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Design of a large inflatable kiteplane

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[Abstract] This paper presents the various structural considerations in designing a large inflatable kiteplane. Material issues are addressed and a departure from conventional inflatable kites is suggested by using a single material instead of a structural foil and an internal gas barrier. Furthermore, rigging the kite using bridle lines is given attention. It is shown that the required internal pressure for a beam to keep it stiff is greatly influenced by the location of the bridle line. An optimum placement of the bridle line is found through analysis of the bending behavior of the beam in combination with a stress-based wrinkling criterion.

Nomenclature

b_1	=	Length from the wing tip to the bridle line
b_2	=	Length from the bridle line to the wing root.
b_{taper}	=	Length of the tapered section of the wing spar
F	=	Force
M	=	Bending moment
p	=	Internal overpressure
q	=	Span wise Lift distribution
r	=	Beam radius
r_r	=	Beam radius at the wing root
r_t	=	Beam radius at the wing tip
t	=	Laminate thickness
tr	=	Taper ratio
w	=	Laminate width
σ_l	=	Stress in longitudinal direction
σ_c	=	Stress in circumferential direction

I. Introduction

In 2000 the European Space Agency formulated a project to design and build a kite which could break the world altitude record for a single kite on a single line. This project came to be known as the KitEye project. It quickly became apparent that there was little known about the behavior of kites on a single line. Whereas the experience of conventional aircraft is extensive, in the world of kites the knowledge is limited to empirical data and rules of thumb. From KitEye, the project grew into a more general research project on the behavior of single line kites. In order to be able to draw parallels between conventional aircraft and kites, a kite was designed which closely resembled a conventional aircraft configuration. [REF 1] outlines the design of a scale model made out of lightweight foam and Aramid fiber composites. Figure 1 shows the kite.

Figure 1. The scale model.

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[REF 1] Deals mostly with the flight dynamics characteristics of the kiteplane design. It was concluded that due to the low-drag characteristics of the kiteplane, it had some instability issues concerning dutch roll and inverse pendulum motions. These instability motions were overcome by the incorporation of control surfaces in the wingtips. This degree of control also allowed the kite to be steered from the ground, using a remote control.

Scaling up the design was to be the next step. But in this scaling process, structural limitations became apparent. The foam used for the scale model had a weight of 20 grams per liter. Scaling it up would mean a significant increase in the amount of foam needed. This combined with the fact that a larger foam kite would need more Aramid reinforcement to make it stiff enough makes it a heavy structure. In order to make the kite lighter, a shift was made to the principle of inflatable structures. This paper will outline the major structural design issues of the inflatable kiteplane

II. KiteLab

In order to obtain accurate and reliable data on kiteplanes, the Delft University of Technology has created the worlds first kite laboratory called KiteLab. KiteLab is situated on the top floor and the roof of the faculty of Aerospace Engineering and consists of three parts. The first section is located on the top floor and is a manufacturing and preparation section for kites and kiteplanes. The second section, located on the top floor as well, is a monitoring section where data is gathered and logged. And the third section is the operations section on the roof of the faculty building. This is where kites can be flown in a controlled environment. The operations section consists of two 25-meter high towers, between which flight tests can be conducted. The towers also function as a platform for sensors and cameras. A total number of three cameras observe the kite in flight from different angles. KiteLab allows for controlled kite experiments and it can accommodate kites up to 15 meters in wingspan. Figure 2 shows The KiteLab.

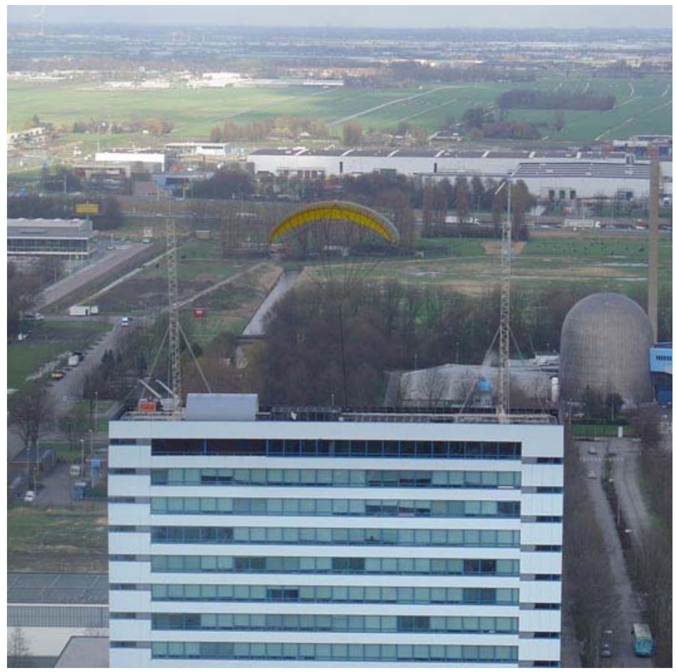

Figure 2. KiteLab.

III. The inflatable kiteplane

The inflatable kiteplane closely resembles the design of a conventional sail plane. This is due to the fact that many of the flight characteristics of a sail plane, such as high lift-over-drag and low airspeed, also hold for a high-altitude kite. Furthermore, this way it can be used as a good test bed to compare flight dynamics theory of aircraft with that of kites to determine what the addition of a cable does for the stability and performance. From a structural point of view, the main wing is of primary interest. It will be the most heavily loaded part of the kiteplane. Figure 3 shows a rendering of the inflatable kiteplane design.

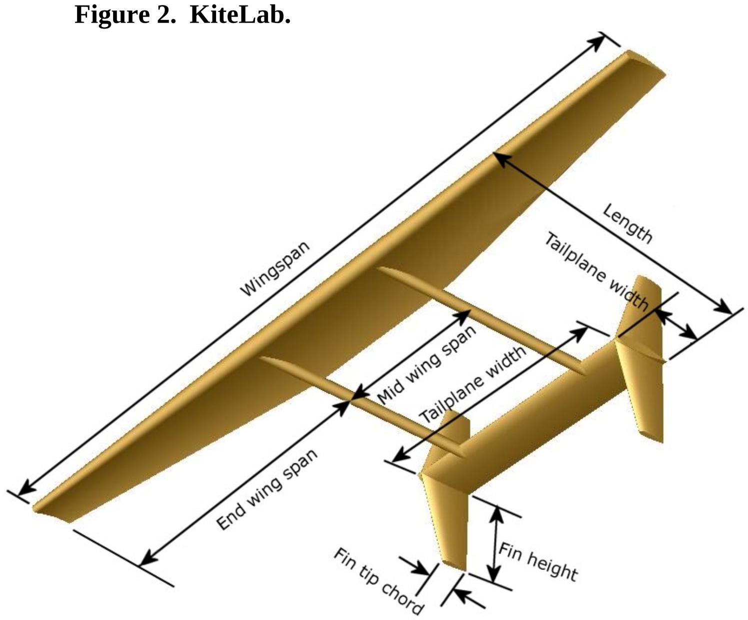

Figure 3. The inflatable kite layout.

The main wing is a single membrane sail wing. The leading edge is formed by an inflatable tube. The surface of the wing is comprised by a cloth pulled backwards from the leading edge and is held in place at the trailing edge by a trailing edge wire. The structural rigidity is provided solely by the pressurized beam in the leading edge. The beam consists of three pieces in total. One mid section (mid wing span in figure 3) and two outer wing sections (end wing span in figure 2). The mid section is a straight inflatable beam, and the outer sections are tapered beams with a taper ratio of 0.5;

$$tr = \frac{r_t}{r_r} \tag{1}$$

In the total wing span, the mid section takes up one fifth of the total wing span, leaving two fifth of the wingspan for each of the two outer wing sections. The result is a double tapered beam with a straight midsection.

IV. Scaling

A first foam-based kite had a wingspan of 3 meters. The foam was flexible polypropylene foam which required reinforcements by means of a rigid composite, laminated to the surface as a spar cap. In the case of this kite, an Aramid composite was used. For small prototyping, the foam proved to be a suitable, but vulnerable solution. Rapid building was possible by using a heated wire to cut the wings from the big blocks of foam. But there were several downsides to this method of construction. Often, the blocks of foam would have internal stresses which would warp a wing which was cut from it. Also, the blocks had a limited size, limiting the size of the largest piece of wing which could be cut in one go. Also, the length of the cutting wire was limited due to cooling of the middle part of the wire. The wire was heated using an electric current. At the handles, the wire would be red hot, but in the middle, it would be significantly cooler. If the wire was made too long, the middle of the wire would lag behind during cutting, creating discrepancies in the middle of the wing section. Lastly, when scaling the design up, the wing sections would simply become too heavy. The amount of volume the wings would be comprised off would take too much foam. Figure 4 shows the weight of a foam wing with regards to the wing span. Also, the weight of the inflatable wing is displayed as well. The pressures noted in the legend are overpressures above 1 atmosphere.

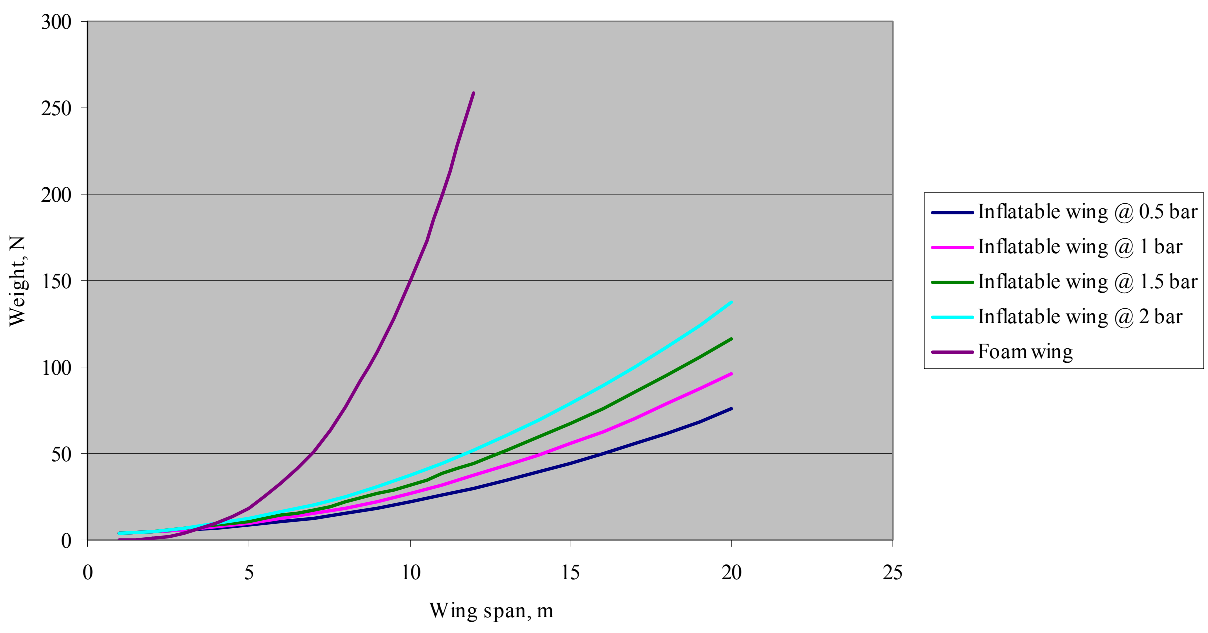

Figure 4. Wing weight.

For the inflatable wing, the weight of the internal air cannot be neglected. As can be seen from figure 4, there is a significant weight increase with increasing internal pressure due to the fact that with increased pressure, more air has to be carried. The increase in weight is not an increase in weight due to a reinforced structure to withstand more pressure. The same material was used in the analysis for all four of the inflatable kites. For larger wings, the inflatable wing is far lighter than the equivalent foam wing. Up to a wingspan of about 4 meters, the foam is applicable. For larger wings, an inflatable solution is necessary. In order for the next kiteplane to still be manageable using the facilities that were available, it was decided to scale to three times larger than the foam kite. This results in a kite with a 9 meter wingspan.

V. Material analysis

Currently, inflatable kites are far from rare. The fast growing kite surfing market has provided one of the biggest commercial boosts in the world of kites. Surf kites use a number of inflatable principles such as ram air inflation and pressurized tubes. In the kites with the pressurized tubes, henceforth called a “tube kite”, there is a distinct division of functions of the material. Generally, the material in any inflatable structure fulfills two major functions. The first function is that of structural strength. To carry the loads that are exerted on the structure, either externally or internally. The second function is the function of gas containment. To contain and hold the pressurized gas which pre-tensions the material and gives it structural rigidity. In conventional tube kites, these two functions are fulfilled by two separate materials. Usually, the structural strength is provided by a Dacron outer shell, while the gas is being contained by a thermoplastic poly-urethane bladder. In the world of surf kites, this proved to be a durable solution. The internal pressure of a tube kite is generally no higher than 0.5 bar overpressure. For the inflatable tube in the kiteplane, a much higher pressure is to be expected. In order to carry the loads, the Dacron structural layer would become too thick and therefore too heavy. This combined with the additional TPU bladder would make it a heavy structure.

Figure 5. The re-orienting of free fibers under internal pressure (pressurized on the left, unpressurized on the right [Ref 1]

Tests have been performed in the pas on fiber reinforced beams [Ref 1]. These beams consisted of a gas bladder and a glass fiber braid as reinforcement. The fibers laid bare and were free to change their bias angle (angle between the fiber and the longitudinal axis through the beam. [Ref 2] outlines the design of optimal pressure vessels. Through the use of netting theory. It was found that the optimum bias angle is 54.7 degrees. When inflating a beam where the fibers are bare, they will try and re-orient to the optimum angle of 54.7 degrees. In a test done in [Ref 1], the beam shortened significantly while its fibers re-oriented from 45 degrees to 54.7 degrees. Furthermore, it showed very little structural rigidity during this process. Figure 5 shows the re-orienting of fibers.

Obviously, such a mechanism is undesirable in the inflatable kiteplane as it would lead to poor rigidity and a drastically changing shape under pressure. In order to prevent the re-orientation of fibers, the fibers must be locked inside a matrix of some sort. Also, in bare fiber structures like these, the fibers are vulnerable to abrasion and retardation due to outside elements.

In order to keep the kiteplane as light as possible, the two functions of structural strength and gas containment will be fulfilled by a single material. This material would have to have a higher specific strength than Dacron and have a low gas permeability as well. The material which seemed suitable, affordable and available is a laminate of an Aramid and glass-fiber weave in a Mylar matrix. The Mylar matrix prevents the re-orientation of fibers and protects them from outside influences. Furthermore, Mylar has proven to be extremely creep resistant. In this laminate, the Aramid fibers are oriented at 0 and 90 degree angles, and additional glass fibers are oriented at 55 degrees, close to the optimal 54.7 degrees obtained in [Ref 2]. Figure 6 shows the laminate up close.

In conventional tube kites, the Dacron fabric is sewn into tubes. This is no longer possible for an Aramid/Mylar laminate. Not only would the puncturing of the laminate by the needle create a multitude of tiny leaks, the threads would rip through the Mylar foil under tension. Therefore, a different bonding technique is needed. A suitable bonding technique which would result in a sufficiently strong bond is a hot glue technique. It consists of a heated glue gun which forces glue at 170 degrees Celsius through a nozzle under pneumatic pressure. All seams in the kiteplane are glued using this hot glue system. The seams themselves are all 3 centimeters wide which results in sufficient surface for bonding.

In order to determine whether the laminate is strong enough and whether the bonds are strong enough, tests were conducted on a test bench to determine the ultimate load. For the purpose of this test, samples were cut which were 3 centimeters wide and 22 centimeters long. Half of the samples were one-piece samples and the other half consisted of two pieces bonded together with an overlap of 3 centimeters. All samples were tested to failure. Figure 6 shows the curve of the one-piece unbonded test samples.

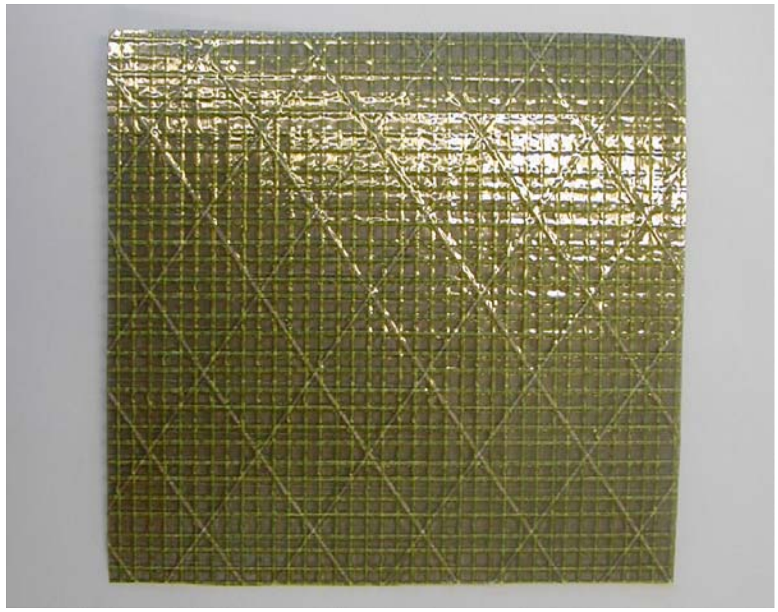

Figure 5. Picture of the laminate used.

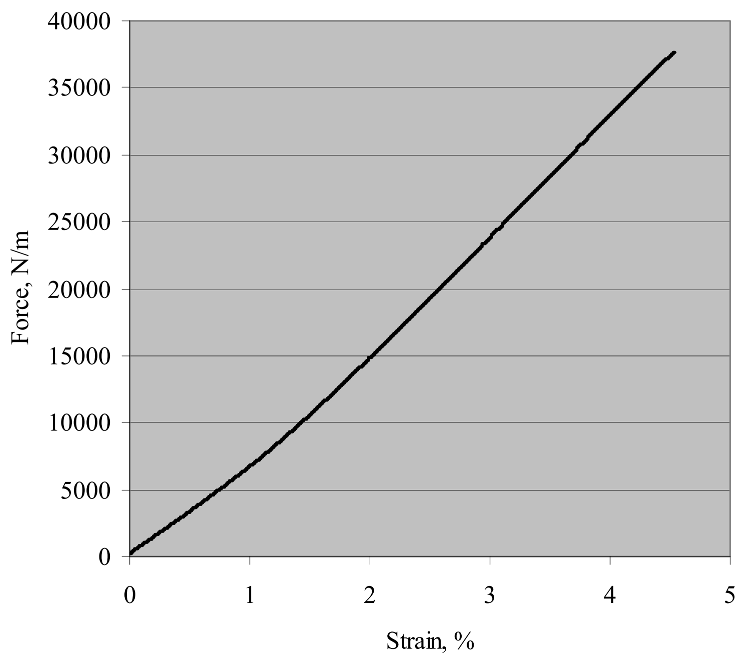

Figure 6. Test result of the unbonded laminate.

The curve in figure 6 is a trend curve, fitted to the actual test curves from every sample. The sample curves were very close together for every test. Even though the material is inherently anisotropic, it still behaves fairly linear. There is a slightly decreased climb in the curve for the first 1% to 1.5% of strain. This is due to the initial alignment of the fibers in the Mylar matrix. The effect is only minor. Due to the linear behavior, a constant modulus of elasticity can be assumed. This E-modulus is approximately 3.2Gpa. The stress on the samples is noted in Newtons per meter width instead of the more familiar Newtons per square meter (pascals). This is done to take the constant thickness of the material out of the equation. All unbonded samples failed above 35kN/m with a maximum strain of approximately 4.5%. Only the test samples where failure occurred well away from the clamps were taken as valid data. Samples which failed at the clamps were discarded. Failure occurs when the Aramid fibers can no longer sustain the tension. Failure is instant. Once the fibers break, the entire sample breaks.

For a pressure vessel, we can write the boiler equations:

$$\sigma_l = \frac{pr}{2t} \tag{2}$$

$$\sigma_c = \frac{pr}{t} \tag{3}$$

As can be seen in these equation, the stress in circumferential direction will determine the maximum pressure achievable. We can write:

$$\sigma_c = \frac{F}{w*t} = \frac{pr}{t} \tag{4}$$

And thus:

$$\frac{F}{w} = pr \tag{5}$$

Equation 5 gives the maximum obtainable internal pressure as a function of radius. F/w can be obtained from figure 6. It is important to realize that it is practically impossible to make a beam out of one single piece of uninterrupted laminate foil. There will have to be at least one seam. In order to test what the effects of bonded seams are on the ultimate strength of the laminate, several bonded samples were tested in the same manner as the unbonded samples. Figure 7 shows the result of these tests. Again, this curve is a composition of several curves which were extremely close together. The sample fails at a little over 30kN/m. This is somewhat lower than the 35kN/m at which the unbonded samples failed. All the samples failed at the edge of the bonding overlap. This is where the sudden change in thickness results in a stress concentration which makes the fibers fail in this location. Important to notice is that in none of the samples the bond layer came apart. This leads to the conclusion that the bonding system is performing very well. Using equation 5, it can be determined that for a beam with a radius of 9cm, a representative value for the kiteplane leading edge, the maximum achievable internal overpressure is 3.3 bar. This is an ultimate internal pressure. Incorporating a safety factor of 1.5, the practical internal pressure should never exceed 2.2 bar.

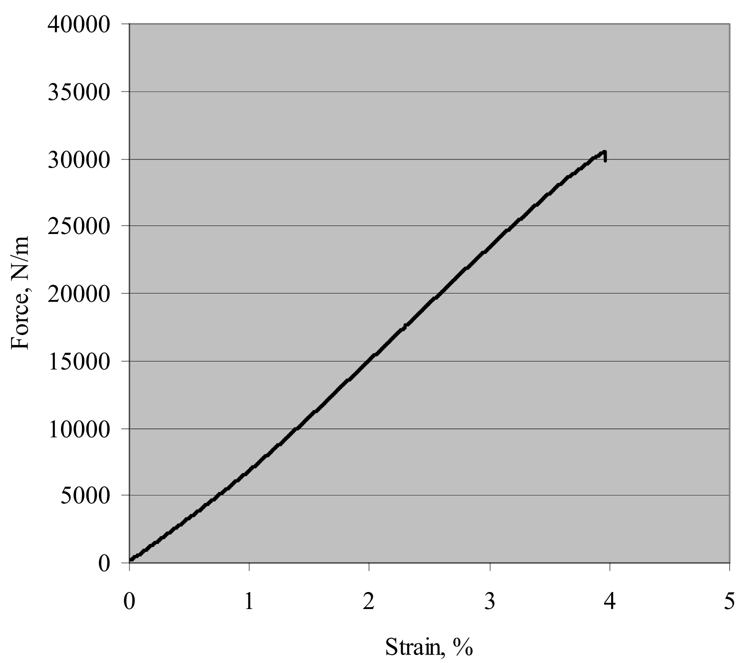

Figure 7. Test result of the bonded laminate.

Just as important as achieving an internal overpressure is to maintain it for a certain period of time. In practice, small leaks and gas permeability of materials will make the pressurized gas leak out of the structure, reducing the internal pressure. Leaks will most likely occur at the seams and the end caps and the gas permeability of the laminate itself can slowly leak internal gas along the entire surface of the structure. In order to determine the susceptibility of the designed structure to gas leakage, a test beam was built. This test beam has a radius of 15 cm and is 2 meters long. The end caps consist of two thick Plexiglas plates which are glued into the laminate tube and are clamped in place by large hose clamps. Figure 8 shows the test beam. The test beam was inflated to 0.25 bar and disconnected from the compressor. A manometer was used to see how fast the beam leaked its internal gas. It became immediately apparent that the beam slowly leaked gas at about one pascal per second. Soapy water was used to locate the leaks. The major leaks occurred at the end caps where the seam of the beam was glued to the Plexiglas endplate. These points therefore require extra attention during production. Furthermore, the seam itself seemed to not leak any gas, at least not enough to make it visible using the soapy water. No bubbles whatsoever occurred on the seam itself. The Mylar laminate also proved to be sufficiently airtight. The beam proved to be very stiff, especially in torsion.

Figure 7. The test beam.

VI. Structural analysis

The bending moment along the span of the wing is of great importance to the structural integrity. Together with the beam radius, the bending moment determines when and where wrinkling, and ultimately collapse, will occur. The geometry of the wing is determined by aerodynamic considerations. The bending moment in the main inflatable beam is a result of lift forces acting on the wing and the force the bridle lines introduce into the main inflatable spar. The bridle lines are attached to a number of places on the kite. These bridle lines come together at approximately 10 meters under the kite and continue down as the main kite line. The number of bridle lines, as well as the location of the attachment points greatly influence the bending moment in the wing. The more bridle lines on the main spar of the wing, the more the beam will be supported and the less the bending moment will be. But a large number of bridle lines is undesirable in the sense that they create a lot of drag. Furthermore, more bridle lines and more attachment points with their reinforcements will also add to the weight of the kite. Careful consideration on the number of bridle lines and their location is required.

We consider a wing with a lift distribution q(x) where x is the coordinate running from the wingtip to the wing root. Due to symmetry, only one wing will be taken into account. For the bending moment, we can write:

$$M = \iint -q(x)dxdx \qquad (6)$$

In order to determine the optimum placement of the bridle line, we analyze in what location wrinkling will occur first. By moving the attachment point of the bridle line, the location where wrinkling will occur will move as well. And not only the location of the first wrinkles will change, also the pressure at which first wrinkling will occur will change with the location of the bridle line. In essence, we are looking for a location of the bridle line at which first wrinkling will occur at the lowest internal pressure. This location of the bridle line will give the most rigidity at the lowest internal pressure. Important to note is that the kite is not designed to prevent wrinkling to occur at all. As a matter of fact, wrinkling in inflatable beams is fully reversible and even in a wrinkled state, the structure will exhibit rigidity. In a wrinkled state, an inflatable beam flexes considerably more than in an unwrinkled state, but this is not something that needs to be prevented. The minimum internal pressures calculated in this analysis are therefore not the final internal pressures at which the kite will fly. They are used to find the optimum location of the bridle line because it is assumed that the location where the first wrinkles will occur is also the same location where collapse will occur. It is simply a benchmark to determine what location of the bridle line will give the structure the most rigidity at the lowest required internal pressure.

The inflatable beam consists of a straight section and a tapered section. For the straight section, we write [Ref 3]

$$\sigma_l = \frac{M * r}{\pi r^3 t} = \frac{pr}{2t} \quad (7)$$

In equation 7, we assume that wrinkling will occur when the compressive stress due to bending becomes as large as the tensile stress due to internal overpressure. In this location, the total stress in the membrane will become zero. It is assumed that the membrane cannot sustain compressive stress and therefore, wrinkling will occur. Rewriting equation 7 yields:

$$p = \frac{2M}{\pi r^3} \quad (8)$$

Equation 8 determines the internal pressure at which wrinkling will occur. For the tapered part of the beam, the radius r becomes dependent on the span wise coordinate x. With x starting from the wing tip, r(x) becomes:

$$r(x) = \frac{r_t}{b_{taper}} x + r_t \quad (9)$$

Now we write for the wrinkling pressure of the tapered section of the beam, we write:

$$p = \frac{2M}{\pi \left(\frac{r_t}{b_{taper}} x + r_t \right)^3} \quad (10)$$

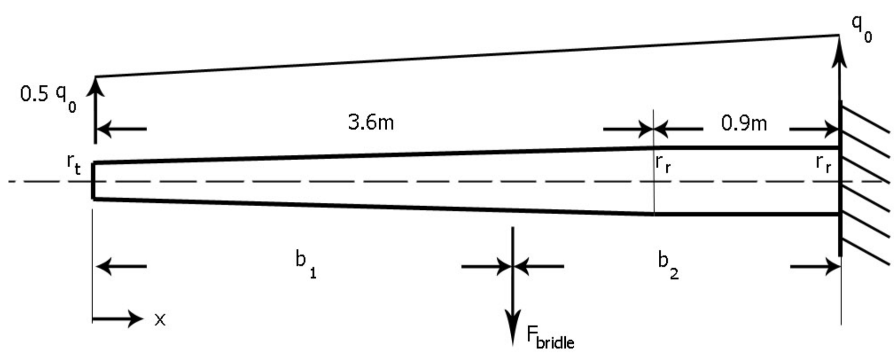

Figure 10. The simplified loading of the kite wing.

Combining equations (6), (8) and (10) will result in the wrinkling pressure for every location along the span wise coordinate x.

To determine the optimum location of the bridle line of the 9-meter span kite we consider a simplified situation depicted in figure 10. This is the situation for the 9 meter span inflatable kiteplane. Figure 10 shows the half span of the wing with $b_1 + b_2$ equals 4.5 meters. The tapered section is 3.6 meters long and the straight section at the root is 0.9 meters long. We assume steady symmetric flight with an air speed of 10 meters per second. With a C_L of 1 and a wing surface of 6.5 square meters this gives a lift of 400N at sea level. Therefore:

$$\tfrac{1}{2} q_0 * 4.5 + \tfrac{1}{2} * \tfrac{1}{2} q_0 * 4.5 = \frac{400}{2} \quad (11)$$

This gives a q_0 of 60 N/m. Using equation (6), we can write for the bending moment:

$$M = \frac{10}{9}x^3 + 15x^2 \qquad \text{for} \qquad 0 \le x \prec b_1 \qquad (12)$$

$$M = \frac{10}{9}x^3 + 15x^2 + 200(b_1 - x) \qquad \text{for} \qquad b_1 \le x \prec b_2 \qquad (13)$$

Combining equations (12) and (13) with the equations (8) and (10) for resp. the straight and the tapered part of the inflatable spar will give the wrinkling pressure as a function of coordinate x. In this analysis r_r = 0.09m and r_t = 0.045m. Figure 11 shows the buckling pressure as a function for x for three different locations of the bridle line (three different values for b_2). For the outer most position of the bridle line (b_2 = 3), the minimum pressure line dips below the x-axis. This does not indicate a negative pressure but merely a resulting negative moment. In other words, this part of the beam now bends the other way and wrinkling can be expected on the other side of the beam. As can be seen from all three the positions, varying the position of the bridle line has great consequences for the minimum required internal pressure. For b_2 = 1, an internal pressure of over 2 bar is required to keep the beam from wrinkling. While for b_2 = 2, little over 1.5 bar is enough. We can say that for b_2 = 2, the structure is a more efficient and a lighter one. For b_2 = 3, we see a minimum required pressure of close to 2 bar again. It is now of great interest to find a location for the bridle line which requires the lowest internal pressure to keep it from wrinkling. This will then be the structure which is the stiffest and the lightest configuration for this kite. The optimum solution for b_2 is found through iteration and is to be found to be 2.6 meters. Figure 12 shows the minimum pressure as a function of x. As can be seen from figure 12, a pressure of a little over 1 bar is

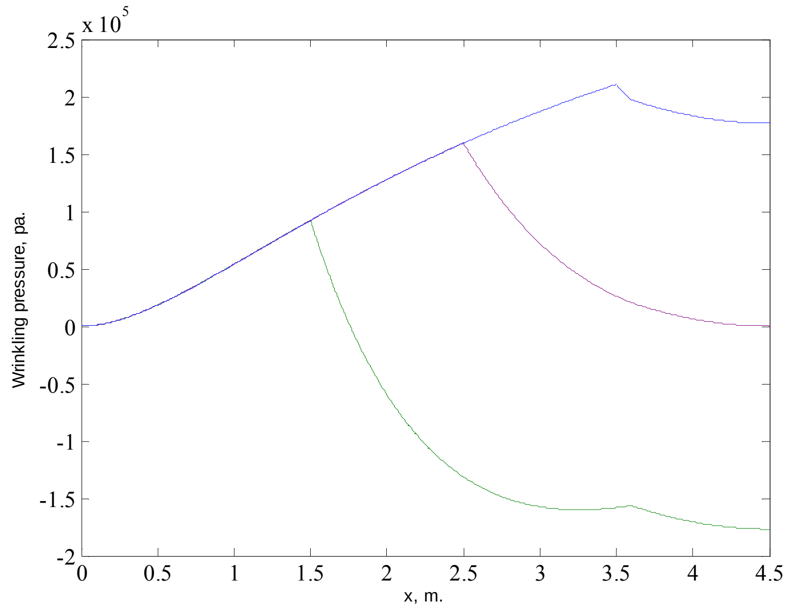

Figure 11. Minimum internal pressures as a function of x for three different positions of the bridle line. b_2 = 1m in blue, b_2 = 2m in purple and b_2 = 3m in green.

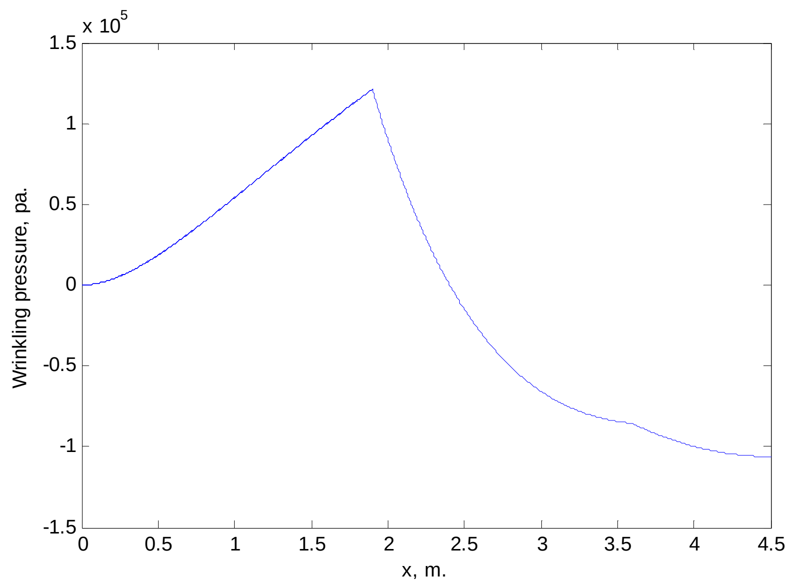

Figure 12. Minimum internal pressures as a function of x for b_2 = 2.6m.

required to keep the beam from wrinkling. Wrinkling can be expected at the attachment point of the bridle line and at the root of the wing. At the bridle line attachment, positive bending will create wrinkling on the upper surface, while negative bending at the root will create wrinkles on the lower surface.

VII. Conclusion

This paper presents the design of an inflatable kiteplane and its structural considerations. It was shown that in order for the a kiteplane of this size, an inflatable structure is applicable. A conventional structure such as foam and composite rigidization simply becomes too heavy. The materials used are of great importance. Conventional inflatable kites use two materials to fulfill both the functions of an inflatable structure. It was shown that combining these two functions into a single material will simplify production and make the structure lighter. The Mylar laminate is strong enough to withstand high pressures and it is bondable using a hot glue system. Furthermore, it was shown that the location of the attachment point of the bridle line greatly influences the required internal pressure of the beam. The optimum location was determined by simple iteration and this cut the required internal pressure by almost a half.

Acknowledgments

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