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Material selection and joining methods for the purpose of a high-altitude inflatable kite.

R.F. Verheul[1] and J. Breukels[2]
Delft University of Technology, The Netherlands

W.J. Ockels [3]
Delft University of Technology, The Netherlands

This paper discusses the requirements for fabrics and joints for use in a long-endurance, high-altitude inflatable kite. Calculations of the expected stresses as well as the consequences of scaling with respect to these stresses are discussed. An overview is given of currently available kite fabrics and their joining methods. Suitable fabrics and joining methods from the sailing and aerospace industry are evaluated. The results of several tests on both fabrics and joints are presented.

Nomenclature

σ	=	stress
p	=	pressure
r	=	radius
t	=	thickness
M	=	bending moment
θ	=	coordinate in parallel direction
s	=	coordinate in meridional direction
α	=	semi-vertex angle
TR	=	taper ratio
x, y, z	=	Cartesian coordinates
q	=	load
γ	=	tension (kN/m)
λ	=	scale factor (L/L_0)
Cl	=	lift coefficient
W	=	weight
A	=	area
S	=	wing area

I. Introduction

Recently there is a renewed interest in kites for high-altitude applications. There is interest in using kites for remote sensing and atmosphere measurements as well as for wind power generation. Kites for this purpose will fly at heights of one up to 10 kilometers or more, encountering a harsh environment in terms of wind velocity, UV exposure, and extreme temperature differences. Kites will have to endure these conditions for prolonged periods of time, putting a whole new set of requirements on materials and construction than for kites currently known. This paper will discuss material selection and associated panel joining methods for a high-altitude kite with an inflatable structure. To illustrate typical requirements, the kiteplane concept will be introduced, a high-altitude kite design currently under development at Delft University of Technology.

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[1] Student, Faculty of Aerospace Engineering, Kluyverweg 1, 2629HS, Delft, The Netherlands.
[2] PhD student, Student, Faculty of Aerospace Engineering, Kluyverweg 1, 2629HS, Delft, The Netherlands.
[3] Professor and chair holder, Faculty of Aerospace Engineering, Kluyverweg 1, 2629HS, Delft, The Netherlands.

II. Kiteplane concept

Delft University of Technology has developed a kite concept for high-altitude applications, named kiteplane[8]. This kite concept has the advantage of being controllable independent of tether tension, or in other words, to be controllable both as a kite and a glider. The construction is closely related to that of popular surf kites, so called ‘tube kites’, having a frame consisting of inflatable tubes, spanned by fabric panels to form a wing structure. An advantage of an inflatable structure in comparison to a rigid frame is easy scalability, combined with a relatively low weight and small packing size. Another advantage is that loading past buckling will not result in permanent damage, but is fully reversible. Typical wing areas may range from 6 up to 50 square meters or more.

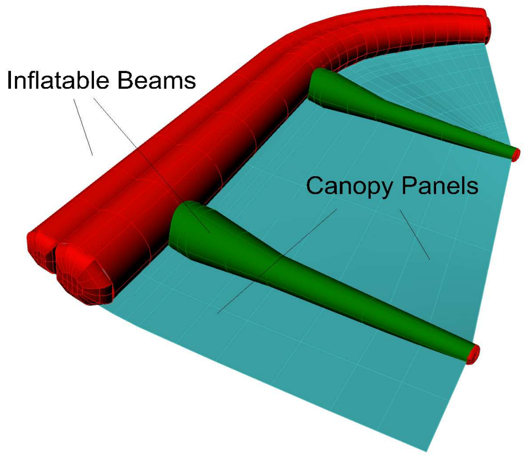
Figure 1. Kiteplane in flight.

III. Material requirements

The kiteplane structure consists of inflatable beams and canopy panels that together form a wing structure (Fig. 2). The inflatable beams are subject to torsion and bending moments, the internal pressure will introduce biaxial loads in the beam membrane. Besides being able to carry these loads, the beam material has to have good gas-containing properties and not deform significantly due to creep. The canopy panels are subject to biaxial stretch loads as a result of the aerodynamic pressure. Creep resistance and a high modulus are important for maintaining the designed shape. The material should be flexible, and not degrade significantly due to folding.

A high-altitude kite will meet a harsh environment in terms of UV-exposure and temperature levels. Since most high-tensile fibers have the tendency to degrade quickly under UV-exposure, the fibers have to be properly shielded by a protective film or coating. Physical properties have to be maintained to a reasonable level at both very low (-60 degrees Celsius) and high temperatures (+40 degrees Celsius).

A very important consideration when selecting materials is the feasibility of assembling the kite with these materials. Feasibility of assembling is related to the required panel joining method and flexibility of the fabric. As opposed to applications of similar materials for boat sails and LTA (Lighter-than-Air) applications, panels with relatively small and opposite radii have to be joined, even in the case of larger kite sizes (see Fig. 2 for a typical panel layout). It is likely that a customized panel joining method has to be developed in order to process the desired materials.



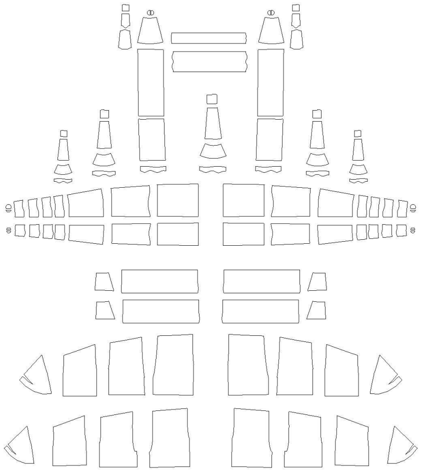


Figure 2. Typical construction and panel layout for a kite with inflatable tubes.

IV. Fabric stresses and scaling

In order to support a decision on material choice it is of importance to have an estimation of the expected stresses in both the canopy and beam fabric. Especially the stresses in the canopy fabric are not easily evaluated using analytical formulas and only a rough estimation is given here using the Young-Laplace equation. A more detailed analysis is beyond the scope of this paper. The stresses in the beam fabric can be predicted using a membrane approach at a for this context reasonable accuracy.

A. Tension in beam membrane

Consider a wing section with surface area S_0, composed of an inflatable beam and a canopy membrane. The wing section experiences a distributed load as a result of the aerodynamic lift forces, denoted as F_L. Figure 3 shows the typical deformation mode of the wing as experienced in wind tunnel tests. It shows that the wing beam will bend upwards and backwards under load and the torsional moment is relatively small. For this simplified case the beam is considered to be subject to bending only. Figure 4 shows the wing section simplified to a conical inflated cantilever beam, subject to a distributed (aerodynamic) load $q(x)$.

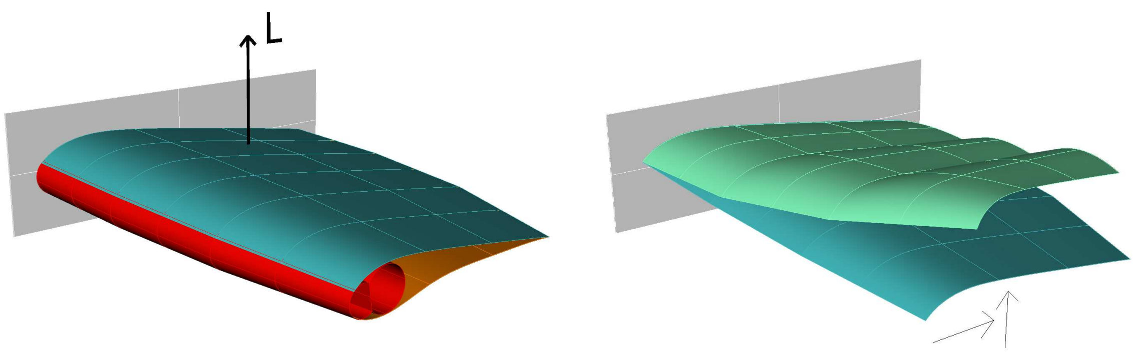


Figure 3. Wing section and typical mode of wing deformation.

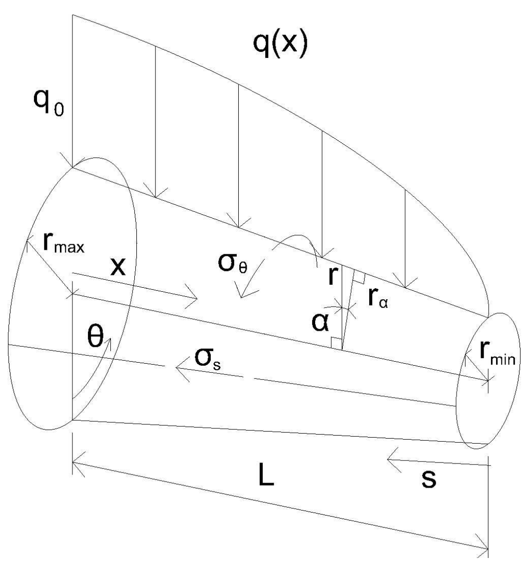


Figure 4. Wing simplified to a conical inflated cantilever beam model.

The beam is considered to be in the taut region, with no wrinkles occurring under the considered load. The membrane approach is used as described by Veldman[2], derived from theories developed by Stein[6] and Webber[5]. The membrane stresses in direction of the two principal curves σ_θ and σ_s for a conical inflated beam are given as:

$$\sigma_\theta = \frac{pr_\alpha}{t} \tag{1}$$

$$\sigma_s = \frac{pr_\alpha}{2t} - \frac{M_x}{\pi t r_\alpha{}^2}\cos\theta \tag{2}$$

Where:

$$r_\alpha = \frac{r}{\cos\alpha} \tag{3}$$

$$r = \left[1 + (TR - 1)\frac{x}{L}\right] r_{\max} \tag{4}$$

$$TR = \frac{r_{\min}}{r_{\max}} \tag{5}$$

$$\cos\alpha = \frac{L}{\sqrt{L^2 + (1 - TR)^2 r_{\max}{}^2}} \tag{6}$$

The function M_x is the bending moment as a result of the lift distribution on the wing *q(x)*. The bending moment is obtained by double integrating this distributed load[18]:

$$M_x = q(x) d^2 x \tag{7}$$

For fabrics it is common to reduce *t* out of the equation; the membrane tension γ (force per unit length) is then deducted from Eqs. (1) and (2):

$$\gamma_\theta = pr_\alpha \tag{8}$$

$$\gamma_s = \frac{pr_\alpha}{2} - \frac{M_x}{\pi r_\alpha{}^2}\cos\theta \tag{9}$$

The membrane tension in the parallel direction θ is not affected by a bending moment while the tension in the meridional direction *s* increases or decreases under influence of the bending moment, depending on the chosen value for θ. Consider the case the bending moment M_x is limited to the point that the membrane tension becomes zero at $\theta = 0$ (at this point the beam will be at the transfer point from the taut region to the wrinkled region). Then from Eq. (9):

$$\underset{\theta=0}{\gamma_s} = \frac{pr_\alpha}{2} - \frac{M_x}{\pi r_\alpha{}^2}\cos 0 = 0 \Rightarrow M_x = \frac{\pi p r_\alpha{}^3}{2} \tag{10}$$

Using Eq. (9) and inserting Eq. (10) while knowing the maximum tension will occur for $\theta = \pi$:

$$\gamma_{\substack{s\\ \theta=\pi}} = \frac{pr_\alpha}{2} - \frac{M_x}{\pi r_\alpha^{\ 2}}\cos\pi = \frac{pr_\alpha}{2} + \frac{\pi pr_\alpha^{\ 3}}{2\pi r_\alpha^{\ 2}} = \frac{pr_\alpha}{2} + \frac{pr_\alpha}{2} = pr_\alpha \tag{11}$$

Comparing this result with Eq. (8) it can be concluded that the tension in the meridional direction *s* will not exceed the tension in the parallel direction θ in the taut region. The maximum tension occurring in the beam membrane is then only a function of the internal pressure and local radius of the beam and can be calculated with Eq. (8).

B. Tension in canopy panels

If the canopy fabric is treated as a membrane, the local tension γ in a panel segment can be estimated by knowing the pressure difference p normal to the surface as a result of aerodynamic forces and the average curvature radius r_x and r_y in perpendicular directions (see figure 5). In this case the Young-Laplace equation is given as:

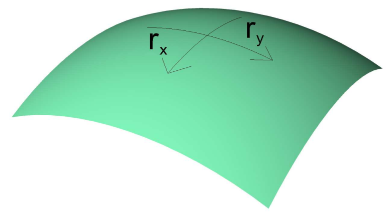


Figure 5. Panel segment.

$$\gamma = \frac{p}{\left(\frac{1}{r_x} + \frac{1}{r_y}\right)} \tag{12}$$

For this simplified case the fabric tension is linearly dependent on the curvature radius in both directions.

C. Scaling

In the scope of future applications kites will be developed that have the same geometry, but differ greatly in size. For selection of materials it is of interest to have an approximation of the tension in both the beam membrane and the canopy membrane, and how they change with scaling.

1. Scaling of beam membrane

Consider λ being the ratio between a scaled wing with length L_λ and a reference wing with length L_0:

$$\lambda = \frac{L_\lambda}{L_0} \tag{13}$$

Then also:

$$r_{\alpha\,\lambda} = \lambda r_{\alpha\,0} \tag{14}$$

$$t_\lambda = \lambda t_0 \tag{15}$$

Now suppose the load *q(x)* in Fig. 4 to be of elliptic shape (as would be the case for an aerodynamically idealized wing):

$$q(x) = q_0\sqrt{1-\left(\frac{x}{L}\right)^2} \tag{16}$$

Integrating twice with boundary condition $M_x=0$ at $x=L$:

$$M_x = \frac{1}{2}L\left(-\frac{1}{3}\left(1-\frac{x^2}{q_0{}^2}\right)^{3/2} q_0{}^2 + \sqrt{1-\frac{x^2}{q_0{}^2}}q_0{}^2 + x\sin^{-1}\left(\frac{x}{q_0}\right)q_0\right) \tag{17}$$

Suppose we are interested in the bending moment at x=0; then Eq. (14) reduces to:

$$M_0 = \frac{1}{3}Lq_0{}^2 \tag{18}$$

Assume a constant Cl indifferent of the chord length or wing size. Taking this into account the value of q for every x relates linearly to the local wing chord, and therefore q relates also linearly to the scaling factor λ:

$$q_\lambda(x) = \lambda q_0(x) \tag{19}$$

Using Eq. (13), (16), and (19), the bending moment from Eq. (18) scales with:

$$M_{0\ \lambda} = \frac{1}{3}\lambda L(\lambda q_0)^2 = \lambda^3 M_{0\ 0} \tag{20}$$

If it is required that the deflections of the wing as a result of the bending moment are proportional to the wing scale, the membrane stress (and therefore the strain) is to be kept constant , or:

$$\sigma_{s\ \varsigma} = \sigma_{s\ 0} = \sigma_s \tag{21}$$

This leaves the internal beam pressure p in Eq. (2) as the variable to be determined. Rewriting this equation for x=0:

$$p_0 = \frac{2t_0\sigma_s}{r_{\alpha\ 0}} + \frac{2M_{0\ 0}}{\pi r_{\alpha\ 0}{}^3}\cos\theta \tag{22}$$

For a wing with scaling factor λ:

$$p_\lambda = \frac{2\lambda t_0\sigma_s}{\lambda r_{\alpha\ 0}} + \frac{2\lambda^3 M_{0\ 0}}{\pi\left(\lambda r_{\alpha\ 0}\right)^3}\cos\theta = \frac{2t_0\sigma_s}{r_{\alpha\ 0}} + \frac{2M_{0\ 0}}{\pi r_{\alpha\ 0}{}^3}\cos\theta = p_0 \tag{23}$$

So given the requirement of constant stress in the membrane at the beam root the overpressure p is to be kept constant with scaling. When combining this result with Eqs. (8), (9), and (14), the fabric tension γ in both principal directions as a function of the scaling factor is given as:

$$\gamma_{\theta\,\lambda} = \lambda \gamma_{\theta\,0} \tag{24}$$

$$\gamma_{s\,\lambda} = \lambda \gamma_{s\,0} \tag{25}$$

It is concluded that for a beam with a distributed load of elliptic shape the fabric tension in the root of the beam increases linearly with the scaling factor given the assumption of constant *Cl* indifferent of chord length.

2. *Scaling of canopy panels*

If again the scaling factor is defined as the ratio between a scaled wing with length L_λ and a reference wing with length L_0 (Eq. (13)) then also:

$$r_{x\,\lambda} = \lambda r_{x\,0} \tag{26}$$

$$r_{y\,\lambda} = \lambda r_{y\,0} \tag{27}$$

$$\gamma_\lambda = \frac{p}{\left(\dfrac{1}{\lambda r_{x\,0}} + \dfrac{1}{\lambda r_{y\,0}}\right)} = \lambda \frac{p}{\left(\dfrac{1}{r_{x\,0}} + \dfrac{1}{r_{y\,0}}\right)} = \lambda \gamma_0 \tag{28}$$

3. *Consequences of scaling for tensions in kiteplane design*

It can be concluded that for all of the investigated load cases the fabric tension increases proportionally with the (one-dimensional) scaling factor. Figure 6 gives an idea of the increase in fabric tension with scaling for a kiteplane design using the above derivations.

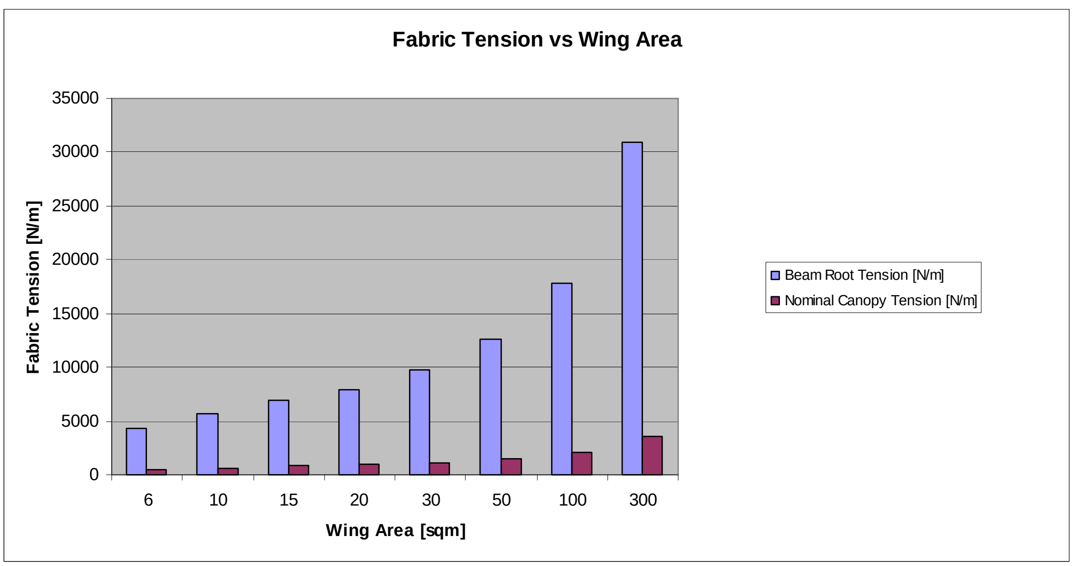


Figure 6. Fabric Tension vs. Wing Area for a kiteplane design.

D. Weight

It is assumed that the weight per unit fabric area W_f is proportional to the tensional stress γ it has to withstand, then from Eqs. (24), (25), and (28):

$$W_{f\ \lambda} = \lambda W_{f\ 0} \tag{29}$$

The membrane area A_m increases with the scaling factor as:

$$A_{m\ \lambda} = \lambda^2 A_{m\ 0} \tag{30}$$

From Eqs. (29) and (30) the total fabric weight W_t then becomes:

$$W_t = W_f A_m \tag{31}$$

Then:

$$W_{\mathrm{t}\ \lambda} = \lambda W_{f\ 0} \lambda^2 A_{m\ 0} = \lambda^3 W_{t\ 0} \tag{32}$$

The wing area S relates to the scaling factor as:

$$S_\lambda = \lambda^2 S_0 \tag{33}$$

The weight per unit wing area W_A is given as:

$$W_A = \frac{W_t}{S} \tag{34}$$

Then:

$$W_{A\ \lambda} = \frac{\lambda^3 W_{t\ 0}}{\lambda^2 S_0} = \lambda^{3/2} \frac{W_{t\ 0}}{S_0} = \lambda^{3/2} W_{A\ 0} \tag{35}$$

Based on Eq. (35), figure 7 shows how the weight per square meter lifting surface of a kiteplane design develops with increasing kite size, both for a polyester based material and a UHMW (ultra-high molecular weight) PE based material. A design requirement for the kiteplane is the ability to fly stationary even in low winds (about 5m/s) in order to increase the operationality and reliability of the kite system. The major components adding to the total airborne weight of the system will be the tether, control appliances, payload and fabric material. For the fabric materials alone, the maximum weight/sqm (lifting surface) aimed for is in the order of 10N/sqm. Looking at figure 7, this would imply kites with a wing area of several hundreds square meters are feasible when fabrics with high-tensile fibers are applied.

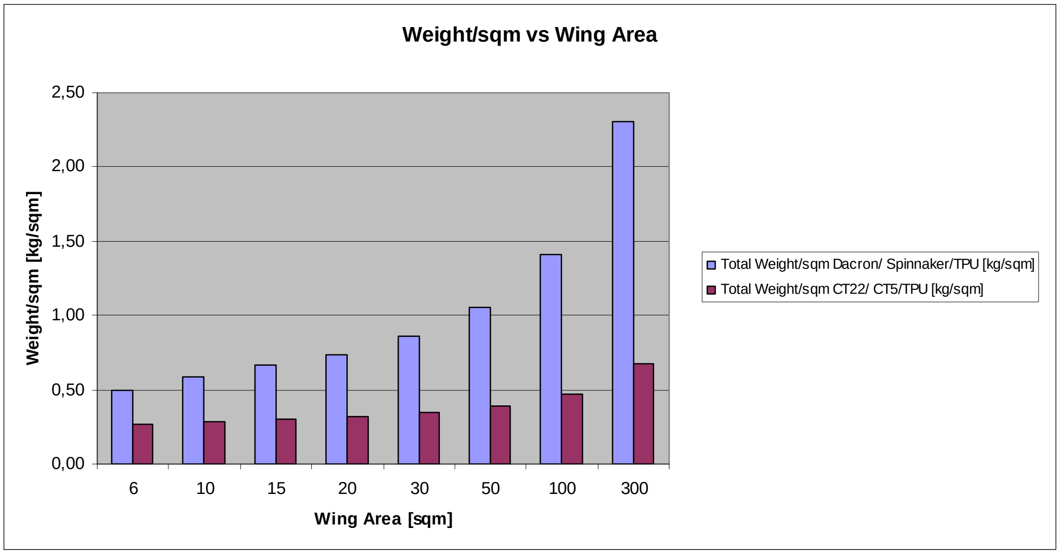


Figure 7. Weight/sqm vs. wing area for a kiteplane design.

V. Fabrics

A. Woven fabrics

Currently woven fabrics are almost exclusively used for kite applications. The technique of weaving cloth is long existing and well understood. Woven fabrics are tough and durable, and are relatively insensitive to flexing/folding. A woven fabric consists of fill and warp fibers, fill being the direction in the width of the cloth and warp the direction in the length (roll direction) of the cloth. A fill-oriented weave means that the fill yarns run in a straight line while the warp yarns pass under and over the fill yarns. In this case the fabric is subject to initial stretch in warp direction due to straightening of the yarns when a load is applied, this is known as crimp. The best stretch properties are found in the fill direction of the fabric, while the poorest are to be found at bias angles. Woven fabrics are often finished by applying a polymer film or resin.

Woven fabrics are almost exclusively used for larger kites these days. So called rip-stop Nylon weighing 30-50gr/sqm is a popular choice for parafoil-style and single line kites. Rip-stop Polyester is used as the canopy material for (inflatable) surf kites. It has better stress/strain and moisture absorption properties compared to Nylon. Weights are in the order of 50gr/sqm, while lighter variants are sometimes used for light-wind single-line kites. Dacron is a trade name for a heavier Polyester cloth weighing at around 170gr/sqm, used for both reinforcements and for the tubular frame of inflatable surf kites.

B. Laminates

Laminating is a versatile way to combine materials with different properties into a fabric tailored to specific requirements. Laminates allow optimal use of high-performance fibers developed in recent decades, a situation that has led to a fast growing interest for this type of fabric construction. Application fields of importance are sailing and lighter-than-air (LTA) applications. For example a laminate may consist of a layer with high modulus fibers (such as Kevlar) and one or more film layers with good shear stiffness and air permeability properties such as Mylar. Because the fibers can be oriented in preferable directions and do not need to be tightly woven, their tensile strength is used more advantageously while crimp is minimized. In general laminates are more sensitive to degradation due to flexing/folding compared to woven fabrics, and are more expensive.

1. Laminates used for Sailing

The development of sailing laminates started in the 70’s and 80’s and was first applied in the America’s Cup, but are now a common sight on performance cruisers with many variants available. Although durability is a requirement, it is accepted that sails need to be replaced several times within a boats life cycle due to stretching and weathering. New developments include the use of melt-processible (PTFE) and UHMW (ultra-high molecular weight) PE fibers for making anisotropic single-layer continuous foil materials[20]. Although this process is still in the research phase, the resulting fabrics may outperform more conventional fiber-laminate structures in terms of UV-stability and/or tensile properties.

2. Laminates for lighter-than-air (LTA) applications

Recently there is a renewed interest in using lighter-than-air (LTA) vehicles for applications such as cargo-lifting and high-altitude surveillance. With this renewed interest comes a new development in hull materials, making use of the latest developments in high-tensile polymers. Laminate development for LTA applications differs from sailing laminates in much more stringent demands in terms of air tightness and UV-stability. Typically, these LTA laminates consists of a high-tensile fiber layer (such as Vectran) for carrying the load, adhesive layers, and an environmental/ gas retention layer. Several options for both the load carrying layer as well as the environmental layer are currently investigated[7].

VI. Joining Methods

A. Stitching

Woven fabrics are typically joined by stitching, sometimes combined with double sided taping. Relative performance is at is best for tightly woven low modulus fabrics, joint strengths up to 50% of the fabric ultimate strength can be reached. Different sewing techniques are well described in literature, the quality of a joint can be judged easily by visual inspection. A high modulus combined with the absence of a tightly woven fabric layer makes most laminates unsuitable for stitching.

B. Gluing Taping, and RF or Ultrasonic welding

Popular gluing techniques for sailing laminates include hot-melt gluing (Ultra Bond™) and RF activated gluing (Q-Bond™). Joints can be stronger than the laminate itself; stress concentrations and possible delaminating may cause the strength of the joint to be limited, tensile tests show joint strengths of 60% to 100% of the fabrics' ultimate strength. The use of acrylic tapes can be a convenient way to join panels, especially in combination with stitching, strengths up to 20KN/m can be reached for suitable materials. Most plastics can be joined by RF or ultrasonic welding; however this technique is not commonly used for high tensile fiber laminates.

VII. Material selection and test results

In order to make a good judgment on the suitability of different materials the following fabric properties are to be investigated:

1. Weight
2. Tensile strength and modulus
3. Creep resistance
4. Air permeability
5. UV-stability and weatherability
6. Possible joining methods
7. Feasibility of joining methods for kiteplane assembly
8. Foldability (flex life)
9. Material and processing costs

For the kiteplane design a number of materials has been evaluated, these include both conventional kite materials as well as fabrics from the sailing and aerospace industry that could fulfill future requirements. Tensile tests of materials and joints have been performed in compliance with ASTM standard no. D5035-95.

Selected fabrics:

A. Toray Chikara™ high tenacity (6,6) ripstop nylon, 40g/sqm
B. Dimension Polyant Dacron, 170g/sqm
C. Contender Maxx, 155g/sqm
D. Cubic Tech CT5K.08/KM.5, 1 side metalized, 56g/sqm
E. Cubic Tech CT22HBKM.5, both sides metalized, 115g/sqm

Joint methods:
1. No joint
2. Triple zig-zag, 15mm overlap
3. Double straight stitch, seam folded to one side
4. Straight stitch and zig-zag, seam folded to one side
5. Double straight stitch, tube closing seam
6. 15mm overlap, 3M Acrylic 300 + 10mm wide zig-zag
7. DP Ultra Bond hot glue, 30mm overlap
8. DP Ultra Bond hot glue, 20mm overlap

	1	2	3	4	5	6	7	8
A	x	x	x	x		x		
B	x	x	x	x	x	x		
C	x					x	x	x
D	x					x	x	x
E	x					x	x	x

Table 1. Tested fabric/ joint combinations.

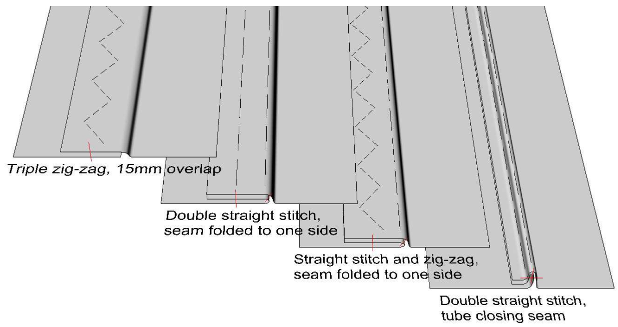


Figure 8. Schematic representation of applied joints.

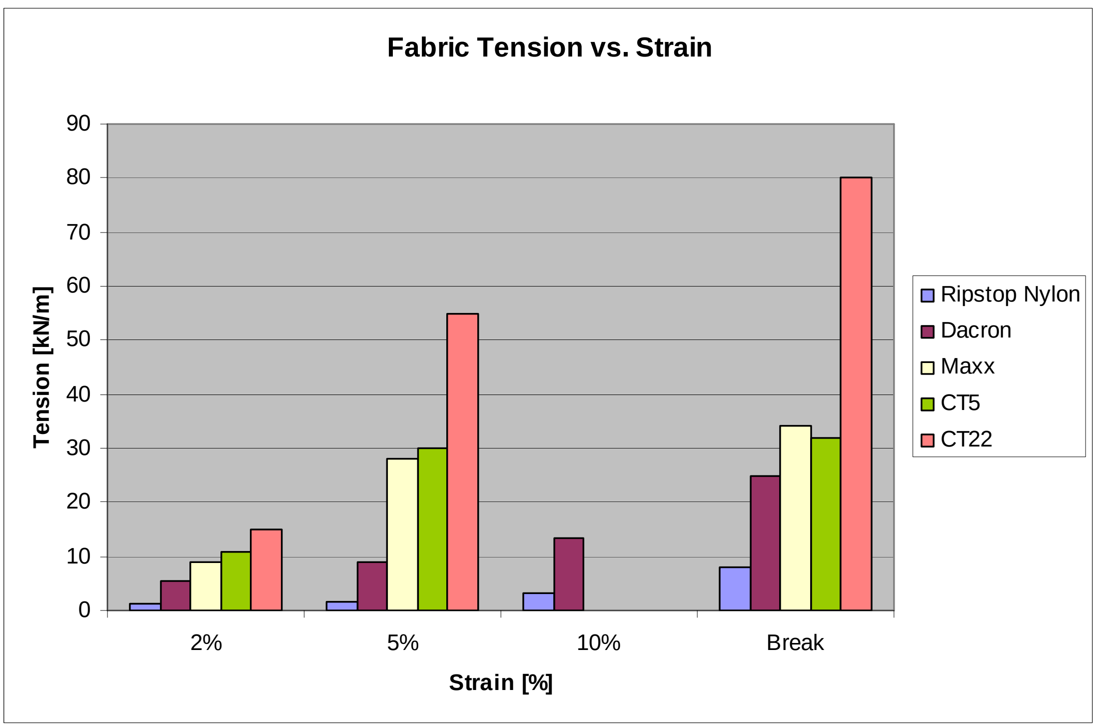


Figure 10. Fabric tension vs. strain.

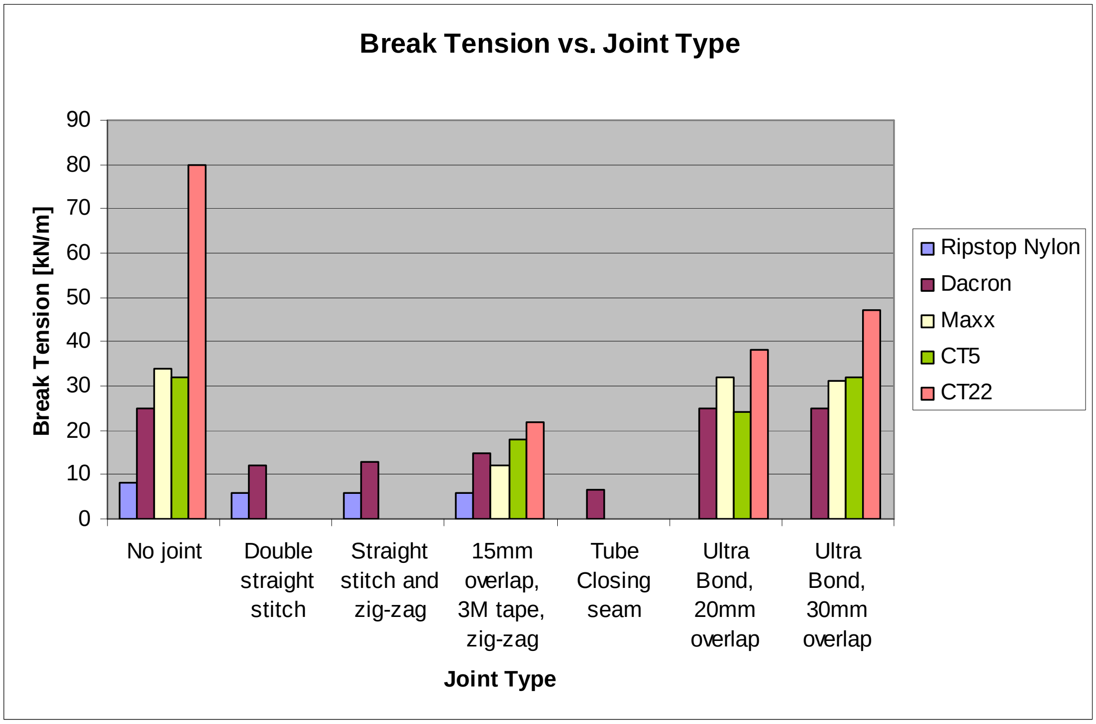


Figure 11. Break Tension vs. Joint Type.

For the kiteplane design, a 2% strain is considered reasonable for the expected nominal loads. Since the joints determine the ultimate strength of the structure, their strength should be well beyond the value for 2% strain. For the conventional (Nylon and Polyester based) fabrics, the strength of the different stitching seams are sufficient in strength. An exception may be the tube closing seam as is commonly used in the kitesurf industry. The more advanced materials are preferably joined with specialized glue to get the required joint strength, however this is not always possible due to the curvature of the joined panels. A good compromise that offers enough flexibility in production is a combination of double sided tape and stitching, but this joint strength is only sufficient for lighter variants of the tested high-tensile fabrics. Since for larger size kites both the panel radii and loads increase proportionally, gluing or welding may become the more viable option for joining panels for these larger sized kites. Also surfaces can be split up into different smaller panels, further decreasing edge radii.

VIII. Conclusion

Fabrics based on high-tensile fibers open up new possibilities for high-altitude kites in terms of weight reduction and durability. Usable fabrics include the use of aramids and UHMW PE fibers combined with protective films, as well as single layer, continuous foil materials such as melt-processible PTFE.

When the kiteplane wing structure is modeled as a conical inflated cantilever beam subject to an elliptic shaped (aerodynamic) load, the weight/lifting surface ratio will increase with the one-dimensional scaling factor to the $3/2^{nd}$ power. Combining this with the tension/weight ratio of the tested high-tensile fabrics, it is possible to build a kiteplane design of several hundreds of meters while keeping the weight below 10kN/sqm lifting surface.

Application of high-tensile fabrics is limited by the flexibility and strength of available joining techniques. Gluing or welding techniques are preferred for joining of panels of bigger kites because of their superior bonding strength, as much as 100% of the fabric strength may be preserved.

In order to better evaluate the applicability of high-tensile fabrics for high-altitude kite purposes, further research should be carried out on areas as creep resistance, foldability and wheaterability of these fabrics.

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