Ultra-thin Carbon Fiber Composites: Constitutive Modeling and Applications to Deployable Structures

Lectures 1-2

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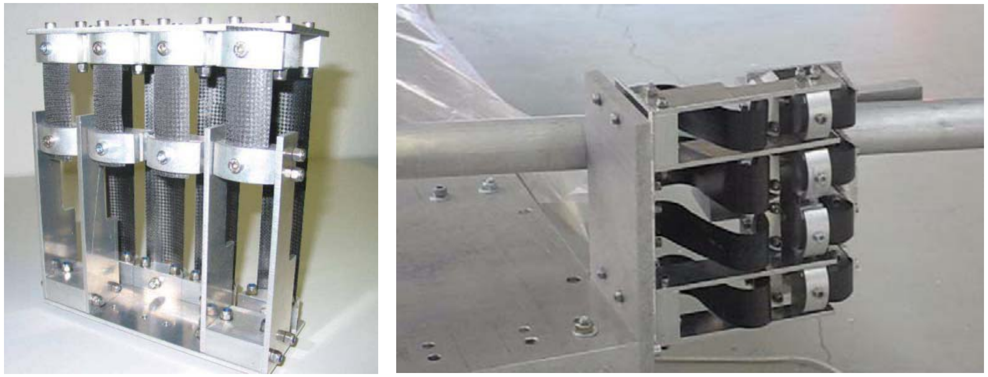
Outline

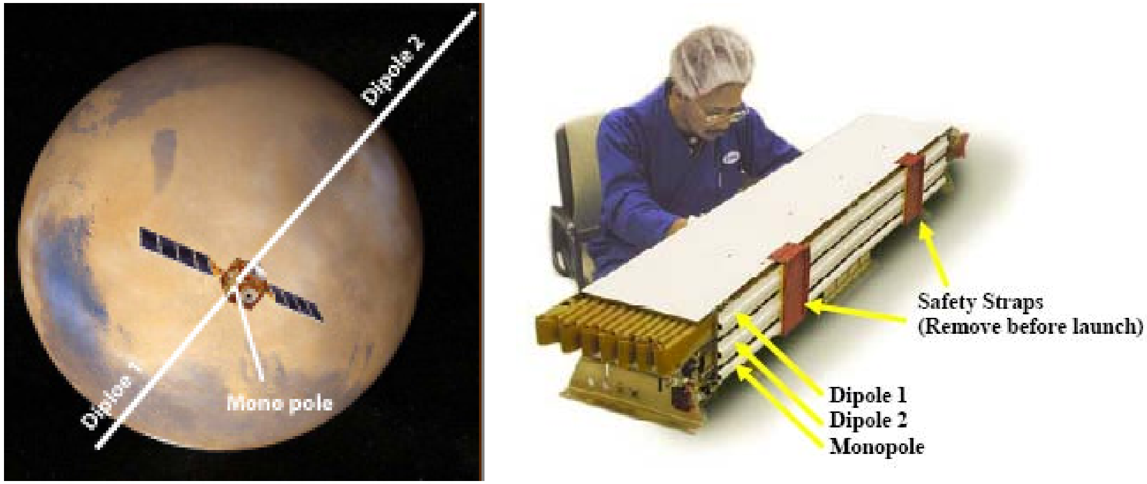
- Applications and examples of ultra-thin composites
- Composites made from single-ply triaxial weave fabric
- Elastic constitutive model

Applications of Ultra-thin Composites in Deployable Structures



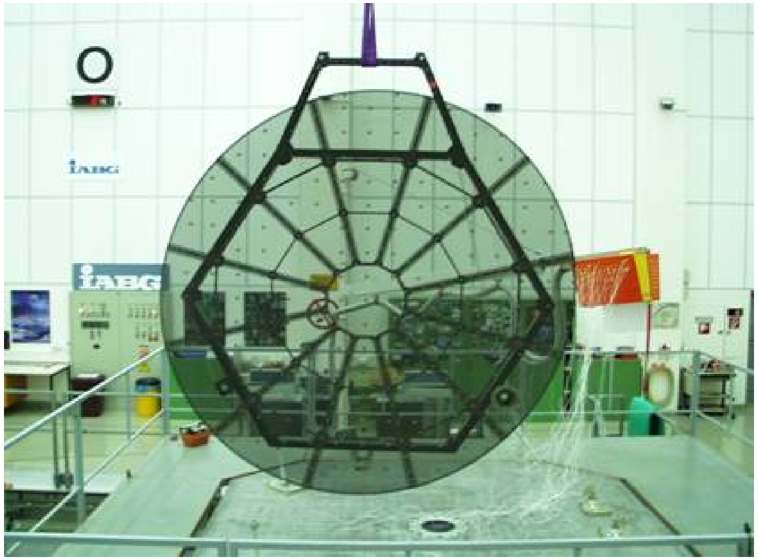
Self-motorized deployment mechanism Boesch et al. (2008)

Ultra lightweight
deployable
CFRP boom
(DLR)



Flattenable Foldable Tube
(Astro Aerospace)

Applications of Ultra-thin Composites in Deployable Structures



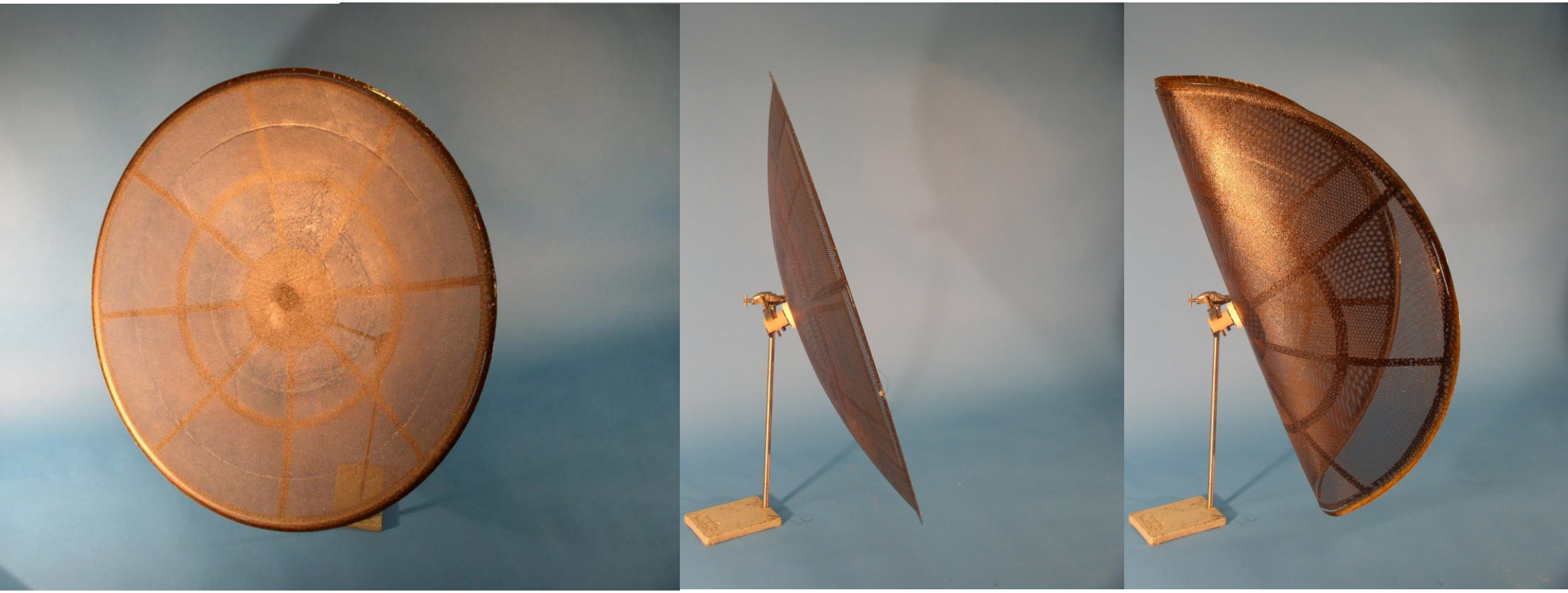
(courtesy of EADS-ST)

- Rigid reflector made of carbon fiber Triaxial Weave Fabric sandwich

Boeing Springback Reflector

- Monolithic structure, mainly single ply triaxial CFRP .
- Folded elastically, deployed dynamically.
- Geometric accuracy issues.

Stiffened Spring Back Reflector



0.8 m diameter demonstrator

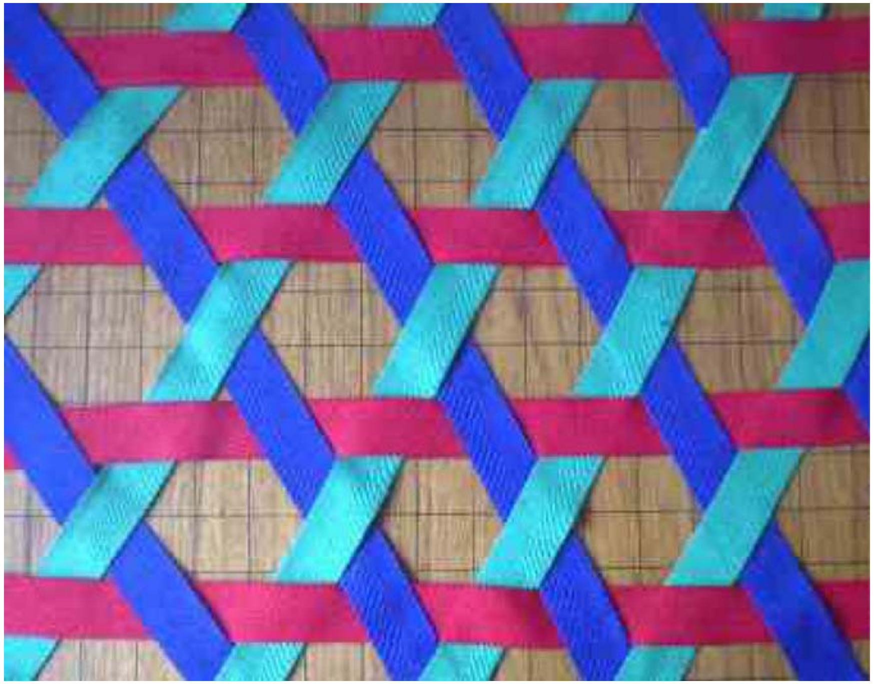
Background to Triaxial Weave Fabric

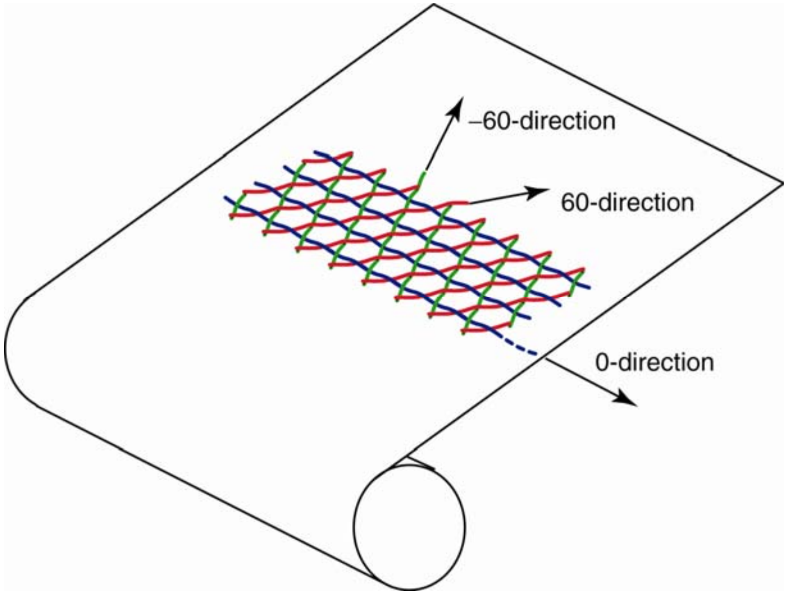
- Invented by Norris Dow (patented in 1969) working with Francis Rogallo on a paraglider for a reentry vehicle from Mercury.
- A model of the paraglider, made of biaxial weave fabric became badly distorted during a test in the Langley wind tunnel
- Dow founded N.F. Doweave, Inc.

Triaxial Weave Fabrics from Sakase

Style No.	Warp	Weight g/m^2	Thickness mm	Density g/cm^3
SK - 702	K 2200dtex	239	0.50	0.48
SK - 801	T300 3K	223	0.37	0.60
SK - 802	T300 1K	74	0.13	0.57
SK - 809	M46JB 1K	41	0.09	0.49
SK - 8801	UHMS-G 3K	98	0.18	0.54
SK - 906	YS-50A 1.5K	152	0.22	0.68
SK - 907	YSH-50A 1K	85	0.13	0.64
SK - 909	YSH-60A 1K	88	0.15	0.59
SK - 910	YSH-70A 1K	79	0.14	0.59
SK - 920	YT-50A 1K	70	0.12	0.59

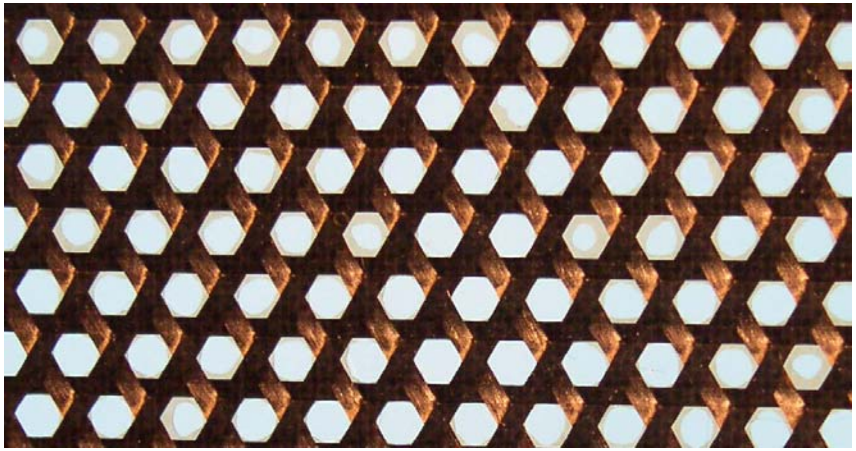
Triaxial Weave Fabric (TWF)





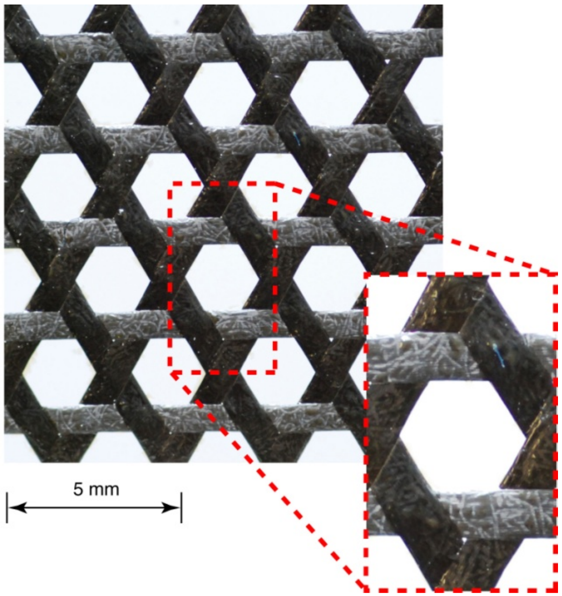
- Three weave directions (basic weave)
- Hexagonal holes cover about 50% of total area
- Comes on a roll

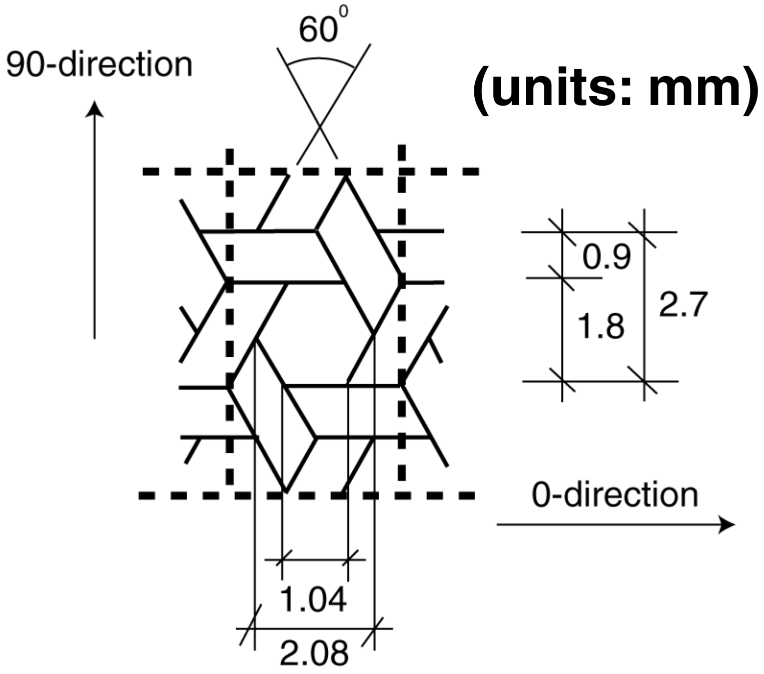
Material Processing



- To minimize voids the composite is placed in a vacuum bag and cured in an autoclave under high pressure.
- Main production steps:
- SK-802 fabric is laid on release fabric; a single layer of semi-solid Hexcel 8552 resin film is placed on the fabric and the fabric is impregnated with the resin using a warm iron.
- This lay-up is sealed in a vacuum bag and it is then heated to a temperature of 110 ^{o}C under a pressure of 6 bar for 1 hour in an autoclave, to allow the resin to melt and seep through the fibres by capillarity, before it hardens.
- The lay-up is cured at a temperature of 185 ^{o}C and a pressure of 6 bar for 2 hours.

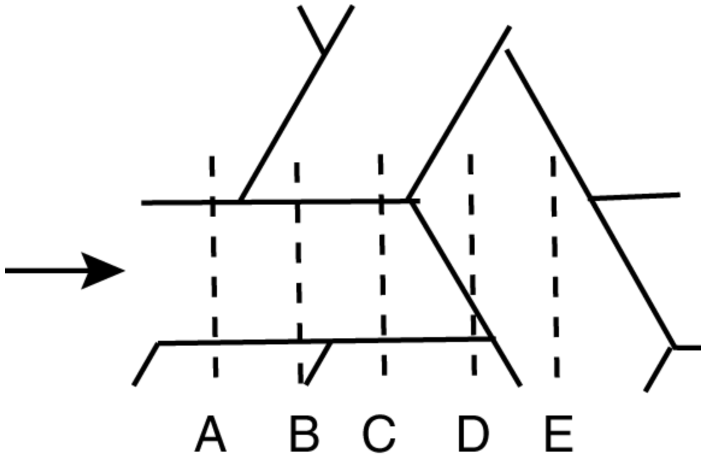
Single-Ply Triaxial Weave Composite

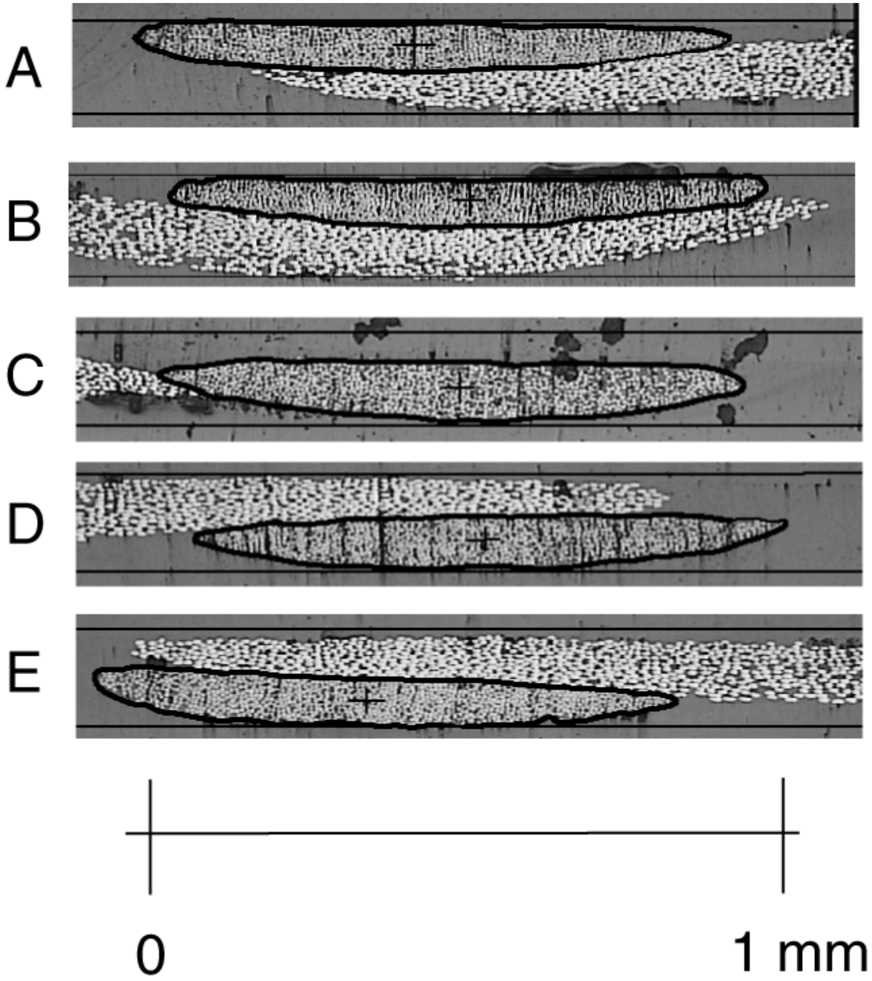




- Sakase SK802 cloth, 1k T300 tows
- Hexcel 8225 epoxy resin, cured at 185 °C
- Areal mass 105 g/m^2
- Overall thickness 0.14 mm
- Fibre volume fraction 0.65 (tows only)

Microstructure





- A *grillage* of transversally isotropic “planks”
- Average tow thickness 0.07 mm.
- Cross-section twists back and forth a few degrees, but effect on constitutive behaviour is small

Volume Fractions

- Volume fractions of fibres and resin are defined with respect to the total volume of composite material, excluding the voids in the weave.
- Volume fraction of fibres is defined as

$$V_f = \frac{\text{Vol. fibres}}{\text{Vol. fibres} + \text{Vol. matrix}}$$

- It can be computed from $V_f = \dfrac{\rho_m W_f}{\rho_m W_f + \rho_f W_m}$

$$\begin{aligned} W_m &= \text{weight per unit area of resin film} \\ W_f &= \text{weight per unit area of dry fabric} \\ \rho_m &= \text{density of resin} \\ \rho_f &= \text{density of dry fibres} \end{aligned}$$

- Then the volume fraction of matrix can be computed from

$$V_m = 1 - V_f$$

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W_m can be measured by chemically dissolving or burning the matrix in a cured tow.

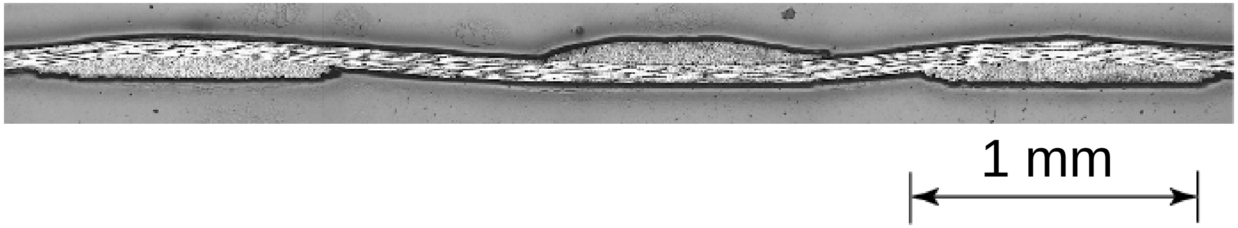
- Then the volume fraction of matrix can be computed from

$$V_m = 1 - V_f$$

Properties of Constituent Material

	Fibre	**Matrix**
Type of material	T300	Hexcel 8552
Density, ρ [kg/m^3]	1,760	1,301
Longitudinal stiffness, E_1 [MPa]	233,000	4,760
Transverse stiffness, E_2 [MPa]	23,100	4,760
Shear stiffness, G_{12} [MPa]	8,963	1,704
Poisson's ratio, ν_{12}	0.20	0.37
Longitudinal CTE, α_1 [/^{o}C]	-0.54×10^{-6}	65.0×10^{-6}
Transverse CTE, α_2 [/^{o}C]	10.08×10^{-6}	65.0×10^{-6}
Failure strain [%]	1.5	1.7

Geometric Properties of Cured Tows



- Average tow cross-sectional area (measured from micrographs with Autocad is A_t=0.0626mm^2
- Maximum thickness of composite (from micrographs) 0.156 mm
- Tow models with rectangular cross section assume width of 0.803 mm and height of 0.078 mm

- Weight of fabric W_f=75 g/m^2
- Weight of matrix W_m=29.5 g/m^2
- Weight of cured composite W_c=104.5 g/m^2
- Fibre volume fraction 0.65

Elastic Properties of Tows

- Each tow is a three-dimensional continuum with transversely isotropic properties; the modulus in the fibre direction is higher than the transverse modulus.
- Let 1 be the direction along the tow axis
- The number of independent elastic constants needed to model a transversely isotropic solid is five:
  - longitudinal stiffness, E_1,
  - transverse stiffness, E_2 ,
  - longitudinal Poisson's ratio, ν_{12}, and
  - shear moduli, G_{12} and G_{23}.

Extensional Moduli and Poisson's ratios

- E_1 and ν_{12} are obtained from the rule of mixtures

$$E_1 = E_{1f} V_f + E_m (1 - V_f)$$

$$\nu_{12} = \nu_{13} = \nu_{12f} V_f + \nu_m (1 - V_f)$$

- E_2 is obtained from the Halpin-Tsai semi-empirical relation

$$E_2 = E_3 = E_m \frac{1 + \xi \eta V_f}{1 - \eta V_f}$$

where

$$\eta = \frac{E_{2f} - E_m}{E_{2f} + \xi E_m}$$

and ξ depends is a measure of reinforcement of the composite that depends on the fibre geometry, packing geometry, and loading conditions. Following Daniel, we have taken $\xi = 2$

Shear Moduli

- $G_{12} = G_{13}$ is found from the Halpin-Tsai semi-empirical relation

$$G_{12} = G_{13} = G_m \frac{(G_{12f} + G_m) + V_f (G_{12f} - G_m)}{(G_{12f} + G_m) - V_f (G_{12f} - G_m)}$$

- G_{23} is obtained by solving the quadratic equation

$$\left(\frac{G_{23}}{G_m}\right)^2 A + \left(\frac{G_{23}}{G_m}\right) B + C = 0$$

where

$$\begin{aligned}
A \quad = \quad & 3V_f (1 - V_f)^2 \left(\frac{G_{12f}}{G_m} - 1\right)\left(\frac{G_{12f}}{G_m} + \zeta_f\right) \\
& + \left[\left(\frac{G_{12f}}{G_m}\right)\zeta_m + \zeta_m \zeta_f - \left(\left(\frac{G_{12f}}{G_m}\right)\zeta_m - \zeta_f\right)(V_f)^3\right] \\
& \times \left[\zeta_m V_f \left(\frac{G_{12f}}{G_m} - 1\right) - \left(\left(\frac{G_{12f}}{G_m}\right)\zeta_m + 1\right)\right]
\end{aligned}$$

contd.

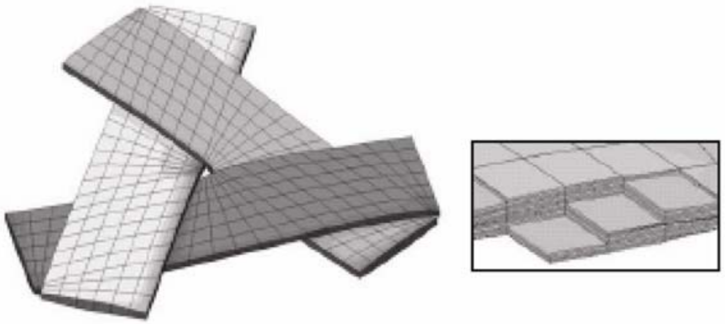
$$
\begin{aligned}
\zeta_m &= 3 - 4\nu_m \\
\zeta_f &= 3 - 4\nu_{12f}
\end{aligned}
$$

$$
\begin{aligned}
B = & -6V_f(1-V_f)^2\left(\frac{G_{12f}}{G_m}-1\right)\left(\frac{G_{12f}}{G_m}+\zeta_f\right) \\
& +\left[\left(\frac{G_{12f}}{G_m}\right)\zeta_m+\left(\frac{G_{12f}}{G_m}-1\right)V_f+1\right] \\
& \times\left[(\zeta_m-1)\left(\frac{G_{12f}}{G_m}+\zeta_f\right)-2(V_f)^3\left(\left(\frac{G_{12f}}{G_m}\right)\zeta_m-\zeta_f\right)\right] \\
& +(\zeta_m+1)V_f\left(\frac{G_{12f}}{G_m}-1\right)\left[\frac{G_{12f}}{G_m}+\zeta_f+\left(\left(\frac{G_{12f}}{G_m}\right)\zeta_m-\zeta_f\right)(V_f)^3\right] \\
C = & \; 3V_f(1-V_f)^2\left(\frac{G_{12f}}{G_m}-1\right)\left(\frac{G_{12f}}{G_m}+\zeta_f\right) \\
& +\left[\left(\frac{G_{12f}}{G_m}\right)\zeta_m+\left(\frac{G_{12f}}{G_m}-1\right)V_f+1\right] \\
& \times\left[\frac{G_{12f}}{G_m}+\zeta_f+\left(\left(\frac{G_{12f}}{G_m}\right)\zeta_m-\zeta_f\right)(V_f)^3\right]
\end{aligned}
$$

Cured Tow Properties

Property	Value
Longitudinal stiffness, E_1 [N/mm^2]	153,085
Transverse stiffness, $E_2=E_3$ [N/mm^2]	12,873
Shear stiffness, $G_{12}=G_{13}$ [N/mm^2]	4,408
In-plane shear stiffness, G_{23} [N/mm^2]	4,384
Poisson’s ratio, $\nu_{12}=\nu_{13}$	0.260

3-fold Symmetric Unit Cells



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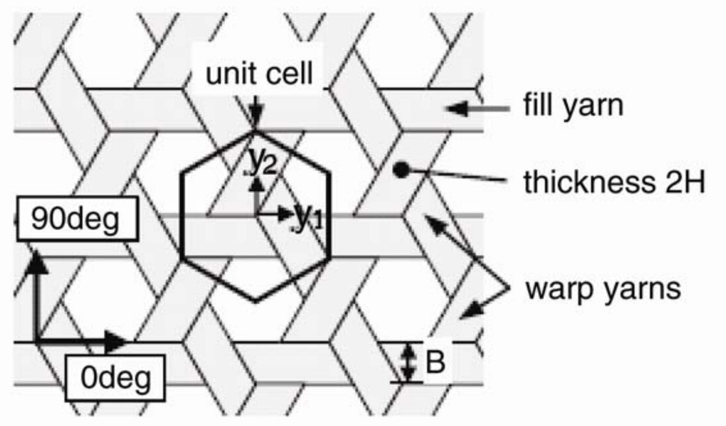
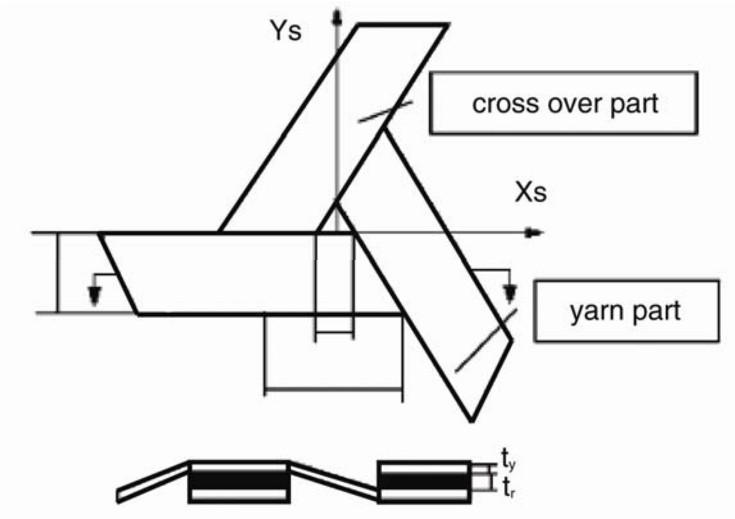


Aoki, T., and Yoshida, K. (2006), Mechanical and thermal behaviors of triaxially-woven carbon /epoxy fabric composite, AIAA-2006-1688.



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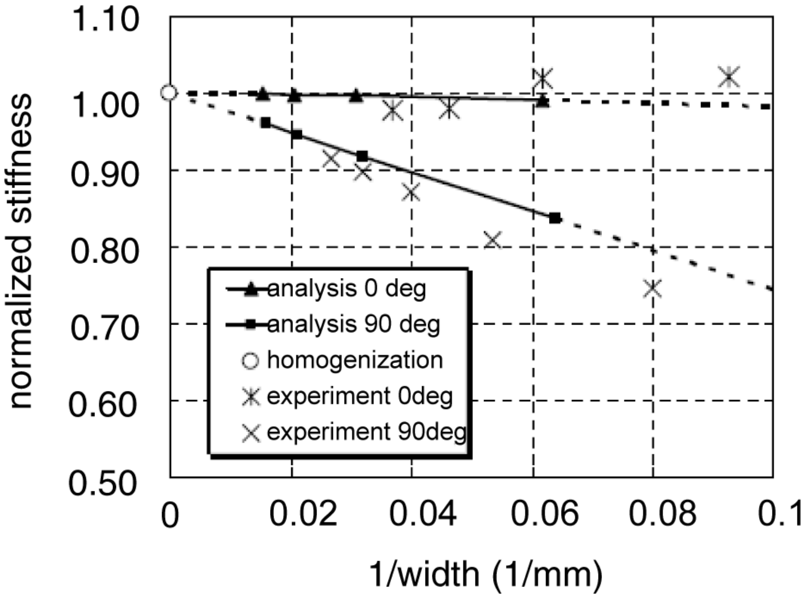
Edge Effects



From:
Aoki, T., and
Yoshida, K.
(2006)

- Plot shows change in normalized stiffness (ratio between stiffness of finite width specimen and that of infinitely wide specimen) vs. reciprocal of specimen width.
- In general, the stiffness is inversely proportional to the width of the specimen, but the variation is much larger when the tows are perpendicular to the direction of loading.
- In pure bending there are similar trends but the stiffness reduction of narrow samples is typically less than 1%