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INFLATABLE STRUCTURES FOR DEPLOYABLE WINGS

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ABSTRACT

Deployable wings are needed for a variety of applications such as extended range cargo delivery, lightweight portable aircraft and gun-launched vehicles. Inflatable structures provide a non-mechanical means for compact stowage and reliable deployment.

This paper provides historical background on early examples of inflatable wings, including several early patents and the Goodyear Inflatoplane.

A new approach to inflatable structures utilizes tubular spars manufactured by braiding high tenacity fibers over a thin gas barrier. Such structures can withstand high inflation pressures, which is the key to high strength before wrinkle onset. Reinforcement with high modulus fibers in the axial direction allows stiffness tailoring.

The strength and stiffness equations for pressurized reinforced braided tubes are presented and discussed. These are considerably different than those found in the literature for woven fabric pressurized tubes.

Examples are given of wing structures, wing deployment and actual flying configurations.

Historical Background

Perhaps the most successful inflatable airplane was Goodyear's Inflatoplane (Figure 1). Twelve of these were built between 1955 and 1972.

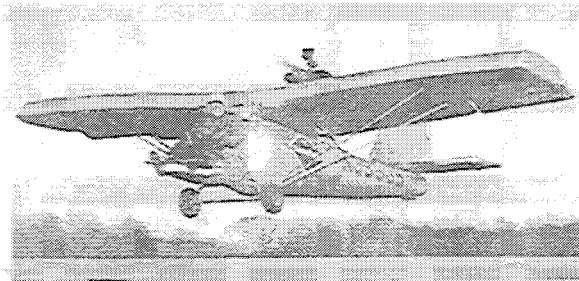


Figure 1. Goodyear Inflatoplane, 1957

The British answer to the Inflatoplane was a tailless design by ML Aviation, also developed in the 1950's (Figure 2).

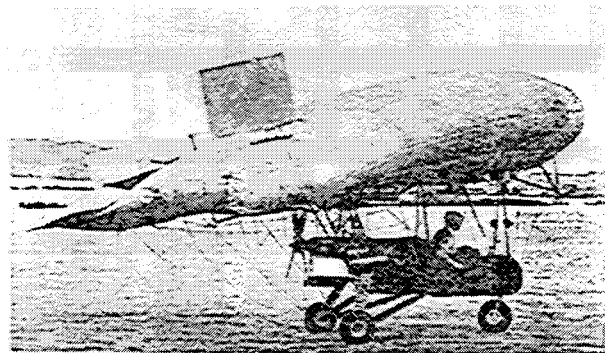


Figure 2. ML Aviation Mk1, 1955

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An early concept was patented by McDaniel in 1933 (Figure 3). He shows an aircraft with tubular spars that might be quite successful with today's materials.

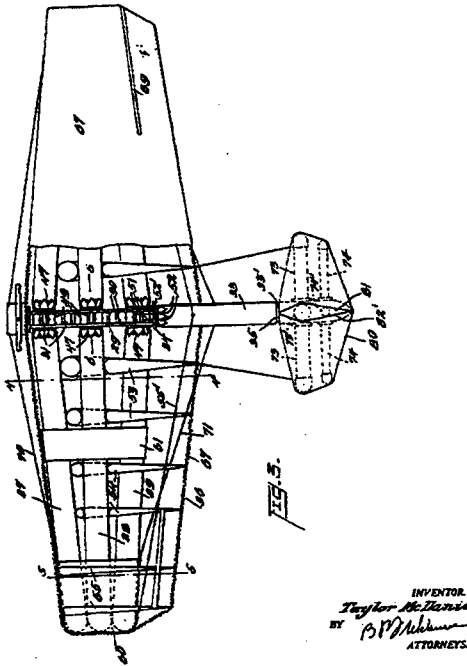


Figure 3. McDaniel, 1933

A concept by Aerospace Corporation published in 1962 marks the other end of the inflatable wing spectrum (Figure 4), a reentry vehicle.

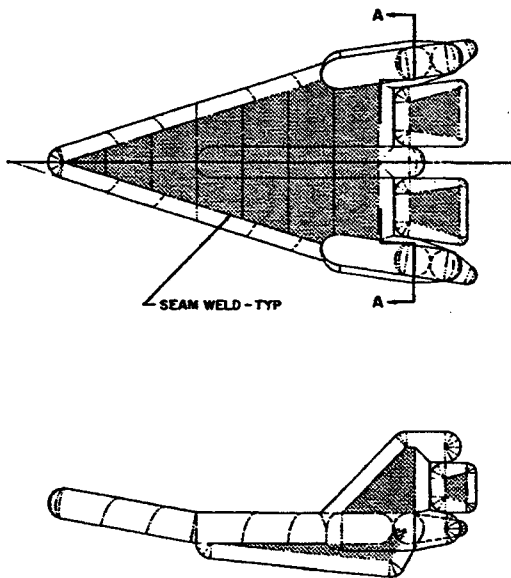


Figure 4. Aerospace Corporation, Inflatable Reentry Vehicle, 1962

Both the Inflatoplane and the ML Aviation MkI pressurized the wing skin while controlling shape with tension elements between top and bottom surfaces. McDaniel used pressurized fabric tubes inside the wing skin envelope as the primary structure.

Both Priddy (Figure 5) and Sebrell (Figure 6), among others, have proposed variations on the tubular spar.

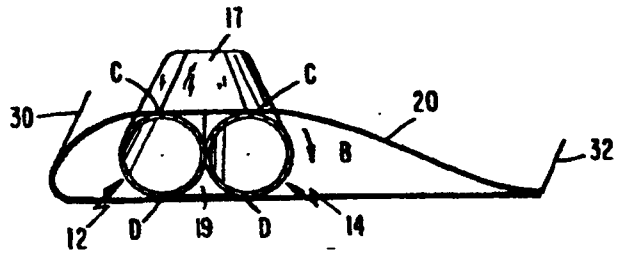


Figure 5. Priddy, 1988

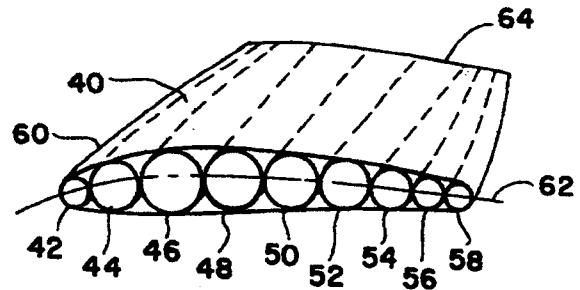


Figure 6. Sebrell, 1976

Bain (Figure 7) takes a different approach, using shaped, double-walled pressurized panels to form a wing.

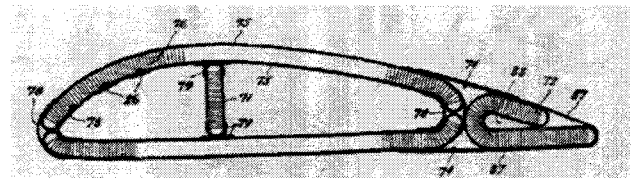


Figure 7. Bain, 1963

Haggard (Figure 8) shows multiple tubular spars surrounded by open-cell foam to control the airfoil shape.

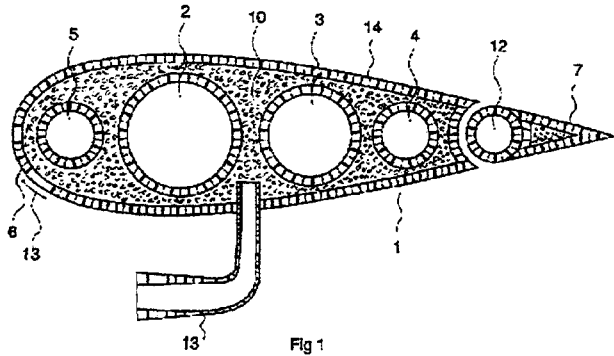


Figure 8. Haggard, 2000

Braided Spars

The focus of this paper is the recent development of braided tubular beam structures, which are particularly well suited for use as wing spars. Commonly known as airbeams, such structures are the result of the availability of high tenacity, high modulus fibers and recent advances in manufacturing technology.

U.S. Army Soldier, Biological and Chemical Command, Soldier Systems Center, Natick, Massachusetts has funded the development of an airbeam braiding facility that is now in operation (Figure 9). The facility has the capability to manufacture braided airbeams up to 50 inch (1.2 m) diameter with length limited only by total yarn weight. In the figure, a 30 inch (0.76 m) diameter, 120 ft (36 m) long airbeam is being braided.

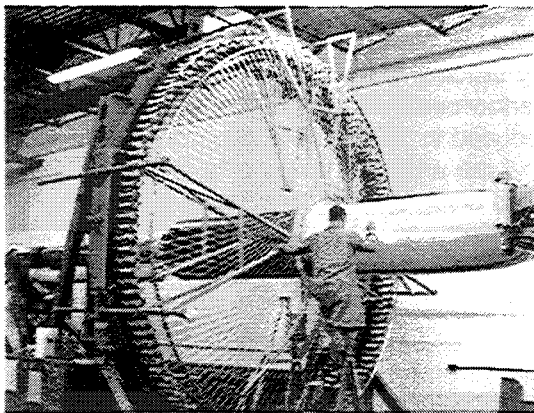


Figure 9. Airbeam Braiding Facility

Braiding produces a tubular structure reinforced by fibers oriented at an oblique angle, the “bias” angle, as measured from the tube axis (Figure 10). This angle is the distinguishing characteristic of braided structures; woven structures have fibers oriented orthogonally with respect to the tube axis. In the figure, multiple yarn “ends” have been braided together to obtain a width sufficient to fully cover the surface.

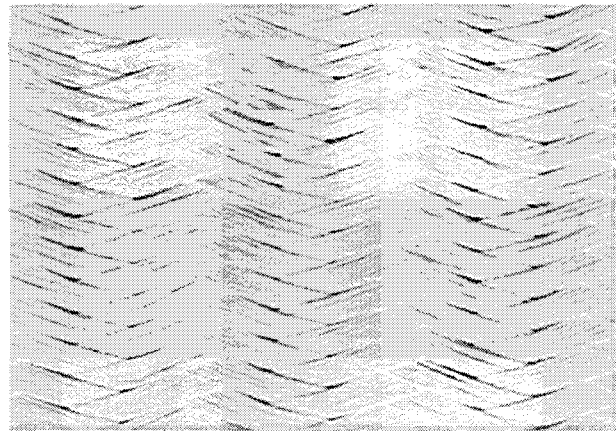


Figure 10. Bias Braid, Surface of Airbeam

Figure 11 illustrates a section of a completed airbeam as might be used for a wing spar. The internal gas barrier is fabricated from an elastomeric film that is impermeable to the inflation gas. The bias braid is responsible for containing the inflation pressure structurally in the circumferential (or “hoop”) direction. The spar caps are axial reinforcements that carry the largest portion of the axial reaction to pressure and provide the spar with bending stiffness.

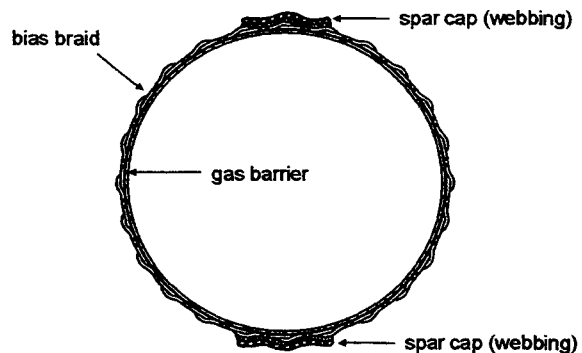


Figure 11. Section of Braided Spar

Bending Strength

The effective bending “strength” of an inflatable beam most analogous to the yield strength of a metallic structure is the “wrinkle” moment. Wrinkle onset is the load condition under which a fiber within the beam section first reaches zero tension. Wrinkling does not necessarily imply a visible wrinkle, but does mark the boundary between small elastic deflections and large deflections leading to buckling. Pre-wrinkle behavior is governed by the same equations as would apply to a rigid composite structure with the same fiber type, distribution, weight and orientation.

A tube of fabric rolled up to form a tube of diameter d , and pressurized to differential pressure P , will wrinkle with an applied bending moment given by this equation:

$$M_{\text{wrinkle_weave}} = \frac{\pi}{16} P d^3$$

This well-known result is presented for comparison with the wrinkle onset moment for the braided spar of Figure 11, having a bias angle β :

$$M_{\text{wrinkle_braid}} = \frac{\pi}{8} P d^3 \left(1 - \frac{2}{\tan^2 \beta} \right)$$

The leading term in the equation is twice the earlier equation because the moment of inertia is doubled by grouping all of the active axial fibers at the extremes of the section for vertical bending, instead of being evenly distributed around the section as with a woven tube.

The term in parentheses accounts for the axial component of tension carried by the bias braid, which is therefore not available as preload in the spar caps. For example, with a bias angle of 75 degrees, this term has a value of 0.86, a 14% reduction in wrinkle onset moment.

A braided spar will therefore never quite be twice as “strong” as a woven spar, but will approach this ideal strength as bias angles approach 90 degrees.

We make note of the important distinction that here, strength does not imply the onset of damage, but rather the onset of larger deflections. Inflatable structures can be designed to survive severe overload without damage.

Inflation Requirements

For a given bending moment, the minimum inflation pressure required is given by

$$P = \frac{8M}{\pi d^3 \left(1 - \frac{2}{\tan^2 \beta} \right)}$$

The weight of the gas required to provide this pressure in the wing spar is sometimes greater than the weight of the spar itself.

Consider, for example, the 1,000 lb cargo glider shown in Figure 12. The single main spar is 14 inches in diameter, 29 feet long, and must resist a bending moment of 120,000 in-lb if it is not braced with wires or struts. The pressure required is 130 psid, and weight of this amount of gas is 34.8 lb. The weight of the wing spar is 36.5 lb.

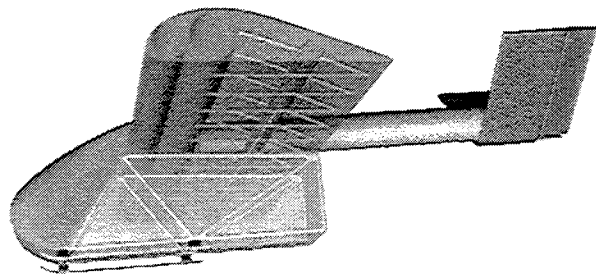


Figure 12. 1,000 lb Cargo Glider

By bracing the wing with wires, which hurts glide performance only slightly, the bending moment is reduced to 26,687 in-lb, the pressure to 45.8 psid, and the weight of the gas to 14.6 lb. If Helium is used along with wire bracing, the weight of the gas is reduced to 1.9 lb.

The estimated weight breakdown for this glider is shown in Figure 13. The inflation system weighs nearly as much as the wing. This weight is “flight weight” only with in-flight deployed wings. If this aircraft were ground-launched, then the inflation system weight would be eliminated.

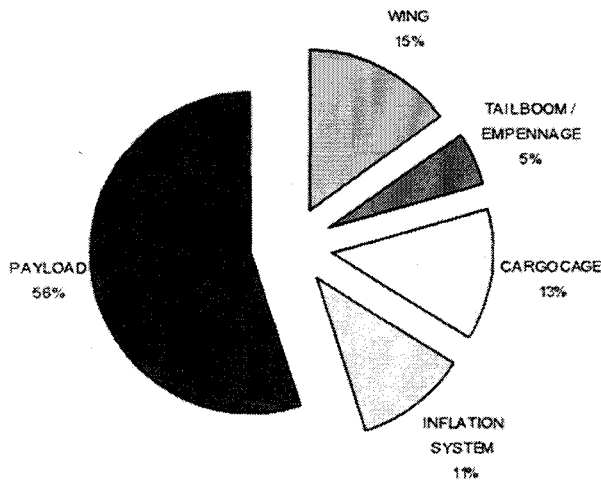


Figure 13. Weight Breakdown for 1,000 lb Cargo Glider

Bending Stiffness

The bending stiffness of a beam can be expressed as the parameter EI , the product of the modulus of the material and the section moment of inertia. Deflection will be determined by the applied bending moment, the stiffness parameter EI , and a constant that depends on the geometry of the loading.

For a single braided spar,

$$EI = \frac{d^2}{2} \frac{dF}{d\epsilon},$$

where the stiffness derivative refers to the spar cap webbing, measured with the preload expected at the working inflation pressure. For engineering estimates, the equation below assumes a linear load-strain curve and allows the spar cap webbing to be sized according to its breaking strength, F_{brk} .

$$EI = \frac{d^2}{2} \frac{F_{brk}}{\epsilon_{brk}},$$

A reasonable approximation for ϵ_{brk} is 1.5 times the breaking elongation of the yarn used to make the spar cap webbing.

Note that these equations apply to pre-wrinkle stiffness and do not contain P . Pre-wrinkle bending stiffness is independent of pressure, as shown in Figure 14. In the figure, the load is applied and deflection is measured at the wing tip. The three sets of curves are taken at three different inflation pressures. The initial slopes are the same. The curves diverge from the initial slope at wrinkle onset, which is proportional to pressure.

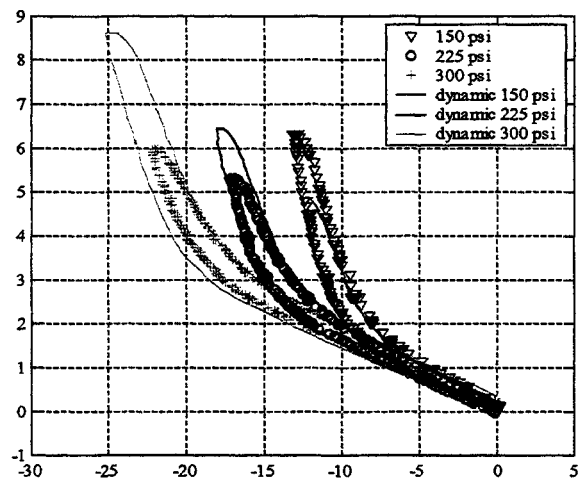


Figure 14. Deflection vs Load for Small Wing

Multiple Spars

When a wing is supported by multiple spars, the situation is considerably more complex. A full exposition of calculations with multiple spars is beyond the scope of this paper. A few comments on this subject are offered below.

- Wrinkle moments are not additive except with equal diameter, co-planar spars. Otherwise the stiffest spar tends to reach wrinkle first, before the other spars have contributed their full wrinkle moment.
- Stiffness (EI) is not additive except for co-planar spars as might be used in a wing with a symmetrical airfoil.

Example Systems

Braided inflatable spars have been used in a variety of prototype air vehicles. The first were parafoils and paragliders. Figure 15 shows an air-reinforced paraglider used to investigate improved ground handling and stability.

Figure 16 shows the airbeam assembly used in the parafoil of Figure 17, which had only eight suspension lines and no leading edge inlets. Glide ratio was approximately 8:1, but control characteristics were poor.



Figure 15. Airbeam-Reinforced Paraglider

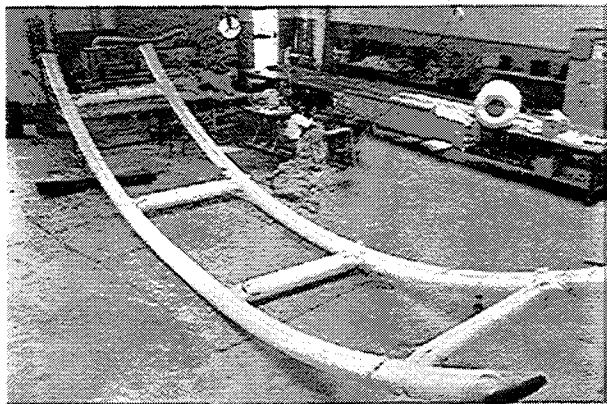


Figure 16. Inflatable Airframe for Parafoil

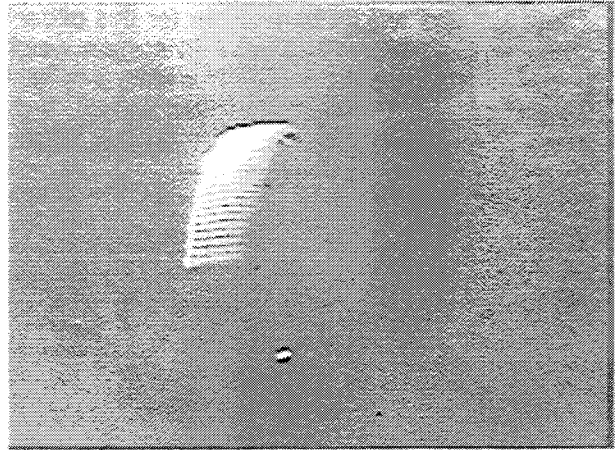


Figure 17. Airbeam-Reinforced Parafoil

Figure 18 shows a section of wing as constructed for the vehicle of Figure 19. This UAV had a tail-less, swept, cantilever wing configuration, which required very high bending and torsional stiffness.

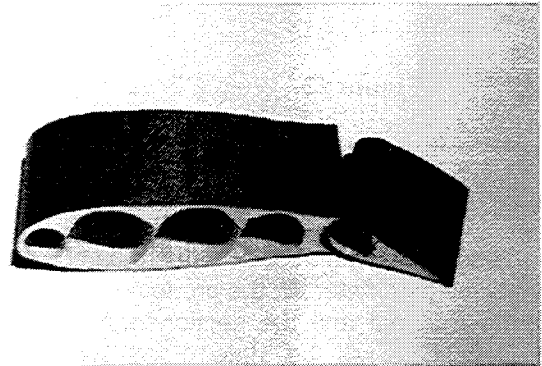


Figure 18. Wing Section Showing Spars

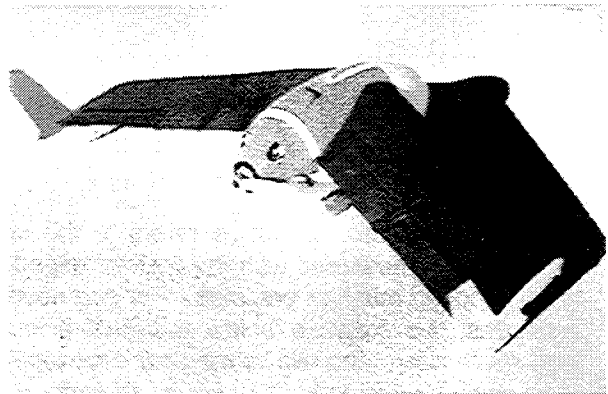


Figure 19. Inflatable Wing UAV

Figure 20 and Figure 21 show gun-launched vehicles. The inflatable wings are packed, in each case, into a 5 inch diameter fuselage that is fired from a gun. The wings deploy near apogee to provide the vehicle with long endurance flight. Figure 22 shows wing deployment from the 5 inch fuselage to the full 62 inch span.

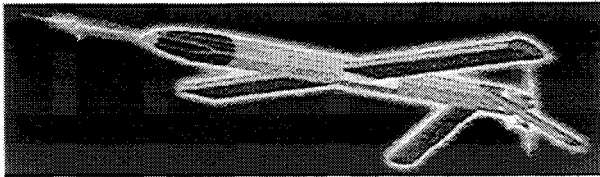


Figure 20. FASM Gun-Launched Vehicle

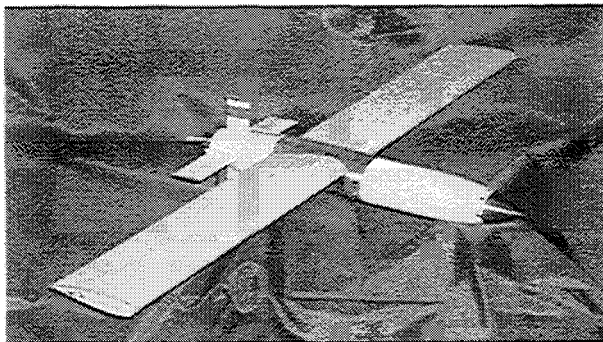


Figure 21. Gun Launched Observation Vehicle (GLOV)

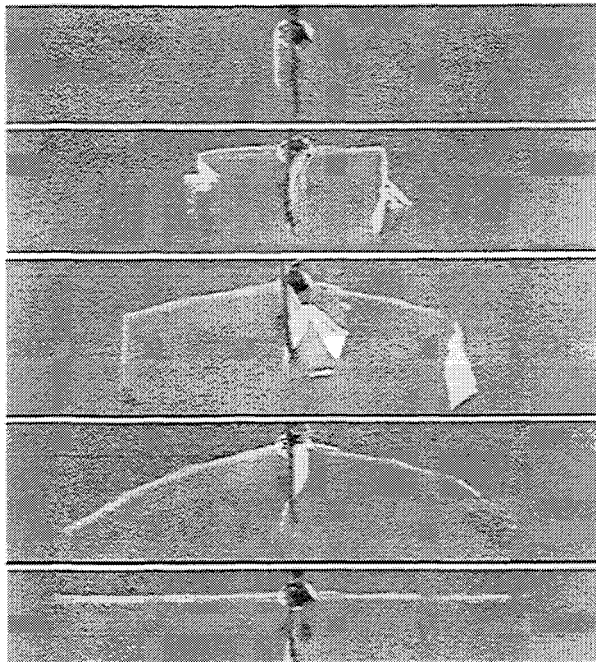


Figure 22. GLOV Wing Deployment

A NASA Dryden concept deploys an inflatable wing from an X-24 lifting body to reduce landing velocity. Tests are planned that include in-flight wing deployment and landing using a scale model, shown in Figure 23.

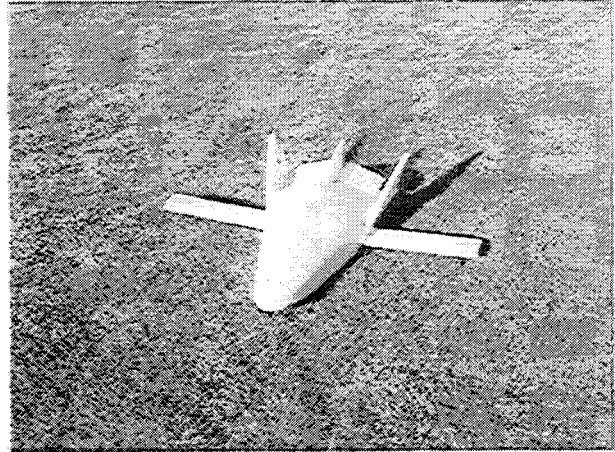


Figure 23. X-24 Lifting Body with Inflatable Wing

Larger scale air vehicles are also feasible. Figure 12 earlier showed a 1,000 lb cargo glider and Figure 24 shows a larger, 12,000 lb version. These would be extracted from cargo aircraft at high altitude, deploy wing and tail, and glide to a distant objective to deliver vehicles and cargo.

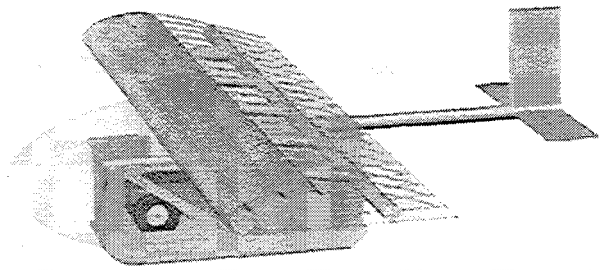


Figure 24. 12,000 lb Cargo Glider

CONCLUSIONS

Inflatable wing aircraft have been of interest for many years, but their successful employment has been hampered by material and manufacturing limitations. Today's high tenacity, high modulus fibers have created opportunities in high performance textile structures, inflatable structures in particular. Inflatable wing aircraft are a particularly interesting application for such structures.

Braided airbeams are one class of high performance textile structure particularly well suited for inflatable wing aircraft. The basic equations for strength and stiffness of braided wing spars have been presented. These are sufficient for making engineering estimates related to conceptual designs. More sophisticated FEA tools are recommended for detailed analysis.

We have presented examples of prototype inflatable wing aircraft that have successfully flown, some that are in current development, and some that are just future plans. These examples demonstrate that the braided spar structural element can be the basis for a wide range of air vehicle configurations and sizes.

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