Parachute Materials and Stress Analysis

Dean F. Wolf

Parachute Seminar

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Definitions

- **Fiber** - slender, threadlike structure; “tiny microscopic beams”
- **Filament** - a man-made fiber having great length compared to natural fibers
- **Staple** - a measure of length and/or fineness of a fiber
- **Yarn** - a generic term for continuous strands of textile staple fibers or continuous filaments in a form suitable for knitting, weaving, or otherwise intertwining to form a textile structure.
Definitions (continued)

- **Denier** - term used to describe the weight and size of a fiber or yarn (weight in grams of 9000 meters of material). Difficult to measure diameter of fibers.
- **Tex** - term found more commonly in Europe - grams per 1000 meters of yarn
- **Selvage** - specially woven edge that prevents the fabric from raveling (or unraveling)
Definitions (continued)

- **Tenacity** - strength of the fiber or yarn (units are grams per denier, gpd). Higher tenacity yarns must be of smaller denier to maintain adequate flexibility for weaving.

\[
\text{Denier} = \text{weight (in grams) of 9000m of yarn} = \text{Volume} \times \text{Specific Gravity (S.G.)} = 9000m \times 10^2 \text{ cm/m} \times A \text{ (cm}^2\text{)} \times \text{S.G.}
\]

\[
\text{Tenacity} = g/d = g/[9 \times 10^5 \text{ cm} \times A \text{ (cm}^2\text{)} \times \text{S.G.}]
\]

Solving for Force vs. Area (stress)

\[
\text{Stress @ Break} = g/A \ (g/cm}^2\text{) = 9 \times 10^5 \text{ cm} \times \text{Tenacity} \times \text{S.G.} = F/A \text{ (psi)} = 12,800 \times \text{specific gravity} \times \text{tenacity (gpd)}
\]

**Stress @ Break (psi) = 12,800 X specific gravity X tenacity (gpd)**
Definitions (continued)

• **Warp** - refers to the direction in a fabric, tape or webbing that run in the length-wise direction when coming off the loom.

• **Fill** - refers to the direction perpendicular to the “Warp” direction. (Also referred to as the “weft” or “woof”).

• **Picks per inch** - a measure of the yarn density in given direction (Warp or Fill) - number of threads per inch.

• **Fiber translation efficiency** - the ratio of the strength of the woven material to the total strength of the warp yarns.
## Types of Materials

<table>
<thead>
<tr>
<th>Natural</th>
<th>Man-made</th>
<th>Organic Fibers</th>
</tr>
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<tbody>
<tr>
<td>Wool</td>
<td>Mineral Fibers</td>
<td>Rayon</td>
</tr>
<tr>
<td>Silk</td>
<td>Glass</td>
<td>+</td>
</tr>
<tr>
<td>Cotton</td>
<td>Metal</td>
<td>+ Rayon</td>
</tr>
<tr>
<td>Hemp</td>
<td>+ Glass</td>
<td>+ Rayon</td>
</tr>
<tr>
<td>Flax</td>
<td>+ Metal</td>
<td>+ Nylon</td>
</tr>
<tr>
<td>Others</td>
<td>+ Dacron</td>
<td>+ Teflon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Nomex</td>
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<tr>
<td></td>
<td></td>
<td>+ Kevlar</td>
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<tr>
<td></td>
<td></td>
<td>+ Spectra</td>
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<tr>
<td></td>
<td></td>
<td>+ Vectran</td>
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<td></td>
<td></td>
<td>+ Zylon</td>
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</tbody>
</table>
Nylon

- Developed shortly before WWII
- A primary parachute material (Nylon 6-6)
- Polyamide resin with high tenacity due to long, highly oriented molecules and high intermolecular forces
- Tenacity is 2.5 to 9.5 grams/denier (6.6 for Nylon 6-6)
  \[ \text{Stress @ Break (psi)} = 12,800 \times \text{specific gravity} \times \text{tenacity (gpd)} \]
  \[ = 12,800 \times 1.14 \times 6.6 = 96 \text{ ksi} \]
- Minimum elongation specified as 20%, actual elongation 30-40% at break
- Sensitive to ultraviolet light
- Does not burn readily, but melts at 480F
Dacron

• Polyester based man-made fiber
• Similar to nylon, but requires more treatment for stability
• Slightly lower elongation than nylon
• Better temperature resistance than nylon
• Slightly less weight and volume for comparable strength nylon, once making it attractive in sport parachutes
Polytetrafluoroethylene, PTFE

- Telflon (DuPont), Fluor (ICI)
- Fluorocarbon based man-made fiber
- Very low friction coefficient
- Very expensive
- Used for deployment bag liners
- Used as buffer material where cotton cannot be used
- Expanded PTFE (Goretex) available as a slit film fiber with a tenacity of 3 grams per denier
Nomex

• Polyamide man-made fiber
• Moderate tenacity of 5.4 grams per denier -> 90 ksi (s.g. = 1.38)
• Elongation at break about 16%
• Retains 50% of its strength at 500 F
• Used for flight suits and high-temperature buffers
• Has been used as cloth in parachutes in high temperature environments (e.g. F111 CEM stabilization parachute)
Kevlar

- High strength, high modulus, para-aramid fiber developed for use in radial tires
- Version used for parachute materials identified as “Intermediate Modulus Para-Aramid”
- Each fiber is 0.00047 inches in diameter and is approximately 1.5 denier
- Tenacity is quoted to be 20-22 grams per denier -> 370 ksi! (s.g.=1.44) (Mild Steel ~100 ksi)
- Elongation at break is 3-5%
- Does not melt or burn, but sensitive to UV
- Abrasion resistant, but is very abrasive itself
- Cannot be hot cut or have the bitter ends seared
Spectra

- High-strength polyethylene fiber
- Tenacity 30-35 grams per denier -> 380-440 ksi !!!
- Elongation at break is 2.7%
- Subject to loss of strength at temperature (10 g/d @ 212 F)
- Low coefficient of friction
- Sometimes difficult to get good seam efficiencies
- Used extensively in sport parachutes for suspension lines
- Becoming common as a deployment bag material for high density packs
- For more information see [http://www.performancefibers.com/products/spectra.html](http://www.performancefibers.com/products/spectra.html)
Vectran-LCP

- LCP - Liquid Crystal Polymer
- Tenacity - 23 g/d => tensile strength = 300 ksi
- Elongation - 2-3%
- Friction properties similar to Spectra
- Immune to acids and UV
- Specific Gravity slightly less than 1.0
- Experiences zero creep under constant load
- Just entering the field of parachutes
Zylon

- New fiber from TOYOBA (Japanese firm)
- “Rigid-rod chain molecules of poly(p-phenylene-2,6-benzobisoxazole) (PBO)
- Tenacity - 43 gpd => 840 Ksi !!!
- Elongation at break - 3.5/2.5
- “Decomposition Temperature in Air” - 650 °C
- Much lower friction coefficient than Kevlar
- **Significant strength reductions with prolonged exposure to light (65% reduction in 6 months)**
- For more info see [http://www.toyobo.co.jp/e/seihin/kc/pbo/main.html](http://www.toyobo.co.jp/e/seihin/kc/pbo/main.html)
Effects of Light on Zylon

![Graph showing the effect of light on Zylon](graph.png)

- Zylon AS
- Zylon HM
- p-Aramid
- p-Aramid HM

Time (hr):
- 0
- 100
- 200
- 300
- 400
- 500

Strength Retention (%):
- 100
- 80
- 60
- 40
- 20
- 0

Xenon weatherometer

83°C
Comparison of Some Materials

![Tensile stress-strain curves for various materials](image)

- **KEVLAR aramid**
  - Type 49
  - Type 29
- **DACRON Polyester**
  - Type 68
- **DU PONT Nylon**
  - Type 728
- **NOMEX Aramid**
- **Teflon TFE Fluorocarbon**

![Stress-strain curve for different materials](image)

- **Zylon AS**
- **Zylon HM**
- **p-Aramid**
- **p-Aramid HM**
- **copoly-Aramid**
- **Carbon**

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Temperature Effects

The graph illustrates the strength retention of different materials (NYLON, DACRON, KEVLAR) as a function of test temperature (°F). The x-axis represents the test temperature, while the y-axis shows the strength retention percentage. As the test temperature increases, the strength retention decreases for all materials, with KEVLAR retaining strength better than NYLON and DACRON at higher temperatures.
Specifications

- **Military Specifications**
  - Have been deactivated but are still commonly used to specify materials in purchases

- **Commercial Specifications**
  - Supplier
  - National organizations (e.g. SAE, PIA)

- **Customer Specifications**

- **Detailed vs. Performance Specifications**
  - Suppliers prefer performance specs
  - Must make sure all necessary properties are specified in specifications
Specifications (continued)

- **Performance**
  - Strength
  - Weight
  - Elongation
  - Permeability
  - UV resistance
  - Allowable defects
  - Color, etc.

- **Detailed**
  - Threads per inch
  - Weave pattern
  - Yarn twist
  - Width, etc.

See Knacke, Sections 6.6.3 and 6.6.5.3 for an extensive (but not exhaustive) list of material specifications.
Products of Weaving

- Broad-goods
- Narrow-goods
- Cord
Broad-goods

• Produced on looms
  – Shuttle
  – Rapier
  – Water-and-air jet

• Woven in 36-, 48-, 60-, and 72-inch widths and different weave patterns
  – Plain
  – Twill
  – Taffeta
  – Satin
  – Ripstop
  – Selvage Edge
Finishing

- Greige goods
- Finishing processes (Converters)
  - Washing/Bleaching
  - Dyeing
  - Calendering
  - Coating
Narrow Goods

- Usually less than 12 inches wide
- Weavers very skilled in developing new weaves
  - Compromise between fiber translational efficiency and joint efficiency
- Used in parachute systems for
  - Suspension lines
  - Radials
  - Reinforcements
  - Risers
  - Bridles, etc.
Braided Cord

- With Core
- Coreless
Thread

- Obviously used for sewing joints
- Twist can confound use in sewing machines
- Used to tie or tack textile components together for various reasons
- Many times waxed when used for tacking
- Generally use the same type thread material as being sewn (e.g. Kevlar in Kevlar, Nylon in Nylon)
- Nylon thread can melt in sewing machines if precautions are not taken
Textile Drawings

• Different than more common solid modeling drawings
  – Thickness depicted only by a single line for fabric, tapes, or webbing. (Cord can be shown as circular or elliptical in cross-section)
  – No cross hatching of textile components in “cutaway” views
  – Hidden edges not depicted
  – Dashed lines used to show stitching
• Defined in ANSI/AIAA-S-017-1991
Outline

• Stress Analysis Methods
• Stress Analysis Code Examples
• Simplified Stress Analysis Examples
Parachute Stress Analysis Tools

- Simplified methods
- CANO code
- CALA code
- Commercial finite element codes
Simplified Methods

- Load carrying structure – suspension lines, radials or other reinforcements
  - Estimated distribution of total load in parallel elements
  - Estimates based on geometry, shape from photographs, material stiffness
- Pressurized structure – canopy
  - Membrane theory – load/unit length = (K) (pressure) (radius of curvature)
    - K = 1.0 for cylinder
    - K = 0.5 for hemisphere
  - Radius of curvature from photograph or characteristic length
CANO Code

- Developed by Northrop Ventura in 1960s
- Initial solutions used desk calculators
- Used for stress analysis of Apollo parachutes
- Many modifications now exist
- Good users manual written by University of Minnesota
- Version exists that includes verticals in ribbon parachutes
- Non-vertical solutions take seconds on modern PCs
CANO Code

• Early “finite element” code
• Original convergence algorithm not sophisticated
  – **May require patience**
• Modified algorithm developed by University of Minnesota
• Solutions starts at skirt and converges at vent
• Models parachute canopy gore
• Inputs
  – **Element geometry, parachute load, normalized pressure distribution, load/strain tables for materials**
**CALA Code**

- Developed at Sandia in the 1980s
- More modern numerical formulation than CANO
- Solution starts at vent and converges at skirt
- Models parachute canopy gore
- More general boundary conditions
  - **Pull-down vent**
  - **Attached pilot chute**
- More complicated input than CANO
- Input
  - **Element geometry, dynamic pressure, pressure coefficient distribution load/strain curves for materials**
Commercial Finite Element Codes

- Several commercial PC-based finite element software packages exist
- Specialized input/output formats for parachute stress analysis needed to make them user friendly for parachute engineers
- Potential for analysis of more general parachute canopy shapes and types of construction than CANO and CALA
- Potential for dynamic inflation modeling
Stress Analysis Examples

- SRB lightweight main parachute
- Space Shuttle Orbiter main parachute
- Space Shuttle Orbiter pilot parachute
- X-38 pilot parachute
- First stage floor panels for X-38 parafoil
- Fabric foam container
SRB Lightweight Main Parachute

- New main parachute designed to reduce weight and increase Shuttle payload
  - Existing parachute weight = 2150 lb
  - New parachute weight = 850 lb
- 124-ft Kevlar/Nylon ribbon parachute with solid cloth material near the skirt
- Design load increased from 175,000 lb to 210,000 lb
- Canopy design was polyconical (5 section) approximation to a quarter spherical shape
  - Primarily to reduce canopy loads and reduce material weight
SRB Lightweight Main Parachute

- CANO analysis used to support decision to use polyconical design
- Comparison with traditional 20 degree conical design
- Loads in primary load carrying structure were shown to be similar for both designs
SRB Lightweight Main Parachute

- Horizontal ribbon loads were shown to be significantly lower for the polyconical design
  - Higher points are for ripstops
  - Lower curves are for ribbons and fabric
- Lower loads allowed use of lighter materials
SRB Lightweight Main Parachute

- CANO results were also used to show that inflated shapes would not be much different than for conical canopy
  - Conical canopy performance experience would still be valid
  - Reefing data for conical canopies could be used
SRB Lightweight Main Parachute

- 1st test showed some fabric failures near the skirt during canopy overinflation
- CANO results were used to study the fabric loads in an overinflated canopy
SRB Lightweight Main Parachute

- A pressure distribution was derived that produced the same CANO shape as that observed during the 1st test.

![Graph showing pressure distribution across canopy elements.](image)
SRB Lightweight Main Parachute

- CANO loads for the overinflated shape were not sufficient to cause failure of undamaged fabric
- The very lightweight fabric near the canopy skirt was being damaged during deployment at the high SRB bag strip velocities
Orbiter Drag Parachute

- Decision to reuse the Orbiter drag parachute required detailed loads analysis
- A CANO analysis provided the loads data necessary for inspection and repair work at the KSC PRF
Orbiter Drag Parachute

- Load/strength ratio provides the inverse of available design factor in structure
- Parachute was originally designed without reefing so reefed loads are low
Orbiter Drag Parachute
Comparison of Ribbon Load Estimates

- Full Open Design Load $F = 100,000$ lb and Projected Area $A = 628$ ft$^2$
- Average Pressure $p = F/A = 159$ lb/ft$^2$
- Hoop Tension Formulas
  - $T/e = (\delta p) R$ for cylinder
  - $T/e = (\delta p) R / 2$ hemisphere
- From CANO Analysis Maximum $T/e = 38$ lb/in
- For Hemisphere $T/e = 93$ lb/in - Too High
- For Cylinder With $R =$ Gore Width, $T/e = 40$ lb/in
Orbiter Pilot Parachute

- Decision to reuse the Orbiter pilot parachute also required CANO loads analysis to support inspection and repair
- Radial strength not robust
X-38 Pilot Parachute

- X-38 Project wanted to use Orbiter mortar and pilot chute to reduce development costs
- A much higher design load was required for the pilot parachute
  - 12,000 lb for X-38
  - 4500 lb for Orbiter
- Kevlar suspension line and radial overlay was added to the existing canopy to provide the required strength
- Total weight was slightly less than all Nylon chute
X-38 Pilot Parachute

- Radial load distribution in modified Orbiter pilot parachute
- Required strength in Kevlar load carrying structure
X-38 Pilot Parachute

- Horizontal load distribution in modified Orbiter pilot parachute
- Adequate strength in existing horizontals
- Stiff radial structure keeps loads in horizontals low
X-38 Parafoil First Stage Floor Panel

• During the X-38 parachute development program, a “zero” reefed stage was tried to promote inflation symmetry in the first reefed stage
  – The “zero” stage reefing was suspension line reefing that pulled the parafoil corners down into a semi-round configuration

• Unfortunately, disreef from the “zero” stage was very rapid and dynamic
  – A parafoil floor failure occurred
  – The very large radius shape at failure suggested a membrane stress calculation
X-38 Parafoil First Stage Floor Panel

- **Hoop Tension**  \( T/e = (\delta p) R \)
  - \( \delta p = \) pressure across fabric
  - \( R = \) radius of curvature
- **Unsteady Pressure**  \( \delta p = \delta C_p \, C_k \, Q \)
  - \( \delta C_p = \) steady pressure coefficient across fabric
  - \( C_k = \) shock factor
  - \( Q = \) dynamic pressure
- Estimate  \( \delta p = (1.2)(2)(10 \text{ lb/ft}^2) = 24 \text{ lb/ft}^2 = 0.17 \text{ lb/in}^2 \)
- **Maximum Radius** = Suspension Line Length = 767 in
- **Hoop Tension**  \( T/e = (0.17 \text{ lb/in}^2)(767 \text{ in}) = 130 \text{ lb/in} \)
X-38 Parafoil First Stage Floor Panel

- Floor Panel Fabric Strength was $T/e = 100 \text{ lb/in}$ so decision was made to increase fabric strength.
- Under steady state conditions, the radius of curvature was proportional to the cell width because all suspension lines were loaded.
- Maximum radius = 3 times cell width = 144 in.
- Hoop tension $T/e = (0.17 \text{ lb/in}^2)(144 \text{ in}) = 25 \text{ lb/in}$
- Original design was adequate under steady state conditions.
Fabric Foam Containers

- Aqueous foam has been used as an effective medium for the mitigation of explosive effects
- Lightweight portable fabric structures were developed to contain the aqueous foam around the explosive charge
- Several different containment structures were developed and tested under realistic deployment conditions
- Containers were designed to hydrostatic pressure using membrane equation
50-ft Conical Container

- Sketch with dimensions of 50-ft conical container
50-ft Conical Container

- 50-ft conical container filled
- Conical containers were filled from top
50-ft Conical Container

- 50-ft conical container personnel access opening
- Access openings were closed with heavy duty zippers
70-ft Conical Container

- 70-ft conical container filled
- Container deliberately overfilled to test structure
70-ft Conical Container

- Close up of 70-ft conical container filled
- Personnel access opening zipper at base in center
Vertical Wall Container

- Sketch with dimensions of vertical wall container
Vertical Wall Container

- Predicted shapes of different sized vertical wall containers
- Membrane theory used to predict shape
Vertical Wall Container

- Vertical wall container filled
- Vertical wall container filled from top