THE IN SITU TRANSVERSE LAMINA STRENGTH OF COMPOSITE LAMINATES

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The objective of the work reported in this presentation is to determine the in situ transverse strength of a lamina within a composite laminate. From a fracture mechanics standpoint, in situ strength may be viewed as constrained cracking that has been shown to be a function of both lamina thickness and the stiffness of adjacent plies that serve to constrain the cracking process. From an engineering point of view, however, constrained cracking can be perceived as an apparent increase in lamina strength. With the growing need to design more highly loaded composite structures, the concept of in situ strength may prove to be a viable means of increasing the design allowables of current and future composite material systems.

As a means of introducing the current research, some earlier results for cross-plied graphite/epoxy and glass/epoxy laminates and $[\pm 25/90_n]_s$ graphite/epoxy laminates are presented. In this work the strain at onset of transverse cracking is seen to be a strong function of 90^o-laminae thickness. In the figures that follow, ε represents the total or measured strain and $\bar{\varepsilon}$ represents the elastic strain ($\bar{\varepsilon} = \varepsilon - \alpha\Delta T$). Data are also presented indicating that for an off-axis loading angle greater than about 5^o, matrix cracking is the initial lamina failure mode. Experimental results from this research are given, and the σ_2 stress (in situ transverse strength) in the 90^o laminae of the $[\pm\theta/90_n]_s$ laminates is plotted, based on laminated plate theory predictions, at the onset of transverse cracking. The separate contributions of applied and residual thermal stresses on the predicted in situ strength are illustrated, and the effect of the different constraining $\pm\theta$ laminae on in situ strength (which has been termed an interaction effect) is examined.

A simplified one-dimensional analytical model is presented that is used to predict the strain at onset of transverse cracking. While it is accurate only for the most constrained cases, the model is important in that the predicted failure strain is seen to be a function of a lamina's thickness d and of the extensional stiffness bE_θ of the adjacent laminae that constrain crack propagation in the 90^o laminae.

The possibility is investigated of using a Weibull brittle failure model, in which the probability of failure is related to the volume of stressed material, to predict the in situ strength. Using a shape parameter determined for a material system (T300/5208) similar to that used in the current investigation (T300/934), it was seen that the Weibull model underestimated the observed thickness effects. Additionally, there is no mechanism in the model to account for the interaction effect on in situ strength. However, it was interesting to note that by assuming that the shape parameter was not a material parameter, we could quite accurately fit the experimental behavior.

In closing, perhaps the most important conclusion that can be drawn from these results is that strength predictions for failure modes associated with matrix cracking in composite laminates should not be based upon the concept that strength is an intrinsic material property. Work is currently under way to investigate the possibility of integrating these results into existing strength theories.

REFERENCES

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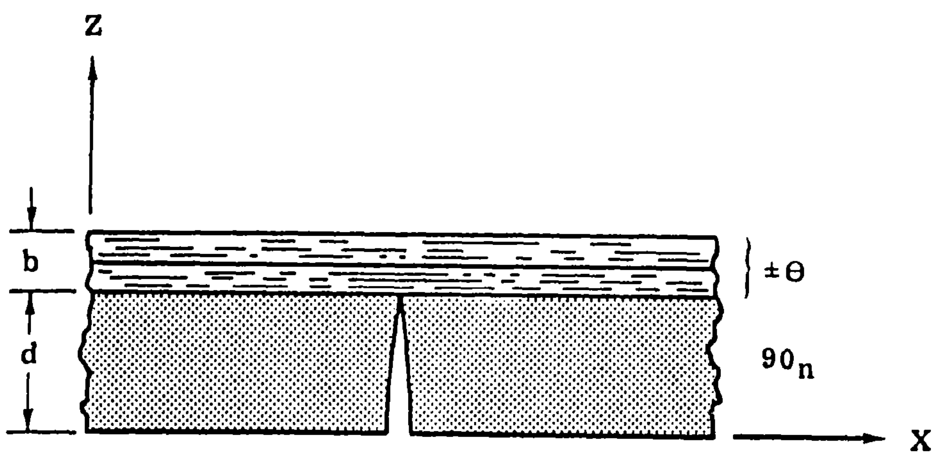
2. Crossman, R. W.; and Wang, A. S. D.: The Dependence of Transverse Cracking and Delamination on Ply Thickness in Graphite/Epoxy Laminates. Damage in Composite Materials, K. L. Reifsnider, ed., ASTM STP 775, 1982.

3. Bader, M. G.; and Curtis, P. T.: The Micromechanics of Fibre Composites - Carbon Fibre Programme. Dept. of Metallurgy and Materials Technology, Univ. of Surrey, U.K., 1977.

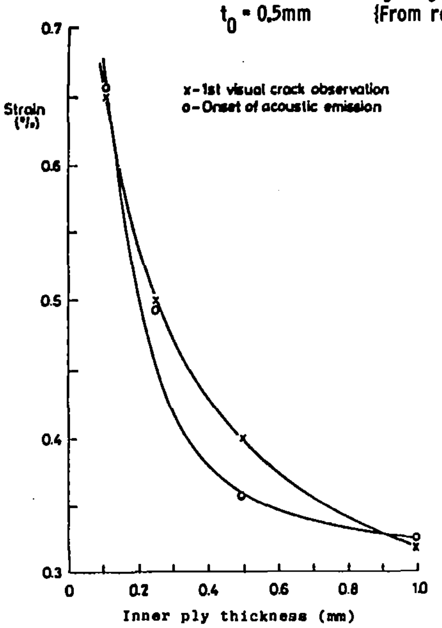
Fracture modes in off-axis tensile loading of $(0_8)_T$ Modmor-I/epoxy laminates

Mode	Load angle
Longitudinal tension	$0 < \theta < 5^0$
Intralamina shear	$5 < \theta < 20^0$
Mixed mode	$20 < \theta < 45^0$
Transverse tension	$45 < \theta < 90^0$

Laminate geometry of $[\pm\theta/90_{n\ s}]$ specimens



Strain at initiation of transverse cracking in graphite/epoxy $[0/90/0]_t$ laminates;
$t_0 = 0.5$mm {From ref. 1}



t_{90} (mm)	$\bar{\varepsilon}_2$
0.125	.798
0.25	.627
0.50	.495
1.00	.461

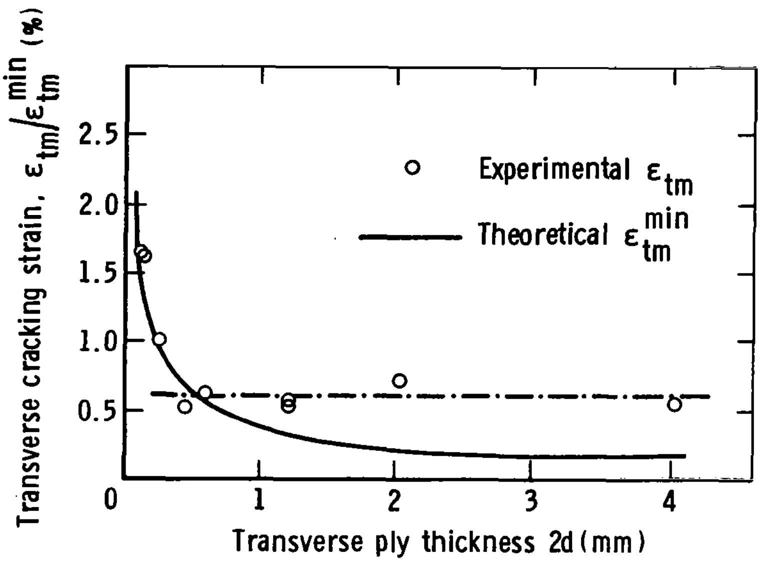
Calculated transverse stress in 90^0 plies of $[\pm 25/90_n]_s$
T300/934 laminates at transverse cracking onset
{From ref. 2}

N	YT*	ϵ_x(%)
.5	106 (15,370)	.650**
1	111 (16,095)	.665**
2	83.9(12,165)	.415
3	76.5(11,092)	.360
4	71.2(10,324)	.325
6	69.4(10,063)	.330
8	69.2(10,034)	.345

*MPa (Psi)

**Ultimate failure strain

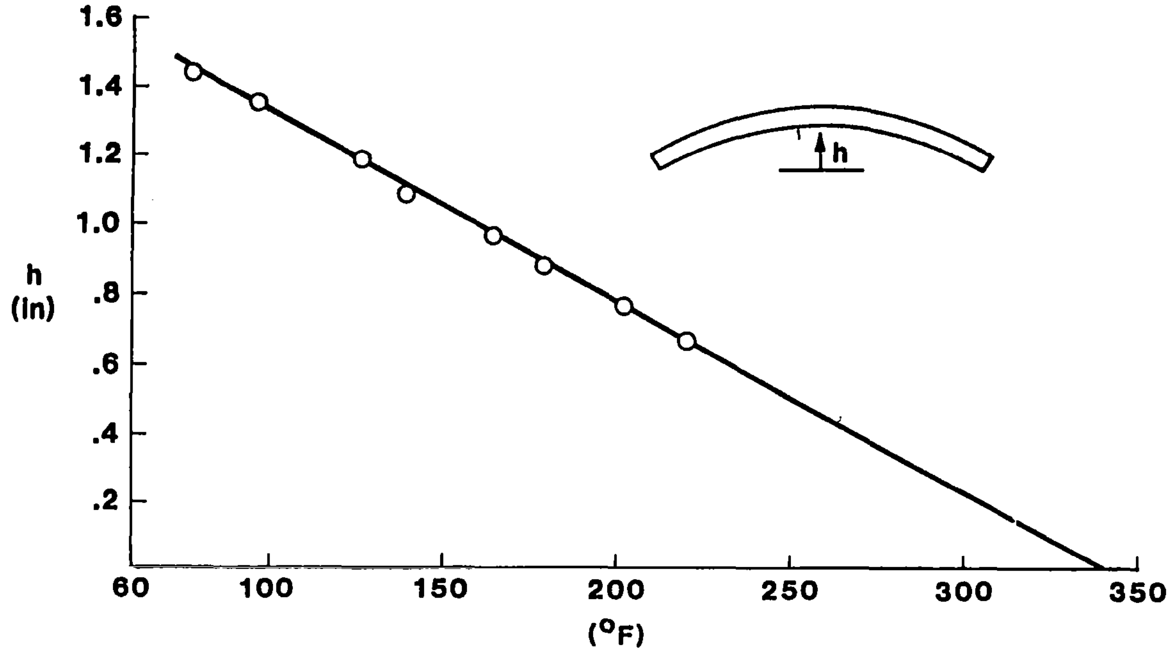
Mechanical strain at onset of transverse cracking in $[0/90/0]_t$ glass fiber/epoxy laminates; $t_0 = 0.5$mm {From ref. 3}



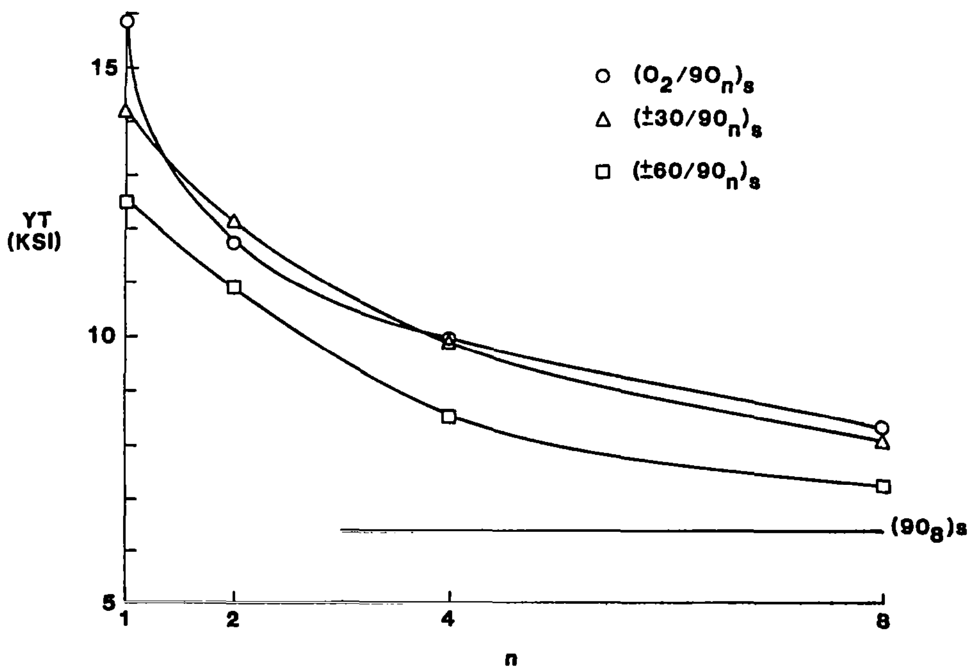
Experimental results

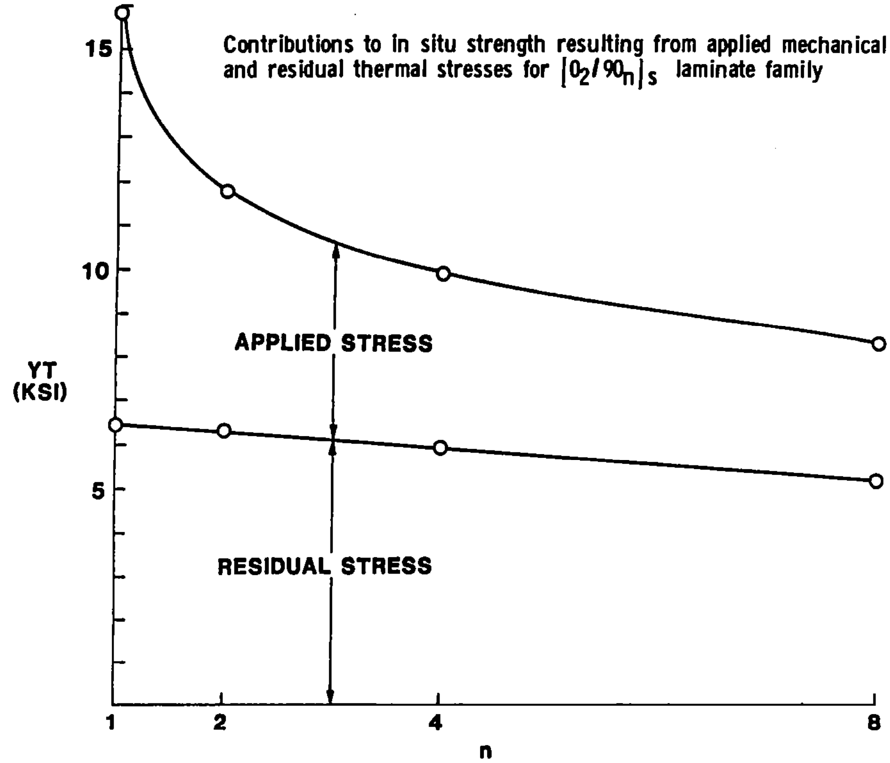
Specimen Family	n	Number of Specimens	E_x(Msi)	ε_x(%)	N_x(lb/in)
$(0_2/90_n)_s$	1	4	13.73	.555 (.549-.562)	2428.9 (2390.4-2491.0)
	2	4	10.92	.319 (.287-.378)	1456.3 (1381.5-1676.5)
	4	4	7.51	.236 (.221-.242)	1158.4 (1083.7-1184.6)
	8	5	5.29	.188 (.173-.225)	1034.7 (894.8-1289.9)
$(\pm30/90_n)_s$	1	4	7.73	.498 (.489-.506)	1219.9 (1206.3-1259.8)
	2	4	6.41	.386 (.371-.431)	1036.3 (995.5-1150)
	4	3	4.82	.293 (.267-.338)	865.4 (799.2- 997.5)
	8	4	3.43	.242 (.231-.254)	860.5 (796.9- 898.8)
$(\pm60/90_n)_s$	1	2	2.08	.592 (.568-.615)	387.1 (374.4- 399.7)
	2	4	1.95	.553 (.475-.596)	449.5 (399.8- 474.5)
	4	4	1.86	.453 (.405-.503)	511.1 (471.7- 524.3)
	8	4	1.73	.405 (.387-.416)	717.2 (701.8- 742.2)

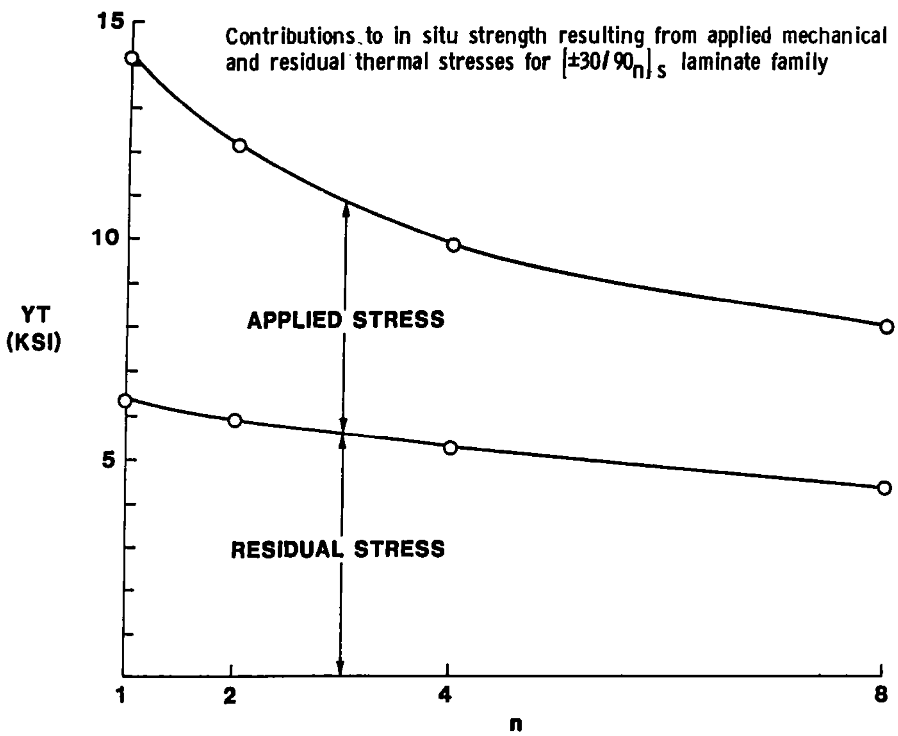
Cord height of nonsymmetric $[0_4/90_4]_t$ T300/934 laminate as a function of temperature

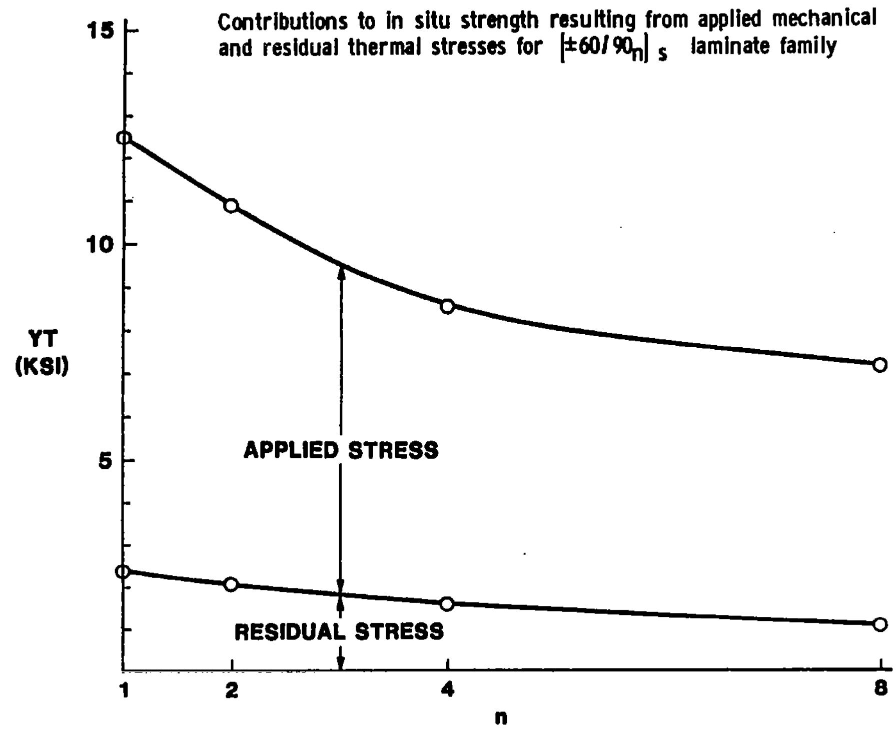


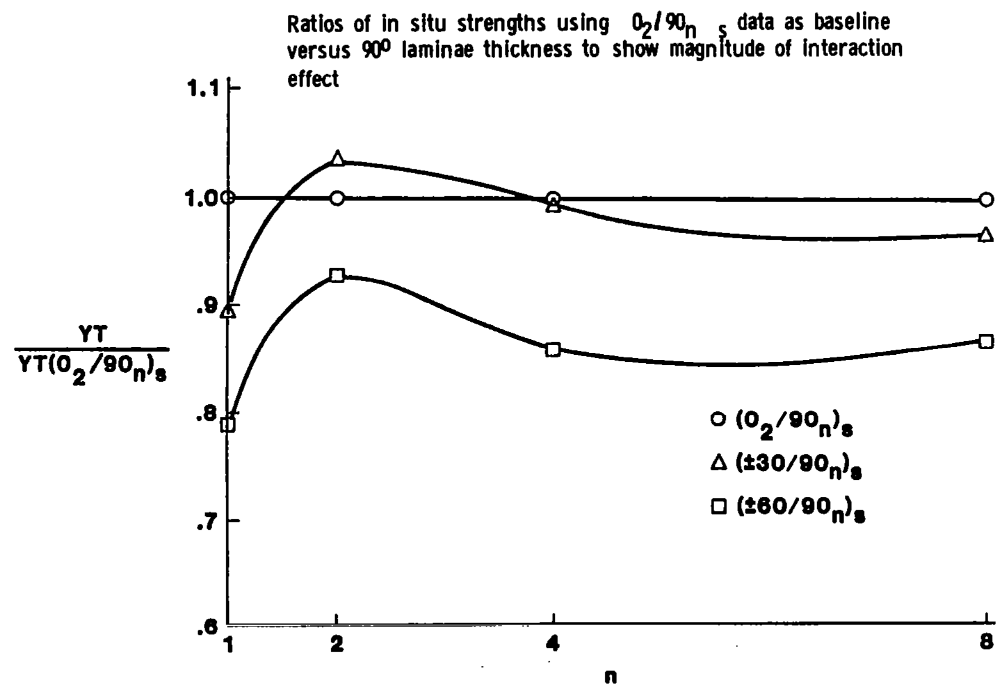
In situ transverse lamina strengths as a function of thickness and orientation of adjacent ±θ laminae.




Contributions to in situ strength resulting from applied mechanical and residual thermal stresses for $[0_2/90_n]_s$ laminate family
15
10
5
YT
(KSI)
APPLIED STRESS
RESIDUAL STRESS
1
2
4
8
n


Contributions to in situ strength resulting from applied mechanical and residual thermal stresses for $[\pm 30/90_n]_s$ laminate family
15
10
5
YT
(KSI)
APPLIED STRESS
RESIDUAL STRESS
1
2
4
8
n


Contributions to in situ strength resulting from applied mechanical and residual thermal stresses for $[\pm 60/90_n]_s$ laminate family
15
10
5
YT
(KSI)
APPLIED STRESS
RESIDUAL STRESS
1
2
4
8
n


Ratios of in situ strengths using $0_2/90_n$ s data as baseline versus 90^0 laminae thickness to show magnitude of interaction effect
1.1
1.0
.9
.8
.7
.6
$\frac{YT}{YT(0_2/90_n)_s}$
○ $(0_2/90_n)_s$
△ $(\pm 30/90_n)_s$
□ $(\pm 60/90_n)_s$
1
2
4
8
n

Analytical model for predicting onset of transverse cracking

Griffith energy balance used in conjunction with a one-dimensional shear lag model to account for load transfer resulting from a Mode I crack spanning the 90 laminae

Griffith energy balance: $\Delta W - \Delta U = 2\gamma_{90} V_{90}$ (per unit area)

One-dimensional shear lag model: $\Delta\sigma = \frac{d}{b} E_2 \bar{\varepsilon}_2^{TC} \mathrm{EXP}(-\phi^{\frac{1}{2}} X)$

Resulting expression for in situ transverse strength:

$$\bar{\varepsilon}_2^{TC} = \left[\frac{b\, E_\theta m}{(b+d)\, d^2 E_X}\right]^{\frac{1}{2}} \; ; \quad m = \frac{G_{23}\, G_{I_c}^2}{E_2^3}$$

Weibull material (?)

$$P_s(v) = \exp\left\{-v\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^{\alpha}\right\}$$

where $\alpha \equiv$ shape parameter

$\sigma_u \equiv$ strength cut-off

$\sigma_0 \equiv$ scale parameter

$$P_s(v_1) = P_s(v_2) \Rightarrow \left(\frac{v_2}{v_1}\right)^{1/\alpha} = \frac{\sigma_1 - \sigma_u}{\sigma_2 - \sigma_u}$$

For T300/5208, $\alpha = 7.68$; $\left(\frac{v_{n=8}}{v_{n=1}}\right)^{1/\alpha} = 8^{1/7.68} \approx 1.31$

Now, consider the $\left[0_2/90_n\right]_s$ family (assuming $\sigma_u = 0$):

$$\frac{\sigma_1}{\sigma_8} = \frac{15,847}{8,350} = 1.89\ ?$$

Summary of in situ transverse strengths

Specimen Family	n	$\bar{\epsilon}_2^{exp.}$ (%)	$\bar{\epsilon}_2^{pred.}$ (%)	YT(psi)
$(0_2/90_n)_s$	1	.953	.950	15,847
	2	.700	.662	11,751
	4	.590	.465	9,944
	8	.497	.316	8,350
$(\pm 30/90_n)_s$	1	.879	.839	14,154
	2	.739	.579	12,140
	4	.604	.397	9,869
	8	.496	.269	8,063
$(\pm 60/90_n)_s$	1	.721	.815	12,503
	2	.666	.545	10,909
	4	.540	.352	8,540
	8	.463	.223	7,234

Experimental versus predicted in situ strength ratios

$$\frac{YT_n}{YT_1} = \left(\frac{V_1}{V_n}\right)^{1/\alpha}$$

Specimen Family	α	Vol. Ratio, $\frac{V_n}{V_1}$	Experimental, $\frac{YT_1}{YT_n}$	Predicted, $\frac{YT_1}{YT_n}$
$(0_2/90_n)_s$	3.245	2:1	1.349	1.238
		4:1	1.594	1.533
		8:1	1.898	1.898
$(\pm 30/90_n)_s$	3.697	2:1	1.166	1.206
		4:1	1.434	1.455
		8:1	1.755	1.755
$(\pm 60/90_n)_s$	3.802	2:1	1.146	1.200
		4:1	1.464	1.440
		8:1	1.728	1.728

Summary

DESIGN IMPLICATIONS:

- INDIVIDUAL PLIES SHOULD BE DISPERSED RATHER THAN STACKED WHEN PRACTICAL
- LAMINATE FAILURE ANALYSES SHOULD INCLUDE THESE IN SITU STRENGTH EFFECTS AS SOON AS A METHODOLOGY HAS BEEN ESTABLISHED FOR QUANTIFYING THEM FOR GENERAL LOADING CONDITIONS

WORK IN PROGRESS:

- EXPERIMENTAL DETERMINATION OF EFFECT OF τ_{12} ON ONSET OF TRANSVERSE CRACKING
- ANALYTICAL SIMULATION OF TRANSVERSE CRACKING USING A GENERALIZED PLANE STRAIN FE MODEL
  1) BETTER ANALYTICAL REPRESENTATION OF CRACKING PHENOMENON
  2) CAN ACCOUNT FOR MIXED MODE EFFECTS
  3) ANALYTICAL DERIVE DESIGN CURVES