Common Types of Woven Fabric
Basic weave structures

- Plain Weave
- 2/1 twill
- 5 harness satin weave
- 2/2 basket weave
Woven Structure
Orientations in a Woven Fabric

- Machine direction = "warp" or "end"
- Perpendicular direction = "fill" or "weft" or "pick" or "woof"
- Frequently the warp direction corresponds with the 0°, or longitudinal direction
- And fill with the 90° or transverse direction
  - However - this is not necessarily the case and should be carefully noted.
Woven Fabrics

- Generally characterized by two sets of perpendicular yarns systems
- One set is raised and lowered to make “sheds” (these are warp yarns)
- The other set is passed through these sheds, perpendicular to the warp yarns (these are fill, or pick or weft yarns)
Woven Fabrics

- The structure of the woven fabric is the pattern of interlacing between the warp and weft yarns.
- Yarns can “float”, or not interlace for some distance within a woven fabric.
Crimp in Weaves

- The crimp is defined as one less than the ratio of the yarn's actual length to the length of fabric it traverses.
- High crimp leads to
  - Reduced tensile and compressive properties
  - Increased shear modulus in the dry fabric and the resulting composite
  - Fewer regions for localized delamination between individual yarns.
Crimp

- Crimp is defined as the ratio of excess length of yarn in a fabric to the length of the fabric
  - \( C = \frac{l_y}{l_f} - 1 \)
Crimp

- Crimp is determined by the texture of the weave and the yarn size
- Generally, in weaving, the warp yarns have most of the crimp, the fill very little
  - This is a direct result of the warp yarns lifting during weaving and the filling yarn being inserted along a straight path
Crimp

- Various models of crimp exist, the most rigorous developed by Pierce in the 1930s.
Crimp

- \( p_i = (l_j - D \theta_j) \cos \theta_j + D \sin \theta_j \)
- \( h_i = (l_i - D \theta_i) \sin \theta_i + D(1 - \cos \theta_i) \)
- \( c_i = (l_i/p_j) - 1 \)
- \( h_1 + h_2 = d_1 + d_2 = D \)

- Where \( p_i \) = Thread spacing; \( l_i \) = Modular length; \( c_i \) = Yarn crimp; \( d_i \) = Yarn diameter; \( h_i \) = Modular height; \( \theta_i \) = Weave angle; \( D \) = Scale factor; sum of warp and weft diameters
- \( i,j \) = warp and weft directions.
Crimp

- Simplified crimp calculations: assume triangle wave shape
  - $\tan \theta = (t_f + t_w) p_f$
  - $C = 1/\cos\theta - 1$
Thickness

- Thickness is a difficult parameter to measure.
- Thickness is dependent on applied transverse pressure to the fabric.
- Predictions of thickness show variation throughout the unit cell.
Theoretical Predictions of Thickness

- Consider yarns to be ellipses with major axes $a_i$ and minor axes $b_i$.  
- Thickness is between  
  - $4b_w + 2b_f \leq t \leq 2b_w + 2b_f$
Theoretical Predictions of Thickness
Areal Density

- Areal density is a measure of the weight per unit area of the fabric.
  - Usually expressed in g/m$^2$ or oz/yd$^2$.
- Areal density is a more reliable experimental metric for fabrics than thickness.
- Areal density can be correlated to volume fraction.
Areal Density

- Areal density can be calculated as
  \[
  A = \frac{l \left( 1 + C_w \right) n_w L_w + w \left( 1 + C_f \right) n_f L_f}{(w \ l)}
  \]
  - Where \( C_i \) = crimp of the \( i \) yarn, \( n_i \) = number of \( i \) yarns per unit length, \( L_i \) = linear density of the \( i \) yarn, \( w = \) width, \( l = \) length, and \( l=\)warp or weft.
Areal Density
Woven Structures

Twill

Satin

3D Woven

Double Cloth
Mechanical behavior: The Effect of Yarn Crimp

Plain weave
Mechanical behavior:
The Effect of Yarn Crimp

Angle Interlock weave
Mechanical behavior: The Effect of Yarn Crimp

XYZ orthogonal weave
3D Weaves

Layer-to-layer

Through thickness

XYZ
Doubly Stiffened Woven Panel
Variations in Weave Design

- If large yarns are used in the warp direction and small yarns are infrequently spaced in the weft direction, the resulting fabric resembles a unidirectional material.
- Weaves can be formed with gradients in a single or double axis by changing yarn size across the width or length.
- Complex shapes can be achieved through “floating” and cutting yarns to reduce total number of yarns in some section of the part.
Gradations through yarn size
Shape through floats
Issues with shaping woven fabrics

- Tailoring the cross-section of a woven fabric will generally result in:
  - a change in weave angle,
  - a change in the distribution of longitudinal, weaver, and fill, and
  - a change in fiber volume fraction in consequence to the change in thickness.

- Some fiber volume fraction effects can be controlled by tooling. The tailoring occurs in a discrete manner, using individual yarns, whereas most tooling will be approximately continuous.
Example of single taper weave

- Consider a tapered panel where gradation in thickness is achieved by changing yarn size/count across the width.
Design of tapered woven panel

- Pick count is constant, warps and wefts per dent are modified to taper
- Z yarn path changes to accommodate the weave.
This variation in yarn packing results in variations in $V_f$ for the resulting composite.
Variation in weave angle

- The weave angle will also change throughout the width of the part due to varying warp yarn count and part thickness.
Yarn Distributions

- The distribution of warp, weft, and Z yarn will also vary throughout the part.
Variations in Modulus

- All mechanical properties will vary throughout the part
Volume Fraction

- Volume fraction is the percent of fiber contained within a given volume (usually the composite in question)
- Volume fraction can be calculated from areal density
  - $V_f = \frac{A \rho}{t}$
  - Where $V_f = \text{fiber volume fraction}$, $A = \text{areal density}$, $\rho = \text{density of the fibers}$, and $t = \text{composite thickness}$
Process Control and Variability

- Processing Errors
  - Damaged yarns
  - Misplaced yarns
- Sources of error
  - Machinery malfunction
  - Machinery variability
  - Bad control parameters
  - Post-manufacturing deviations
Distortions in Woven Fabrics
On-line Monitoring of Manufacturing

- Realtime feed-back from shedding and insertion mechanisms
- Visual scan of fabric surfaces
- Xray or neutron scan of fabric interior
  - Using tracer yarns
Three Dimensional Weaving

- Uses "standard" weaving technology
- Complexity of weave is limited by number of independent shedding devices
- Some limitations on maximum thickness of fabric due to shed size and beatup limitations
Types of 3-D Woven Fabrics

- XYZ
- Layer-to-layer
- Through-thickness
3-D Weaving

- weaver
- warp
- filling insertion
- shed
- fabric movement
XYZ 3-D Woven Fabrics
Layer-to-layer 3-D Woven Fabrics
Through thickness 3-D Woven Fabrics
Components of 3-D Woven Fabrics

- **Longitudinal yarns**
  - Parallel to warp direction
- **Weaving yarns (web yarns)**
  - Lie in warp-thickness plane
- **Surface weavers**
  - Lie in warp-thickness plane
  - Located at \( t=0, t=\text{max} \)
- **Filling yarns**
  - Lie in fill-thickness plane
  - Generally aligned with the fill direction
Components of 3-D Woven Fabrics
Physical Relationships of 3-D Woven Fabrics

- \( V_f = \sum \Omega_i / \Omega_c \)
- \( \Omega_c = (1/h_p) (1/h_w) t \)
- \( \Omega_i = m_i A_i l_i \)
  - \( l_l = (1/h_p) \)
  - \( l_w = (1/h_p)/\cos(\theta_w) \)
  - \( l_s = (1/h_p)/\cos(\theta_s) \)
  - \( l_p = (1/h_w) \)
Process Variables

- Yarn sizes (all independent)
- Reed size (limited by yarn size)
- Picks per inch (limited by yarn size)
- Weave angle
- Number of filled warp positions
Preform Input Parameters

- Using fiber volume \((V_f)\), thickness \((t)\), ply percentages \((\text{wt}\%)\) as inputs:

\[
V_f = \frac{w}{t} \left( \frac{\text{wt}\%_1}{\rho_1} + \frac{\text{wt}\%_2}{\rho_2} + \ldots + \frac{\text{wt}\%_n}{\rho_n} \right)
\]

Here \(\rho\) is fiber density for each \(n\) fiber type and \(w\) is the preform areal density.

- Yarn spacings needed for each \(i^{th}\) system (warp, fill, weaver) can then be found using the tow linear density \(N\):

\[
yarns\ per\ inch = ypi_j = \frac{w}{N} \cdot \cos \alpha_i
\]
Weave Angle Projection

\[ \tan \alpha = \frac{t \cdot \text{ppil}}{N_p} \]
Determining Preform Thickness Requirements

- Tows required to meet thickness can be estimated assuming a common aspect ratio (AR):

\[ AR = \frac{b}{a} \]

\[ A = \pi ab = \pi a^2 \quad AR \]

\[ a = \sqrt{\frac{A}{\pi}} = d \sqrt{\frac{1}{4AR}} \]

\[ a = \sqrt{\frac{3.9 \times 10^{-4} \text{ in}^2}{6\pi}} = 0.00455 \text{ in} \]

Tows needed for thickness = \( \frac{\text{total thickness}}{\text{tow thickness}} = \frac{t}{2a} = \frac{0.100 \text{ inches}}{2 \times 0.00455 \text{ inches}} = 11 \text{ tows} \)
### 3D Woven Preform Case Study

Two sample preforms were specified, each with a 45° weave angle requested:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>%0° fiber</td>
<td>47</td>
<td>77</td>
</tr>
<tr>
<td>0° fiber type</td>
<td>IM7-12k</td>
<td>IM7-12k</td>
</tr>
<tr>
<td>%90° fiber</td>
<td>47</td>
<td>17</td>
</tr>
<tr>
<td>90° fiber type</td>
<td>IM7-12k</td>
<td>IM7-12k</td>
</tr>
<tr>
<td>%z fiber</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>z fiber type</td>
<td>AS4-3k</td>
<td>AS4-6k</td>
</tr>
<tr>
<td>thickness (inches)</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>Volume fraction (%)</td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>

The preforms were procured from a weaver, then evaluated based on the design methodology.
Example Calculations for Sample 2, using IM7-12k graphite tows for all inputs:

<table>
<thead>
<tr>
<th>Fiber direction</th>
<th>% tows</th>
<th>Directional areal density (oz/yd²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>77</td>
<td>57.23</td>
</tr>
<tr>
<td>90°</td>
<td>17</td>
<td>12.63</td>
</tr>
<tr>
<td>ttt</td>
<td>6</td>
<td>4.46</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>74.32</td>
</tr>
</tbody>
</table>

0°: \( y' = 57.23 \frac{oz}{yd^2} \cdot \frac{10^6 \text{ in}}{25.0 \text{ lbs}} \cdot \frac{lb}{16 \text{ oz}} \cdot \left( \frac{yd}{36 \text{ in}} \right)^2 = 110.4 \text{ ypi} \)

90°: \( y' = 12.63 \frac{oz}{yd^2} \cdot \frac{10^6 \text{ in}}{25.0 \text{ lbs}} \cdot \frac{lb}{16 \text{ oz}} \cdot \left( \frac{yd}{36 \text{ in}} \right)^2 = 24.4 \text{ ypi} \)

z: \( y' = 4.46 \frac{oz}{yd^2} \cdot \frac{10^6 \text{ in}}{25.0 \text{ lbs}} \cdot \frac{lb}{16 \text{ oz}} \cdot \left( \frac{yd}{36 \text{ in}} \right)^2 \cdot \cos \alpha_i = 7.9 \text{ ypi} \)
Applying the Methodology

Sample 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0°</th>
<th></th>
<th>90°</th>
<th></th>
<th>ttt</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Required</td>
<td>Reported</td>
<td>Required</td>
<td>Reported</td>
<td>Required</td>
<td>Reported</td>
</tr>
<tr>
<td>areal weight (oz/yd^2)</td>
<td>34.9</td>
<td>34.9</td>
<td>34.9</td>
<td>34.9</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>yarns per inch</td>
<td>67.5</td>
<td>67.5</td>
<td>67.5</td>
<td>67</td>
<td>18.2</td>
<td>16</td>
</tr>
<tr>
<td>Volume fraction</td>
<td>26.4</td>
<td>22.9</td>
<td>26.4</td>
<td>22.9</td>
<td>3.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Sample 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0°</th>
<th></th>
<th>90°</th>
<th></th>
<th>ttt</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Required</td>
<td>Reported</td>
<td>Required</td>
<td>Reported</td>
<td>Required</td>
<td>Reported</td>
</tr>
<tr>
<td>areal weight (oz/yd^2)</td>
<td>57.2</td>
<td>12.5</td>
<td>12.6</td>
<td>57.2</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>yarns per inch</td>
<td>110.4</td>
<td>24</td>
<td>24.4</td>
<td>110</td>
<td>8.3</td>
<td>6</td>
</tr>
<tr>
<td>Volume fraction</td>
<td>43.2</td>
<td>7.5</td>
<td>9.4</td>
<td>34.6</td>
<td>3.3</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Measuring the Weave Angle

<table>
<thead>
<tr>
<th>Sample</th>
<th>Measured angle</th>
<th>Predicted angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0°</td>
<td>14.4°</td>
</tr>
<tr>
<td>2</td>
<td>22.5°</td>
<td>22.7°</td>
</tr>
</tbody>
</table>
Examining Volume Fraction from Input Parameters

- Evaluating Sample 2:

\[
6 \text{ ypi} = w_z \frac{\text{oz}}{\text{yd}^2} \cdot \frac{10^6 \text{ in}}{11.8 \text{ lbs}} \cdot \frac{\text{lb}}{16 \text{ oz}} \cdot \left(\frac{\text{yd}}{36 \text{ in}}\right)^2 \cdot \cos (22.5) \\

w = 1.59 + 57.22 + 12.45 = 71.26 \text{ oz/yd}^2
\]

\[
V_f \cdot 0.064 \frac{\text{lbs}}{\text{in}^3} \cdot 0.100 \text{ in} \cdot \left(\frac{36 \text{ in}}{\text{yd}}\right)^2 \cdot \frac{16 \text{ oz}}{\text{lb}} = 71.26 \frac{\text{oz}}{\text{yd}^2}
\]

\[
V_f = 53.7\%
\]

It was calculated that 74.3 oz/yd² was needed to meet the 56% volume fraction specified.
Example

- 6 ends per inch, 6 picks per inch, 4 picks thick
- 12K AS-4 yarns long. & fill, 6K weavers, no surface weavers
- Weaver yarn ratio - rise/run = $\tan(\theta_w)$ ar
- Thickness = 0.25 inch
- All warp slots filled
- aspect ratio = $(n_p m_p)/t$
Effect of Weave yarn ratio on Fiber Volume Fraction
Effect of Weave Yarn Ratio on Weave Angle

Weave Angle (deg)

Weave Angle Ratio

4 ppi

6 ppi

0 10 20 30 40 50 60 70 80 90 100

0 2 4 6 8 10 12 14

Hypothetical graph showing the relationship between weave angle ratio and weave angle for 4 ppi and 6 ppi weaves.
Effect of Weave Angle on Distribution

Based on varying weave yarn ratio only
Effect of picks per inch on Fiber Volume Fraction
Effect of picks per inch on Weave angle
Effect of Weave Angle on Distribution

✓ Based on varying ppi only
Production of Complex Shaped Weaves

- Complex shape - complex, but uniform section
- Very complex shape - complex, nonuniform section
Production of Complex Shaped Weaves

- Consider section as consisting of rectangular pieces
- Develop weave parameters for each piece
- Develop interconnection paths
Production of Very Complex Shaped Weaves

- Decompose part into rectangular and shell sections
- Consider impact of cutting yarns
- Consider "folding" type operations
Ideal vs. Actual Geometry
Bad Control Parameters
Bad Control Parameters

- Bad scan of image
- Mistake in keying of "dots and spots"
- Slipped card/chain at pick insertion failure
Compression Induced Errors
RTM & Handling Induced Errors