

ADVANCES IN MATERIAL SCIENCE
AND FABRICATING TECHNIQUES FOR SAILPLANE CONSTRUCTION

by

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Presented at the XV OSTIV Congress
Rayskala, Finland, June 1976

I. Summary Comments

Today's sailplane is truly a highly refined engineering and manufacturing accomplishment. The use of composite non-metallic materials has been advanced considerably, probably matched only in other aerospace applications with the development of helicopter rotor blades and spacecraft assemblies.

The future of sailplane design lies not just in structural and aerodynamic refinement, but also in the broadening use of high technology materials. This can now be done in a knowledgeable way to allow high speed with predictable flutter and gust load capability.

Taking a given set of performance parameters, the engineer can today utilize a broad spectrum of material options. The fibrous materials in composite form allow the adjustment of physical characteristics on the job, tempered only by costing and fabrication limits. The measure of the final effect of material stiffness, as well as sectional design, can be used in preliminary flutter and gust load projections. This would define any specific adjustments of material characteristics during assembly. The concept is not entirely new, but the mathematics is involved. Using computer technology, the problem can be worked in either direction. The engineer can adjust a given design to meet higher performance limits or, starting with a given performance goal, define material and sectional adjustments as needed.

An important challenge in future construction with filament composites lies in innovative production. How do we bring together the advanced materials to produce predicted physical characteristics on a production line basis? The special resins and curing techniques used in the PIK-20 are steps toward the final answers. We need further understanding and technique improvement in the uniform tensioning of fibrous reinforcements proving adequate bonding capability with the matrix for high load and high life expectations.

Today, composite wing structures for large transport category aircraft are being test assembled. Large composite containers for Liquid Natural Gas over 100 feet in diameter are being proposed. Sailplane design and fabricating experience have stimulated the effort in these areas. This will continue because the sailplane is unique as a test bed. The reasonable cost requirements and high performance demands will continue to stimulate the use of new high technology materials in sailplane construction with the continuing benefit to various industrial applications.

II. General Discussion

As we gather together here in Finland for the XVth OSTIV Congress, we should recognize that the Finnish aircraft industry has introduced some new and innovative refinements in fabricating technology. The PIK-20 sailplane, in structural design and fabricating

technology, is a further contribution in scientific advancement. We must give much credit to the mid-Europeans, more specifically West Germany, for the thorough and persistent work in the introduction of fiberglass and composite technology in the early 1960's.

We should recognize that, during the span of the fifteen Congresses of OSTIV, the science of powerless flight has gone from the bare recognition of basic design factors in aerodynamics, structures, and materials to a highly refined science providing the entire aviation industry with a reliable advanced mathematical understanding of critical design influences. With a modern computer it is now convenient to work these resultant mathematical problems with the specific adjustments to variable factors, so as to reduce any compromise in the final design target. For example, in the past a flexible wing structure would introduce serious penalties in aerodynamics, gust loading capability, and flutter resistance. Today, we can adjust that flexibility with a good measure of control, optimizing aerodynamic and structural goals.

Composite material technology is providing some very interesting possibilities in this expanding field of technical endeavor. We must realize, however, that we still have some way to go. Factors relating to fatigue and creep are still important. Aircraft structures are usually concerned with short cycle, high load problems, but fatigue and creep must be considered as important as with metallic or wooden structures.

As we advance into the broader and more refined use of fibers and composite materials, we should appraise these material characteristics very carefully. The rewards could be quite sizable. While our technology at the moment is more specifically concerned with aeronautical applications, we should keep in mind that a big market exists in other industrial and recreational applications. These new structures are castable. Without changing mold shapes, the material's physical characteristics can be adjusted quite markedly. Ability to match precisely calculated aerodynamic shapes is now at hand. These new materials lend themselves to the possibility of providing flexible airfoil shapes and provide a degree of finish and weathering ability not as easily obtained with other materials.

The most important impact of this new material technology is the benefit to the

manufacturing process. We now have a material that is more than equivalent to the metallic materials and utilizes a cheaper raw material with only approximately one third the energy consumption for the total process of manufacture. The physical characteristics of the specific materials can be adjusted in the manufacturing process with little or no mold change. Unfortunately, the existing metal working facilities and skills will have to be updated. The engineering and shop technology will require original thinking in the analysis, personnel selection, process adjustment, and application for a specific design goal. The new materials are not metals. In basic application they are orthotropic or bidirectional, allowing interesting possibilities in fiber orientation to meet specific load paths and, in fact, suggesting a total concept approach in the design and fabricating problem.

III. New Materials in Design and Fabrication

A. Physical Characteristics of Fibrous Composites

Even to an experienced engineer the use of fibrous composite materials is quite difficult. In this growing material science we still have very little information available on material design standards. Strength data varies markedly and is dependent upon fibrous selection, resin selection, fiber-resin ratio, tensioning, temperature influences, and fabricating techniques, including quality control.

For the time being at least, it is probably better to think of these materials as orthotropic or bidirectional. It is here that they will probably be the most competitive. Eventually, I am sure, as we develop a better understanding of the chemical and physical relationship between the fibers and the resin matrixes, including the possibility of chemical or valence bonding between these materials, efficient isotropic fiber composites will be developed.

Figure 1 is presented to show the wide span in physical characteristics of various fiber composite materials. The elliptical shaded areas show a fairly realistic scatter of specific tensile strength to specific modulus for various materials in present day unidirectional composites. The scatter here is directly

related to fabricating technique where emphasis must be placed upon resin selection and uniforming tensioning of fibers.

In the United States we have available certain exotic or advanced materials for composite application, but these materials are being utilized primarily in laboratory testing and prototype applications. The exception has been the successful application of graphite and kevlar materials to various sporting items, i.e., golf clubs, pole vaulting poles, tennis rackets, kyaks, rowing shells, etc. In these specific cases, substantial benefits have come from material selection, but in most cases the application in the fabricating case is not highly refined.

On the European continent, much has been accomplished in the efficient application of these fibrous materials. The fibrous loop, as developed by Prof. Hütter and Egan Hanle, is a major contribution. The sandwich and bonded structures, developed by Fokker during the 1950's, are a major contribution in fabricating technology. The further refinements in mold design, resin selection, fiber tensioning, and curing, as presented by the PIK-20 manufacturers, present another contribution to the growing science of composite materials.

We must admit that fibrous composite structures demand a more critical intermix of technology, including material investigations, engineering design, and fabrication. This is complicated by the fact that today we are quite close to practical applications of chemical bonding between the fiber and matrix material. However, at the moment we have only a limited choice of fiber matrix combinations and their advantages and disadvantages are summarized in a general way in Figure 2.

B. Sandwich Structures

While many may not differentiate in the use of the term 'composite' when it is applied to fibrous composites or structures, there are two interpretations. With the fibrous composite we have, in effect, a high density loading of fiber with a matrix binder to provide bonding

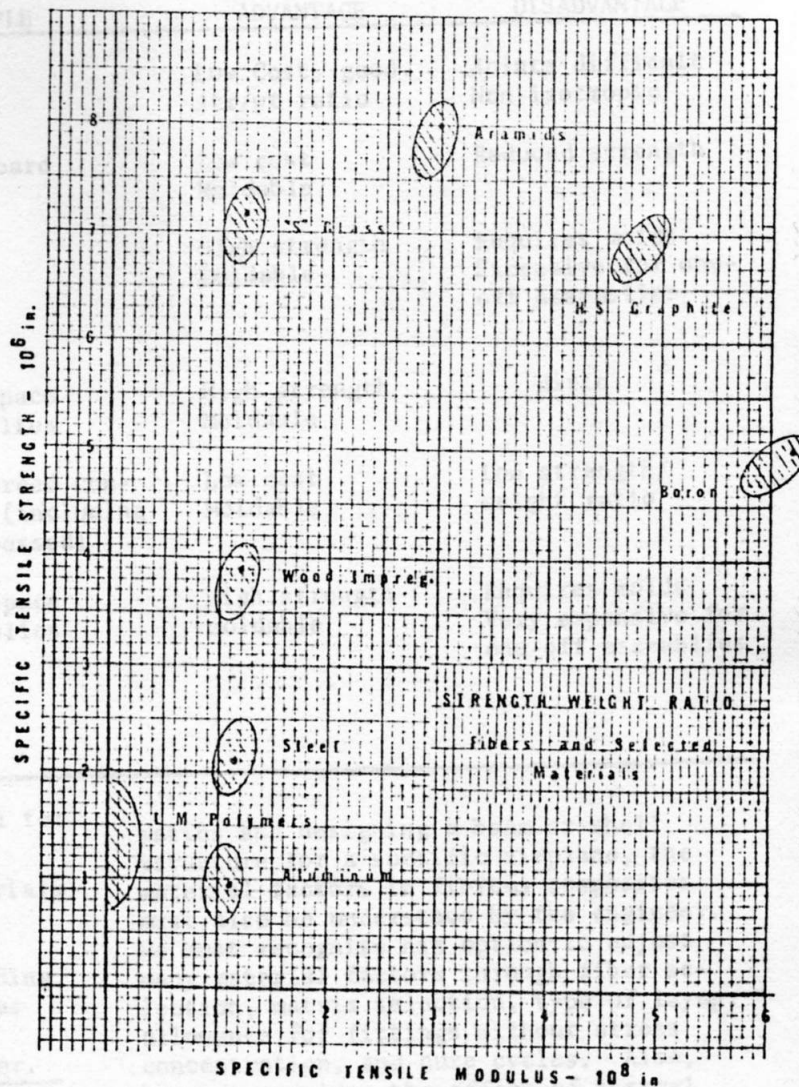


Figure 1. Strength Weight Ratio.

and rigidizing of the assembly. In a structural composite as related, for example, to sandwich structures, we are thinking primarily of a mixture of materials to develop a geometric arrangement in assembly for stiffening. In this case the depth of the sandwich, or the core material, is a major factor. The core material can be relatively light material provided adequate shear capability is proven in the interface between the core and the cap material. The purpose of the sandwich is to improve the sectional moment of inertia. Figure 3 provides a diagrammatical comparison of stiffness changes with changes in sandwich thickness. While other factors need also be considered, in the simplified case the

FIGURE 2. TYPES OF FIBROUS COMPOSITE ASSEMBLIES

MATRIX-FIBER	EXAMPLE	ADVANTAGE	DISADVANTAGE
1. Natural Resin - Natural Fiber (Cellulose)	Wood	Low Cost, good str/wt ratio	Joints difficult Non-isotropic
2. Synthetic Resin - Natural Fiber (Cellulose)	Fiberboard	Low cost Moldable	Reduced strength
3. Synthetic Resin - Synthetic Fiber (Glass, Carbon, Graphite, Aramid, Other)	FRP	High strength Moldable	Requires molds Expensive for one-off assemblies
4. Synthetic Resin - Metal Fiber	Aero space assemblies	High strength Moldable	ditto
5. Inorganic Matrix (Cement) - Metalbars or Glass Fiber	Reinforced concrete (including prestressed)	Low cost Moldable	Low strength/ weight ratio
6. Inorganic Matrix (Metal) Inorganic Fiber (Boron, ceramic, Metallic, Titanates, Asbestos & Other)	Aero space assemblies	High strength moldable	Requires molds Very expensive for one-off assemblies

Note: *Strength and stiffness proportional to:

- a) Matrix to fiber bond
- b) Relative thermal coefficients of materials
- c) Relative material moduli of materials
- d) Uniform tensioning of fibers
- e) Molecular crosslinking or valence bonding
- f) Core utilization in sandwich assemblies

* For given selection of matrix and fiber.

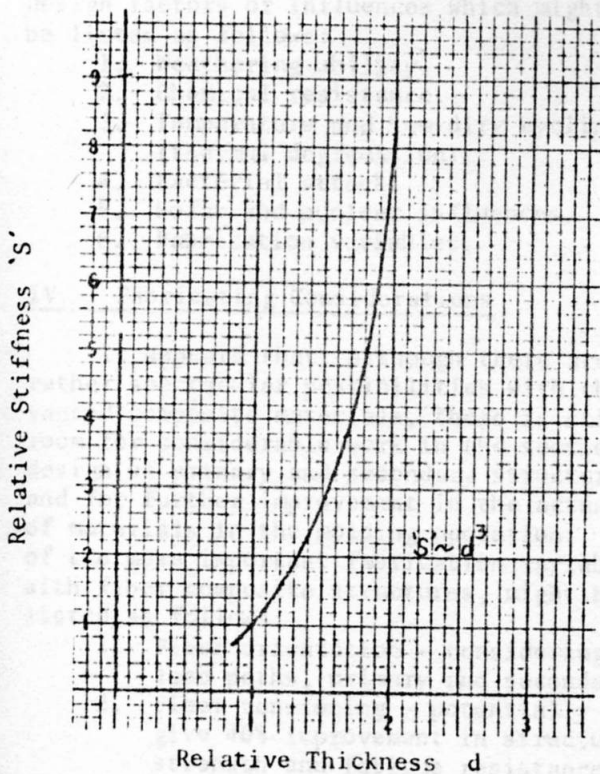
stiffness of the given sandwich assembly increases by the cube (d^3) of the increase in sandwich thickness. The utilization of sandwich structures has hundreds of applications and is not a new idea. Probably one of the first man-made sandwich structures came with the development of ceramic glazing on pottery. But today, in fibrous composite structures and sandwich assemblies, we have new possibilities because of the ability to control and match innumerable combinations of surface or cap materials with various core materials.

C. Factors in Design

Apart from applying the basic mathe-

matics and designing a beam or shell structure for a specific airplane, the material factors in fibrous composites must also be understood by the engineer. He must recognize his option to adjust many material factors through fiber selection, matrix selection, type of layup, allowance for fittings without stress concentration, and cure cycles. Also, he must consider the effect of thermal expansion coefficients and, with certain material mixes, the careful matching of material moduli or stiffness factors. In addition, he should realize that there is far more opportunity, with minimal weight penalty, to adjust a sectional design through sandwich layup techniques.

An interesting example can be given with the structural design of the wing for Alcor, a pressurized test sailplane. Quite early it was apparent that this 20-meter wing would have higher deflections than a comparable metal structure. This was a result of the glass fiber material selection. In design, some adjustment was available by increasing the chord depth at the wing root, this sailplane



Variables in Core

1. Compression Strength
2. Rigidity and Sharing Resistance

Figure 3. Stiffness in sandwich composites.

not being designed for high penetration speeds. As the design progressed, it became quite apparent that an opportunity presented itself to adjust the torsional stiffness to a high level with no weight penalty simply by changing the material specifications to "S" glass cloth, properly tensioned, as a cover for the leading edge box section. After the wing was completed it was quite apparent, with only minimal instrumentation, that there was a high torsional stiffness of this particular wing as related to wing bending.

Some time later the opportunity presented itself to compare this structure, a non-metallic glass structure utilizing "S" glass fibers in critical locations, with the Boeing Compass Cope airplane which includes an exotic metal honeycomb structure. The purpose of the investigation was several fold. One: there was a tremendous difference in cost between the development of the two airplanes which were somewhat similar in geometry and

size. Two: the non-metallic structure appeared to lend itself towards prototype assembly or limited production. Three: once molds are committed, there is considerably more room for adjustment in establishing ultimate load capability through fiber and matrix variations. Figure 4 is a qualitative comparison of these two aircraft. EI represents the structural modulus and the moment inertia in the bending case, and GJ the structural modulus and the moment of inertia in the torsional case. The ratio of EI/GJ is important for a number of reasons, and of primary importance as one of the factors in projecting gust load and flutter resistance. It became quite obvious to many people concerned with this test that an unusual opportunity was presenting itself, with these new materials, for the development of high performance airframe structures at lower costs.

D. Other Considerations

While many companies in Europe have pioneered the initial use of fibrous composite assemblies in airplane construction, this work is also being done in the United States and is being directed primarily on a prototype basis to advanced military and test vehicles. Additional information is being gathered on special

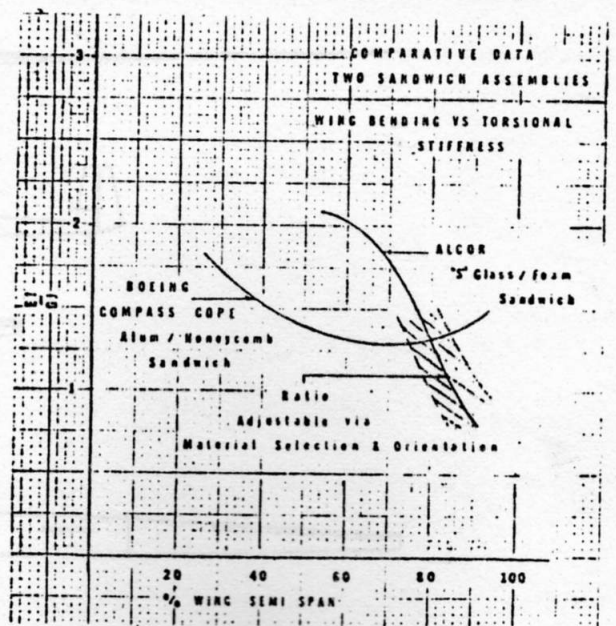


Figure 4. Comparative data for two sandwich assemblies.

design factors or influences which might be listed as follows:

1. Weathering ability.
2. Chemical resistance.
3. Temperature and humidity cycling (thermal degradation).
4. Bacterial attack.
5. Solar and nuclear influences.
6. Fabrication variables.

IV. Fabricating Considerations

It appears that, although there are rather spectacular possibilities with the advanced composite materials, there is still room for considerable work in the sectional design of primary and secondary structures, and for further improvement in the actual use of materials in the molding operation. Some of the more important fabrication variables, with fiber composite structures, might be listed as follows:

1. Fiber orientation - considering all load paths, primary and secondary.
2. Fiber tensioning - potentially can give 40% improvement in structural strength and fatigue resistance over random assemblies. It is important to note here that the glass fiber itself is tensioned in the process of manufacturing, giving rise to some synergistic improvement of fibrous glass strength over bulk glass.

3. Resin selection - Complete wetting of the glass filaments is mandatory with all fibrous structures. The matrix itself, together with the fiber sizing material, if used, must be compatible and develop adequate interface shearing capability with adequate reserves for fatigue cycling at high loads.
4. Curing cycles - The conventional organic resins used in the matrix are ordinary polymers which upon polymerization in the chain provide a degree of cross linking and cast the reinforcing fibers into a hardened shell or resin surrounding and joining the individual fibers. Higher temperatures provide one way to accelerate the curing cycle. However, with higher temperatures other problems are introduced which are not fully understood - there being usually a higher thermal coefficient with the resin as it expands and flows in the liquid form during the exothermic cycle, so that after cure the contraction of the resin does produce some relaxing of the reinforcing fibers. This is counteracted to some degree, first, by tensioning the fibers and, second, by allowing the resin to shrink normally to the surface of the layup. This is a vari-

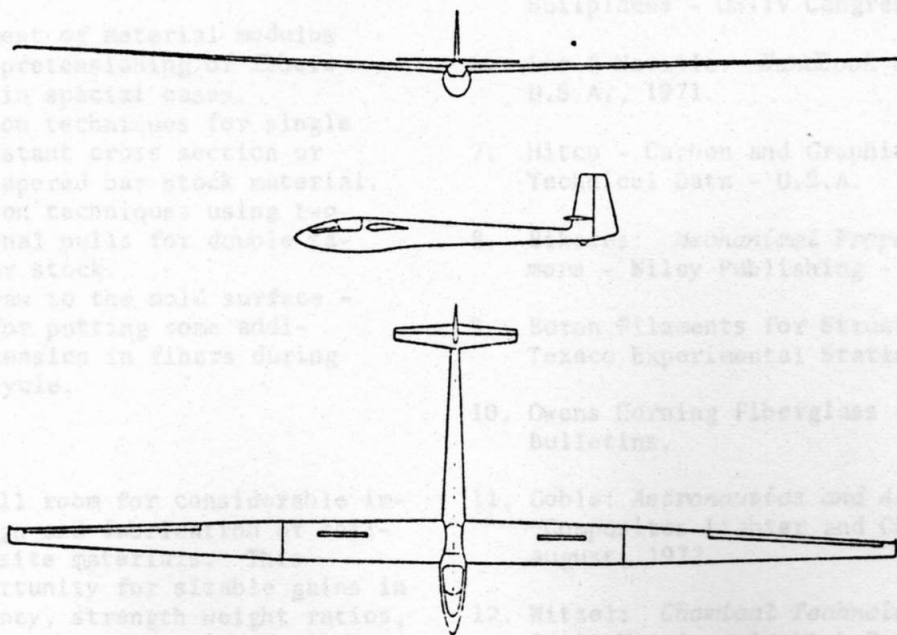


Figure 5. Alcor Sailplane.

able that must be understood during the fabricating process.

5. Joints - One of the difficulties in working with orthotropic materials and, to a lesser degree, with bidirectional composites has to do with joints. These materials cannot be used like metals which are isotropic. Special allowances must be made for joints. While it is admitted that a number of prototype test programs are underway in Europe and the United States, some of these wing sub-assemblies are being manufactured with composite sub-assemblies bolted together to enable prototype testing. This is an interim step. The ideal structure will come once the capabilities of the materials are understood and the assembly laid up in one piece, i.e., wing box structure including spar cap, camber sheets, and spar webs with flanges. Important considerations, during the fabrication of the fiber composite assembly and its future refinement, appear to be in the following areas:
 - a. Balancing of mold-fiber-matrix temperature differentials during the curing cycle.
 - b. Uniform wetting of all filaments or fibers used in the composite assembly.
 - c. Improvement of material modulus through pretensioning of fibers in certain special cases.
 - d. Pultrusion techniques for single pull constant cross section or single tapered bar stock material.
 - e. Pultrusion techniques using two directional pulls for double tapered bar stock.
 - f. Resin draw to the mold surface - method for putting some additional tension in fibers during curing cycle.

V. Conclusion

There is still room for considerable improvement in design and fabrication of sailplanes with composite materials. This includes the opportunity for sizable gains in operating efficiency, strength weight ratios, and cost. The shop facilities must stimulate innovative thinking, must be shielded from compromise by the inertia of current metal

working practices, and must enforce a high level of cleanliness and precise methods of process control.

OSTIV, as a catalyst, has contributed a great deal towards the accomplishments we see here at Rayskala. This will continue in the future. We now have the advanced fibrous materials and the technical understanding for innovative design and fabrication. The sailplane, as a nearly ideal test bed, will show further refinements. This will provide confidence and experience in the technology of composite materials with applications far beyond aeronautical endeavors.

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SOME NOTES ON SOARING FLIGHT OPTIMIZATION THEORY

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SUMMARY

General soaring flight optimization techniques are briefly reviewed. The straight delta mode is examined and an optimal flight policy on course of successive delta mode elements is suggested. Also significant recent references in the field are given.

NOTATION

d	differential operator
w	sailplane's vertical velocity with respect to ambient air
v	sailplane's airspeed
x	distance along the element
λ	Lagrange multiplier
$w(x)$	vertical velocity of the air as function of x
Δh	altitude change in traversing the element (= terminal altitude - initial altitude)

Upward direction is considered positive, downward negative in translation as well as in all velocities.

INTRODUCTION

In recent years there has been a substantial increase of interest and research in the field of soaring flight optimization. The problems of achieving maximum cross-country speeds and maximum distances are fascinating and challenging. Even the very first step, i.e. problem formulation in a real case, calls for theoretical as well as practical intuition.

On an actual soaring racing course the ultimate goal of the pilot would be to follow a flight policy that brings him from the starting to the finishing line in minimum time. On a given day there might exist one or more flight policies that yield the absolute optimum. At this point it is logical to ask: Does the pilot have any means intentionally to pick up the policy or a policy that yields the absolute optimum? The answer is a solid no. The answer may depress a "scientist pilot", but it surely cheers up the "natural pilot", who has perhaps already become anxious about the increasing talk of the application of scientific methods and technical instruments within soaring.

And really -- the problem of finding the flight policy that minimizes the flight time through a general course contains too many independent variables, constraints and