composite, uncracked composite, the longitudinal plies and the transverse plies, respectively.

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Longitudinal Moduli at Onset of Failure for Cross-Ply Laminates E-glass/F922 and HTA/F922 (Ambient Test Conditions)

Material	Measured	Laminate Analysis	Shear Lag Theory
E-glass/F922			
$[0_2/ 90_2]_S$	23.5	22.1	23.1
$[0_2/ 90_4]_S$	16.1	14.5	16.1
$[0_2/ 90_8]_S$	9.4	8.5	11.5
HTA/F922			
$[0_2/ 90_2]_S$	60.7	66.3	67.2
$[0_2/ 90_4]_S$	41.9	44.4	45.6
$[0_2/ 90_6]_S$	31.8	32.3	34.2

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Empirical Approach - Non-Dimensional Temperature Laminate Property Predictions

$$\frac{P}{P_o} = \left(\frac{T_{gwet} - T}{T_{gdry} - T_o} \right)^n \quad \text{where} \quad T_{gwet} = T_{gdry} - gM$$

P Material property (e.g. longitudinal tensile strength)

P_O Initial property value of the dry material at room or reference temperature T_o (296 K)

T Test temperature (K)

T_g Glass transition temperature of the material

g Temperature shift (in K) per unit moisture absorbed

M amount of moisture absorbed (wt %)

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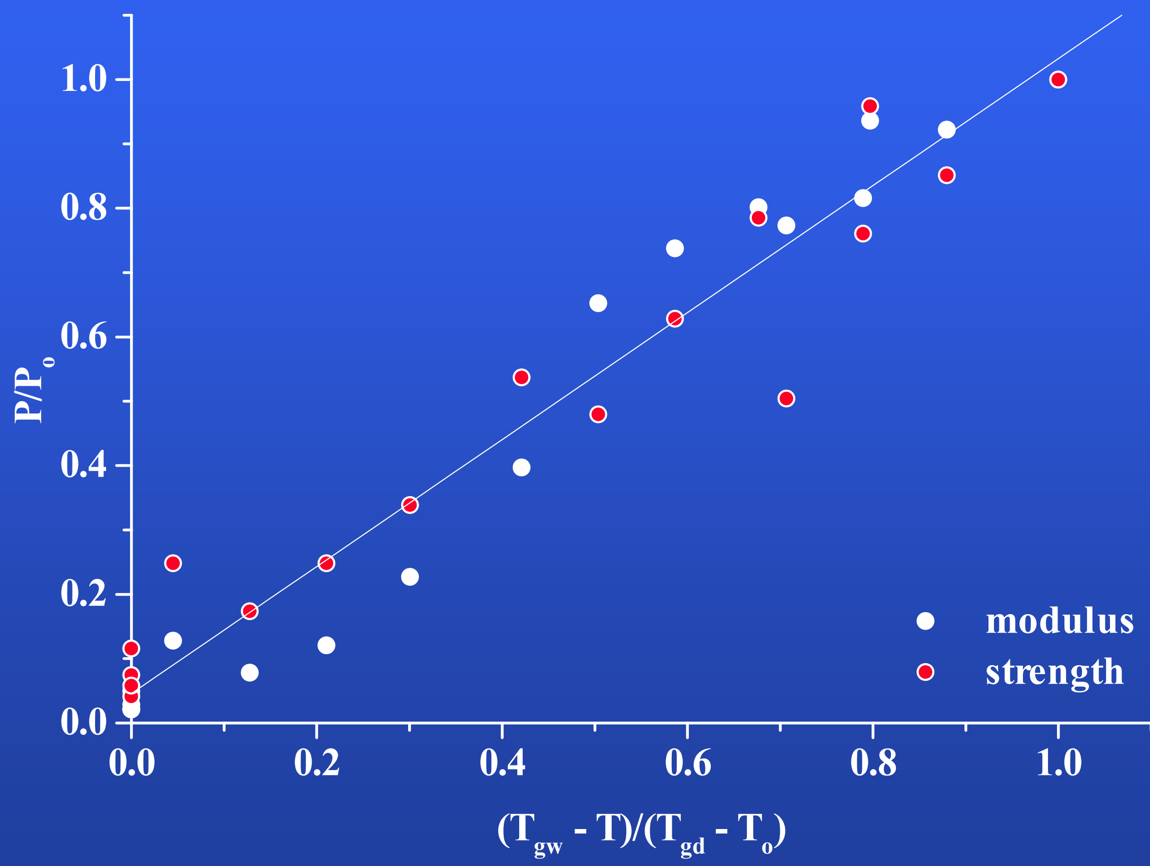
Transverse Properties
Unidirectional E-glass/913 Epoxy



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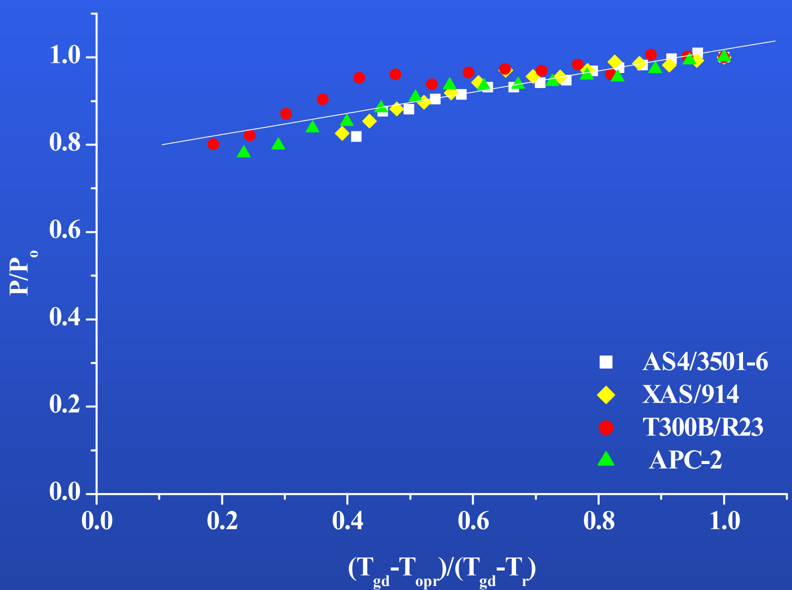
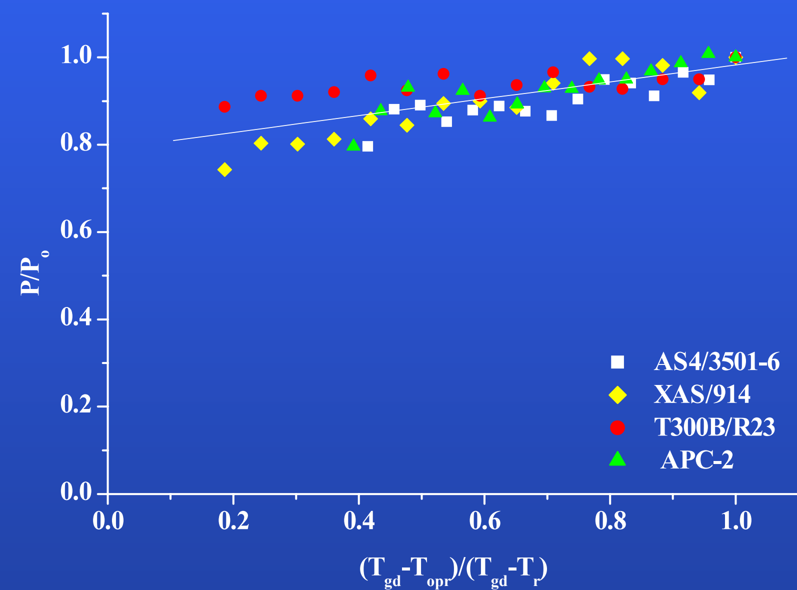
In-Plane Shear Properties
Unidirectional Laminates

Shear Modulus



Shear Strength



Kitagawa Power-Law Relationship
Shear Properties

Kitagawa power-law relationship between shear yield stress, τ, and shear modulus, G, for glassy polymers is:

- $$\frac{T_o \tau}{T \tau_o} = \left(\frac{T_o G}{T G_o} \right)^n$$

T_o Reference temperature (K) - generally room temperature (296K)

τ_o Shear yield stress at T_o

G_o Shear modulus at T_o

n Constant

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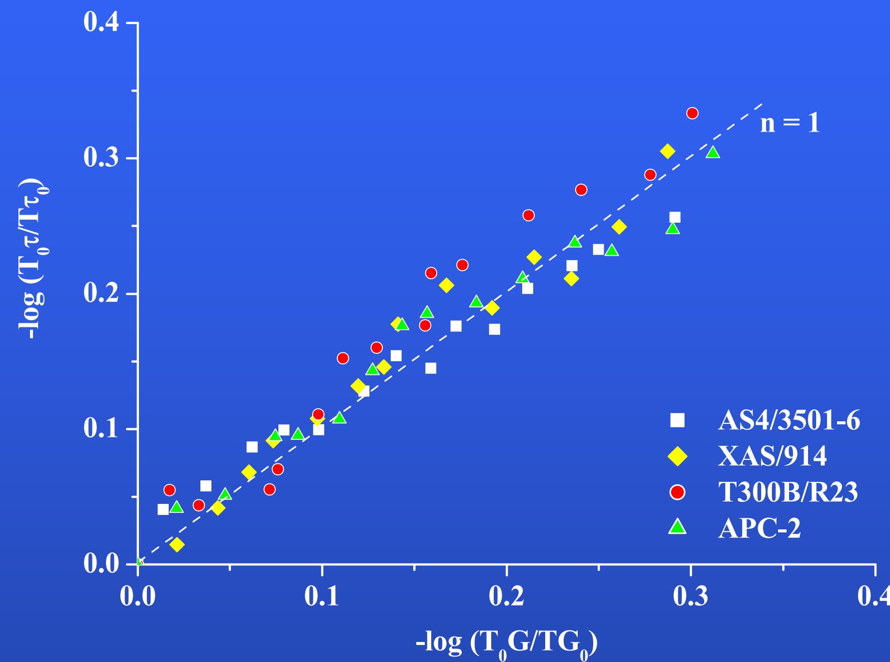
Kitagawa Power-Law – In-Plane Shear Properties Unidirectional CFRP Laminates



Value of Exponent n

AS4/3501-6	XAS/914	T300B/R23	APC-2	Victrex PEEK
0.85	1.00	1.10	0.89	1.07

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Kitagawa Power-Law Relationship
Flexural Properties

Kitagawa power-law relationship between flexural strength, σ_f, and flexural modulus, E_f, for glassy polymers is:

- $$\frac{T_o \sigma_f}{T \sigma_{fo}} = \left(\frac{T_o E_f}{T E_{fo}} \right)^n$$

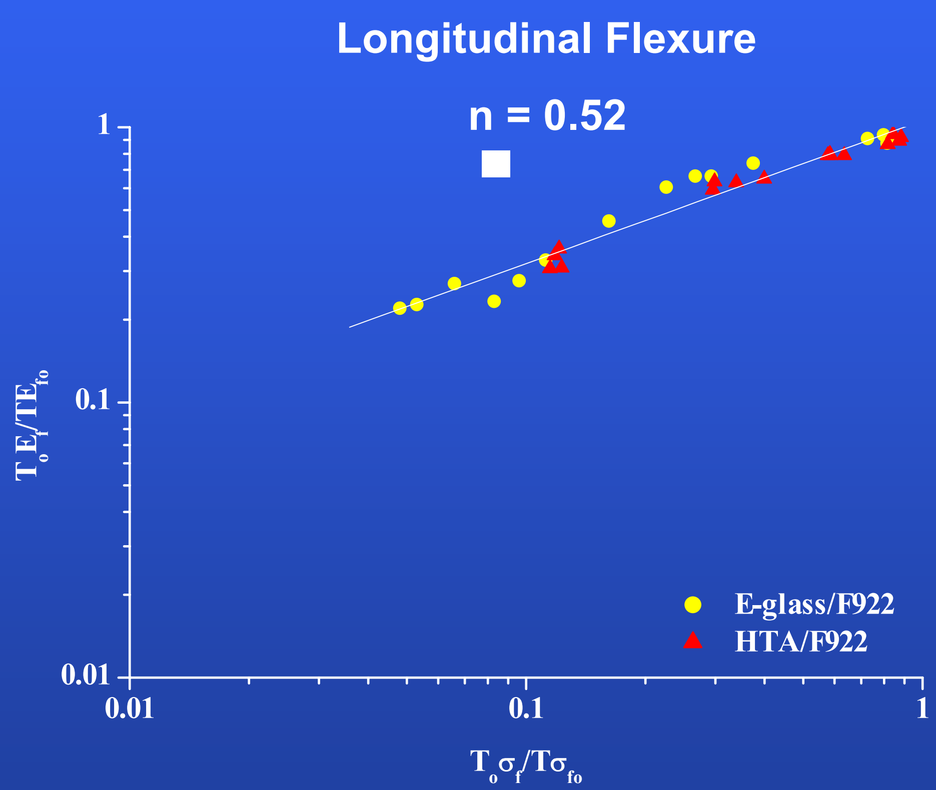
T_o Reference temperature (K)

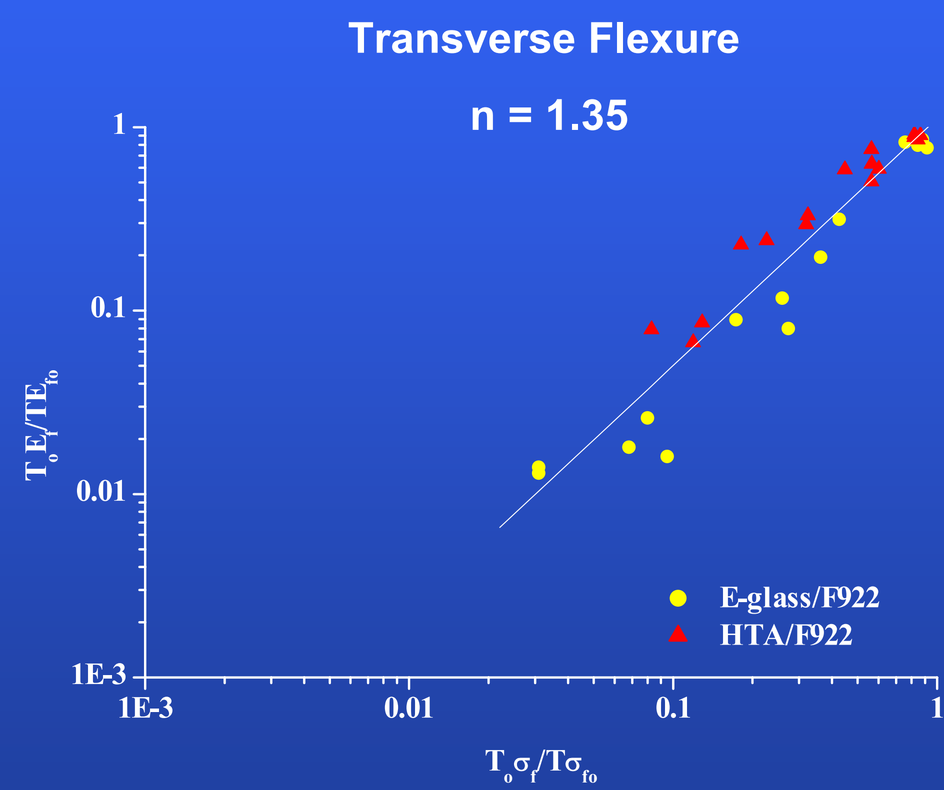
σ_{fo} Flexural strength at T_o

E_{fo} Flexural modulus at T_o

n Constant

Kitagawa Power-Law – Flexural Properties
Unidirectional E-glass/F922 and HTA/F922





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Concluding Remarks

- Micromechanics combined with laminate analysis proved satisfactory for predicting tensile properties of dry and moisture conditioned unidirectional and cross-ply laminates.

- Using ply discount theory, it was possible to determine the elastic properties of damaged cross-ply laminates prior to final ply failure.

- Shear-lag theory can be used to determine changes in laminate stiffness with transverse cracking – mechanistic/physics based models offer improved accuracy.

- Kitagawa power-law + non-dimensional temperature analysis can be used to determine shear and flexural properties of unidirectional laminates as a function of temperature and moisture content.

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