11th von Kármán Lecture

Advanced Composites

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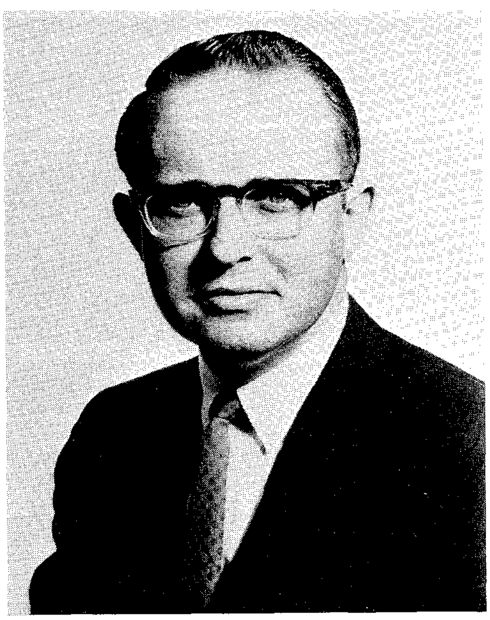
I. Introduction

MODERN composites as they are known today owe their genesis to glass fiber-polyester composites developed over the 1940's, to wood over the past centuries, and to nature over millions of years. Composites are not new for aerospace applications in the sense that early vehicles were made of natural composites, followed by aluminum. In fact, von Kármán's work in buckling of structures was needed in the transition from natural composites to aluminum for aircraft in the 1930's. The emergence of boron filaments gave birth to a new generation of composites in the early 1960's. The composites that employ high modulus continuous filaments like boron and graphite are referred to as advanced composites. This remarkable class of material was cited by *Fortune* in 1967 as one of the most promising developments that could have profound impact on the technologies of the 1970's. Through intensive research and development programs in the U.S., together with important contributions by United Kingdom, Japan, and others, composites have fulfilled their initial forecast of structural performance. As a result, increased applications are emerging in aerospace and recreational industries.

In this address, advanced composites will be compared with those in nature in Sec. II. Early aerospace applications will be cited in Sec. III. This set the stage for the need of high specific modulus, in Sec. IV, beyond that theoretically achievable in aluminum, steel, and titanium. The development of boron, graphite, and high modulus polymeric fibers during the last decade or so provided answers to this need. In Sec. V, the problems associated with the translation of properties of filaments to those of structures result in the growth of advanced composites in



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Dr. Alan M. Lovelace (Member AIAA) is Deputy Assistant Secretary, Research and Development, Department of the Air Force, Washington, D.C. Before assuming this position, he was Director, Science and Technology, Air Force Systems Command (AFSC), Andrews Air Force Base, Md.

He was born in St. Petersburg, Fla., in 1929. He attended the University of Florida and received the B.S. in chemistry in 1951, the M.S. in organic chemistry in 1952, and the Ph.D. in organic chemistry in 1954. In 1954 he was a Lieutenant in the United States Air Force assigned as a Research Chemist in the Polymer Branch of the Nonmetallic Materials Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. His capabilities in the field of chemistry of fluorine compounds were immediately recognized, and in 1956 he received the AFML Charles J. Cleary Award for his outstanding work in fluorocarbon chemistry.

After separation from the service in 1956, Dr. Lovelace remained with the Laboratory in a civilian capacity. He progressed to Senior Project Engineer in the Polymer Branch, and in 1958 was the recipient of the Flemming Award in recognition of his scientific competence in fluorine and polymer chemistry that led to establishment of an extensive research program on inorganic polymers in the AFML. In 1959, he was named Chief of the Polymer Branch. The magnitude of his contribution to polymer science is indicated by his six inventions and more than thirty technical publications. In 1959, he was awarded the Department of the Air Force Commendation for Meritorious Civilian Service for his unusual foresight in the timely development of technical capabilities in the solid propellant field. In 1962, Dr. Lovelace became Chief Scientist of the Air Force Materials Laboratory. In addition to this primary assignment, during the period October 1964 through May 1965, he was Director of the AFSC Boron Working Group of the AFSC Ad Hoc Task Force. In connection with this assignment, he prepared and presented a series of briefings to apprise Government, industry, and research agencies of the vast potential of advanced composite structures.

In July 1967 Dr. Lovelace became Director, Air Force Materials Laboratory. As a result of his expertise in managing the activities of the AFML, he was the recipient of the Air Force Association Meritorious Award for Program Management in 1969, the Office of Aerospace Research Award for Outstanding Contributions to Research in 1970, and the National Civil Service League Career Service Award in 1971. He became a member of the National Academy of Engineering in 1974.

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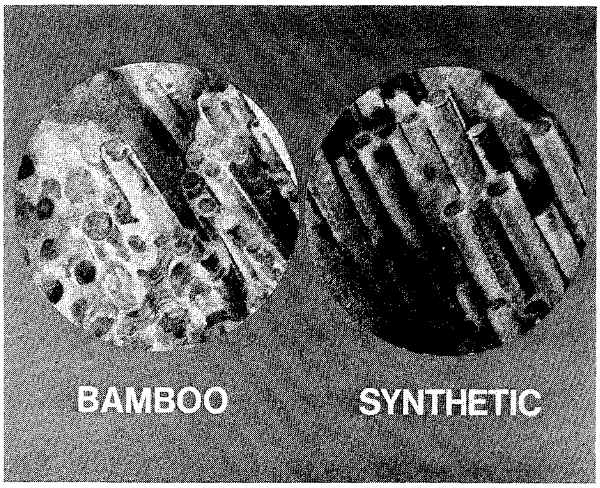

Fig. 1 Scanning electron microscope pictures of bamboo vs graphite-aluminum composites. Pictures are typical of failure surface of unidirectional filamentary composites with portions of filaments exposed after failure. Higher magnifications, however, will reveal the cellular structure of bamboo which is different from the continuous structure of graphite and aluminum.

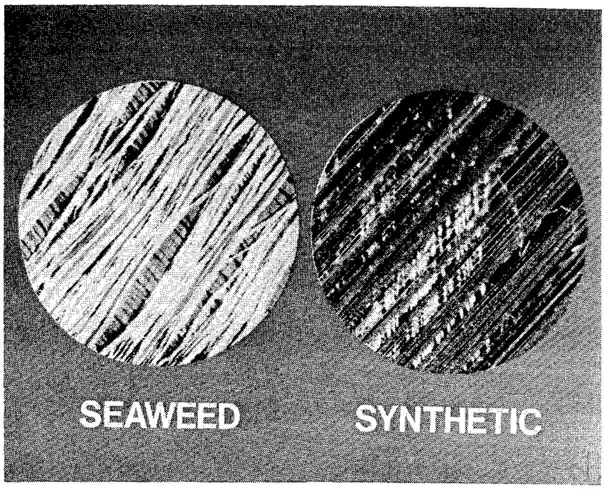

Fig. 2 Boron-epoxy laminates are similar to construction of seaweed. Analogous to unidirectional construction for unidirectional loads, laminated structures for biaxial loads exist extensively in nature and many manmade things like plywood.

the form of filamentary composites, not in the whisker composites. The technology demonstration phase is discussed in Sec. VI, wherein the philosophy of direct substitution of existing vehicles will be followed. In Sec. VII, Composites Recast will be reported which critically assesses the future of composites. Confidence and cost are cited by this study as the major barriers to be confronted by advanced composites. The future promises much expanded applications which will depend on cost competitiveness on an absolute basis, and an innovative design that fully utilizes the features of composites. Examples of achievements in cost and innovative designs are cited in Sec. VIII. It is concluded in Sec. IX that composites for major structural applications for aerospace vehicles will come as a matter of time. As experience factor of advanced composites increases, primarily through usage and vigorous research and development effort, the true story of composites may exceed the fondest expectation of today in terms of cost, performance, and longevity.

It seems appropriate to pay a special tribute to von Kármán for his ability to apply mathematics to practical problems. His mode of effective transition from theory to practice was followed in the advocacy of composites for aerospace applications. The progress of composites to date can be traced to the collective commitment of government, industry, and universities working in a supportive mode putting it altogether. The substance of this paper is intended to reflect upon the contributions of many individuals and organizations working toward a common goal which involved integration across several established disciplines and technologies. Materials scientists cannot work independently from structural designers and aerodynamicists. While von Kármán repeatedly performed his integration of interfaces by himself, most of us have to work with other specialists and managers in advocating advanced composites. As we expect advanced composites to be counted as a new class of engineering materials ready for production, the road ahead may require more concerted effort than that of the last decade.

II. Composites in Nature

Numerous examples of composites exist in nature. For the case of filamentary composites, an example can be found in bamboo, as shown in Fig. 1. The striking similarity between the failure surface of bamboo and that of graphite-aluminum composites is obvious.[1] Another comparison can be seen in Fig. 2 where seaweeds and boron-epoxy laminates are shown.[2] Seaweeds have been in existence for at least 150 million years, and it is interesting that the concept of lamination to support planar configurations was utilized for at least that length of time. Angle-ply construction can also be found in human intervertebral disks.[3] It is, therefore, safe to say that filamentary composites and their laminates are very old indeed.

Through the years, we have learned to work with natural composites such as wood. The properties with and against the grains vary significantly. Such directional or anisotropic properties have provided design approaches to take advantage of the superior properties while suppressing the undesirable ones through the use of laminates. Plywoods, for example, are made with an odd number of laminas. Such stacking arrangement is necessary in order to prevent warping. In the language of modern composites, this is referred to as the symmetric layup or zero extension-flexure coupling. There is no cleavage plane across grains in wood. Splitting due to nailing can be reduced either by driving nails at an angle to the grain direction, or through cross-lamination as is in the case of plywood. This experience factor derived from wood has contributed a great deal to the understanding of filamentary composites. In fact, *Handbook ANC-18*[4] deals exclusively with the use of wood for aircraft structures and the Theories of Anisotropic Elasticity and Anisotropic Plates was motivated by the wood industry in the U.S.S.R., the United Kingdom as well as the United States. The technology of modern composites relied very heavily on the theoretical foundations developed by these earlier works.[5-7]

III. Early Aerospace Applications

The use of natural composites for the Kittyhawk and its successors was a necessity. Wood, canvas, etc. are lightweight materials and can be made to serve the early aero-

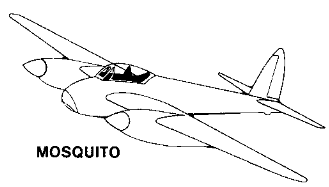

Fig. 3 An example of all-composite plane that provided high performance through increased structural efficiency of sandwich construction and decreased frictional drag due to greater smoothness. Moisture in wood, however, causes decrease in strength and increase in density. The total effect on the specific strength is additive.

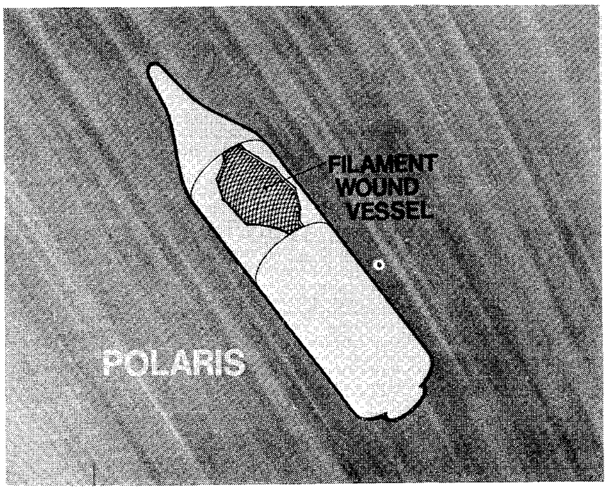

Fig. 4 The first production model of solid propellant motor case by filament winding was pioneered by the Polaris. This was followed by Minuteman, Poseidon, and planned for the Trident. The superior strength of glass was effectively utilized. The lack of stiffness, however, was not a severe handicap for this application.

space applications by the use of big "I," the moment of inertia, to compensate for the low "E," the modulus of elasticity. The biplane construction is an example of the use of big "I" to provide the necessary rigidity to support the required airfoil.

Composites were used for aerospace vehicles since their birth but the Mosquito aircraft are generally recognized as a milestone for the all-composite plane, as shown in Fig. 3. The Mosquito was a highly successful aircraft, of very high performance for its time. It also demonstrated the great promise of lightweight sandwich construction primary structures. This success was achieved despite the disadvantages of wood as a material. Wood varies in moisture content depending on the humidity of the surrounding atmosphere if it is in that atmosphere long enough to come close to equilibrium. The stiffness and strength properties go down with increasing humidity, but the effect is reversible. However, design properties had to be reduced to allow for this.

The application of glass fiber-polyester composites to Air Force vehicles was made in numerous cases during and shortly after World War II. Wings, fuselages, propellers, and many secondary structures were built and tested. The motivation then was the potential cost reduction through ease of fabrication, and the increased durability against corrosion and weather. While primary structures were not placed in production, many secondary structures such as doors and fairings were.

The use of glass fiber for modern aerospace applications reached a significant milestone when the Polaris missile casing was made through filament winding, as shown in Fig. 4. The use of such technology was on a production basis. The Minuteman, Poseidon, and Trident all followed the lead of the Polaris system.

IV. Need for High Modulus

In order to broaden the application of composites and be competitive with the state-of-the-art materials such as aluminum, higher modulus, and higher strength materials for composites were deemed necessary. The development of high-performance glass filaments was initiated by the Air Force, which led to the S-994 filaments which increased the Young's modulus and strength over E-glass by 18 and over 30%, respectively. After the S-glass fibers were developed, emphasis was placed on the development of higher modulus glass fibers. Many glass compositions have modulus of elasticity up to 20 × 10^6 psi. However, in order to be fiberizable, a certain elevated temperature viscosity range was required. This fact, plus keeping the density at about 2.5 or less, limited the composition and the modulus potential. Glass fibers in the range of 14 to 16 × 10^6 psi were successfully developed in the laboratory but were not successfully placed in production. Higher cost and limited demand were additional problems.

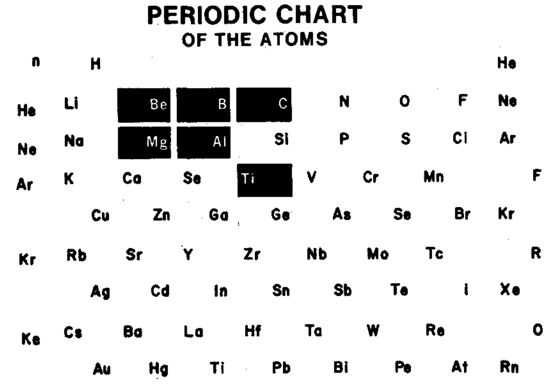

Fig. 5 High specific modulus materials can be made from compounds containing the lightweight elements. While the stiffness of the material remains the same regardless of form, the strength of filamentary or whisker form can be significantly higher than that of the bulk form of the same material. The increase in strength is attributed to the lower number of defects in the internal structure and at the surface.

While the stiffness of aluminum and titanium cannot be increased, glass filament stiffness must be increased three to four times the present S-glass level before glass-epoxy laminates can be competitive against aluminum and titanium on the specific basis. The lack of significant increase in the specific stiffness through modified glass led to the need for high modulus materials from other elements and compounds. In the periodic chart shown in Fig. 5, one can readily identify the lightweight elements from which new filaments might be formed. During this period which started in the late 1950's, several fibers and whiskers consisting of those lightweight elements and compounds emerged.

Boron fiber was the first very-high-modulus high-strength reinforcing fiber for the age of advanced composites. It was developed based on the low density and high modulus as observed on the bulk material. Other fibers included carbon, beryllium oxide, and boron carbide. The moduli were several times the modulus of glass and the density about the same. It was reasoned that if these could be fiberized in fine diameter form, high strengths could be obtained. Therefore research was initiated on methods of forming fibers and filaments from such elements and compounds. The first laboratory success was with boron and beryllium oxide. Since the latter was in short fiber form and the boron was continuous filament, the beryllium oxide fiber development was dropped and the development of boron filament expanded. The process was elevated temperature vapor deposition of boron from the reaction of boron trichloride and hydrogen onto a substrate of very fine diameter tungsten, the latter making up only a small percentage of the total volume.

The development of very-high-modulus graphite fibers by pyrolysis and stress-graphitization of rayon followed shortly thereafter, and subsequently, was followed by graphite fiber from "PAN" (polyacrylonitrile). In recent years, very high modulus and high tensile strength polymeric fibers have been developed. These are highly oriented and crystalline aromatic polyamide fibers. Physical properties and manufacturing processing of fibers and whiskers can be found in recent books by Pratt[8] and Scala.[9]

High-performance synthetic fibers such as boron and later graphite can be seen in Fig. 6. Specific strength and

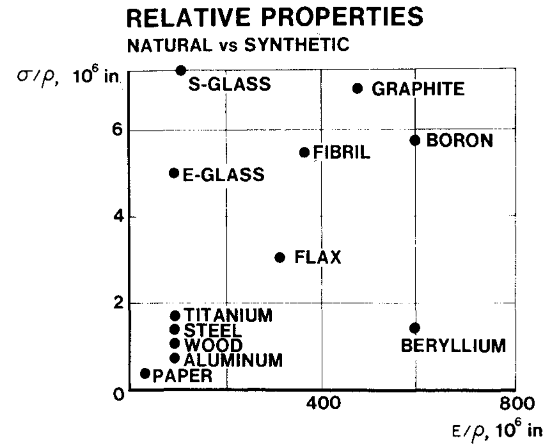

Fig. 6 The advantages of lightweight materials may be seen by the comparative specific properties. Realistic comparison, however, must take into consideration the filamentary bulk forms of materials. Properties of filamentary materials will reduce in the process of translation from constituents to unidirectional plies. Additional reduction must be made as unidirectional laminas are made into laminates for biaxial properties.

specific properties of several fibers and lightweight materials are shown. In this figure, I also show some natural composites including flax and elemental fibril, the specific properties of which are surprisingly impressive in light of the modern synthetic fibers.

The birth of boron was recognized by Project Forecast, an Air Force study in 1963, as a promising new technology. I participated in this study and provided the initial impetus for the demonstration of boron composites as a new generation aerospace material. A moral commitment to exploit this material was made and implemented by the Air Force. Such a commitment gave birth to advanced composites, which distinguishes from the less advanced ones from the standpoint of modulus.

V. Theory of Composites

The superior properties of fibrous materials are meaningless unless they can be efficiently translated into forms usable for applications. Of the new families of fibers and whiskers with high modulus, the translation of their properties can be treated in two categories: 1) Short fiber composites are used here to designate both whisker and discontinuous fiber composites; the short fibers can be aligned or randomly oriented. 2) Filamentary composites refer to continuous filaments in unidirectional laminas from which laminated structures are made.

Translation of whisker properties into composites has not lived up to its expectation for a variety of reasons. Fabrication of whiskers by batch process, sorting of whiskers to attain uniform aspect ratio, whisker alignment, or dispersion for random orientation, and quality control all contributed to the problem of whisker composites. While low cost whiskers and composites may still be possible, the initial forecast of high performance has not been achieved to date.

In Fig. 7, additional problems of this property translation are shown. First, the discontinuities that exist in short fiber composites gave rise to stress concentration in fibers adjacent to points of discontinuities.[10] These discontinuities limit the theoretical strength achievable by short fiber composites to a fraction of those filamentary composites consisting of the same constituents. This stress concentration exists in both whisker and discontinuous composites. Most modern unidirectional composites have longitudinal strengths in the order of 200 ksi while the highest tensile strength measured by aligned short fiber composites rarely exceeds 70 ksi. The same degree of relative strength exists in randomly oriented short fiber composites as compared with quasi-isotropic filamentary laminates.

Another problem of short fiber composites is the lack of uniformity of properties from point to point within the composite. Wide dispersion of modulus and strength for a randomly oriented chopped-glass composite is also shown in Fig. 7. The test data gathered by flexural and tensile tests are shown. Only a small difference was found between 3- and 4-point flexure; but the tensile data were lower than the flexural data.[11] The wide scatter of properties poses special problems to the designer who must learn to engineer around this heterogeneous material system.

The need of moderate strength but low cost composites for complex shapes, however, is rapidly expanding; e.g., in cars, boats, furniture, as well as selected aerospace applications. Short fiber composites fill this need rather than that in direct competition with aluminum or modern filamentary composites.

The translation of filamentary composites to engineering forms evolves around the constituent-lamina-laminate approach. The constituents are the continuous filament

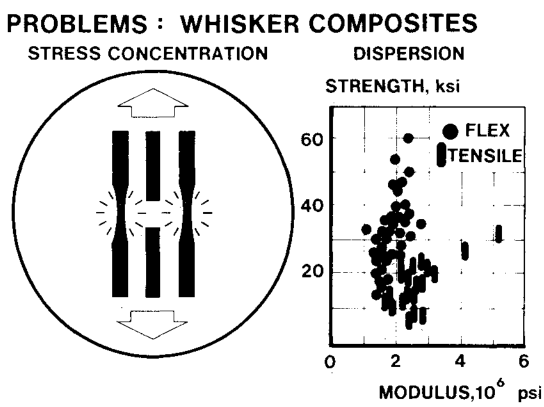

Fig. 7 Whisker or short fiber composites must carry additional internal stresses because fibers adjacent to discontinuities must pick up extra loads. The absolute strength that can be achieved by short fiber composites is only a small fraction of comparable filamentary composites. The low strength is further penalized by the lack of uniformity from point to point with the composites. The scatter of data shown imposes an additional design constraint. Also shown is the difference between the tensile and flexural test data.

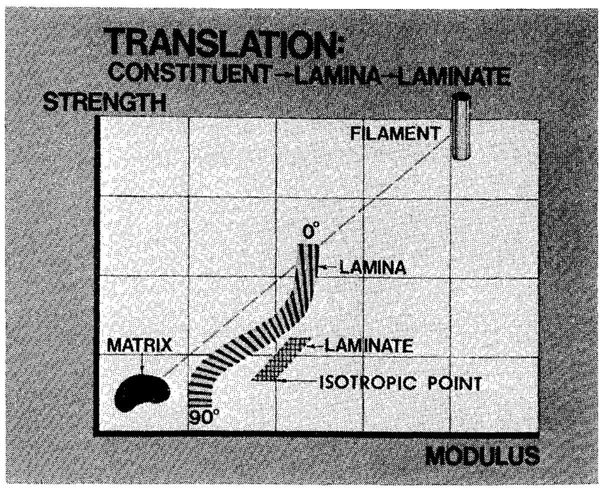

Fig. 8 The efficiency of translation from fibers and matrix into unidirectional laminas is variable and depends on the angle of orientation between 0 and 90°. Laminas can then be made into laminates, the property of which begins with the isotropic point as the lower bound value. The degree of directionality achieved through judicious choice of stacking sequence will improve the performance of laminates beyond the isotropic property, as the slanted bar in this figure indicates.

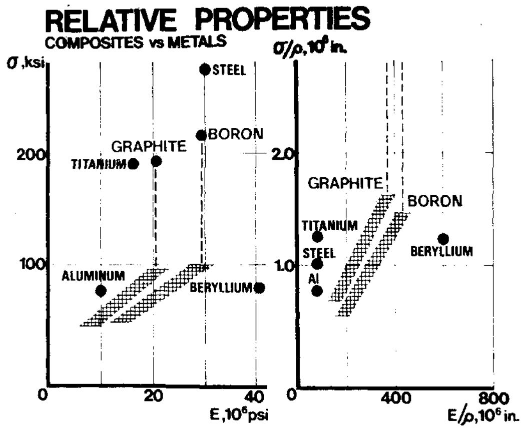

Fig. 9 A more realistic comparison of composites vs metals can be made either on an absolute basis on the left or a relative basis on the righthand side of this figure. The graphite-epoxy and boron-epoxy composites are stiffer than aluminum, steel, and titanium on a specific basis. The relative strength will depend on the specific laminate construction. The outstanding fatigue strength of composites will make composites much more attractive than comparable metals.

Fig. 10 The first generation advanced composites component was demonstrated by the F-111 horizontal stabilizer. This item achieved the objectives of technology demonstration in terms of materials, design, and manufacturing. This empennage technology was readily transferred from General Dynamics to other aerospace companies.

and the binding matrix from which a unidirectional lamina is formed. The properties of this lamina depend on the fiber orientation. In terms of uniaxial properties, the 0° orientation has the highest strength and stiffness. These properties decrease as the angle of fiber orientation moves away from 0°. The lamina as a function of orientations from 0 to 90° is shown as a curved bar in a strength vs stiffness graph, instead of a dot for the common material which is primarily isotropic. This curved bar is shown in Fig. 8.

Laminates are made from stacking unidirectional laminas with predetermined orientations. The resulting properties of the laminates are approximated as a slanted bar in this figure. At the lower end the laminate property is the isotropic point, which can be made with a stacking sequence of 0/±60 or 0/90/±45.[12] This laminate represents the lower bound of the laminate properties; that is, the minimum performance of the filamentary composites. But in actual use of composites, advantages of directional properties can be made to further improve the properties of composites. The desired anisotropy can be designed by judicious choice. The slanted bar shown in Fig. 8 represents this opportunity of tailoring properties to match usage offered by composites.

The highly anisotropic properties of composite laminas provide a design option not available in metals. Both "E" and "I" can be varied to attain the desired structural rigidity. The fixed ratio between bending and twisting rigidities common in isotropic material can now be varied by a wide margin when composite laminates are used. This is an important feature in the design of wings and rotors. But the low transverse strain of unidirectional laminas has been a limiting factor on laminate strength. Although designers to date have learned to live with this problem, improved transverse strain can result in improved laminate strength. Other unusual features of composite laminates derived from the lamina-laminate translation include the high effective Poisson's ratios; i.e., greater than $^1/_2$. This is responsible for the high shear-to-tensile rigidities. The zero in-plane thermal expansion of laminates is also possible with graphite-epoxy systems. This feature has been utilized in space antennas. The out-of-plane expansion, however, is not zero.

One can now compare two advanced filamentary composites against other aerospace materials. This is shown in Fig. 9 where both the absolute as well as specific properties are shown. A direct comparison between anisotropic material vs isotropic ones cannot be made without reference to the exact loading conditions. If uniaxial properties are compared, unidirectional composites on a specific strength basis are off the chart as one can see in Fig. 9. This comparison is valid only if composites are used to carry uniaxial loads. In general, however, composites must carry biaxial loads. The relative position of composites shows that increased specific stiffness composites over aluminum, steel, and titanium can be expected, while the relative strength will depend on the laminate construction. The comparison here is based on the static strength without claiming the superior fatigue strength of composites. Through-the-thickness cracks apparently do not exist in laminated composites. This may furnish a safety feature not available in homogeneous materials.

The specific properties of glass or other fiber laminates can also be represented by slanted bars on this figure. It is important to realize the technology transferability from one filamentary composite to another. The boron tape of unidirectional filaments, the monolayer tape, was an analog of the glass roving for filament winding. The graphite tapes followed the same pattern with a minimum of development. The technology of tape-laying for making laminates is applicable to all available filaments. Future filaments can presumably be made into engineering materials with the same ease of technology transfer.

Certain high-modulus graphite and polymeric fibers have low compressive composite strengths. This low level of translation of fiber to composite property imposes at this time a limit on the use of such composites in areas where compressive strength requirement is low.

VI. Technology Demonstration

In order to insure rapid transition of advanced composites to applications, I proposed to introduce composites to components of existing vehicles by direct substitution. The primary objective was to demonstrate the feasibility of a fully integrated concept of materials, design, and manufacturing and to achieve the anticipated weight savings, flight-worthiness, and other advantages. Examples of the substitution applications, since the middle of 1960's, included numerous secondary structures as well as primary structures. The first demonstration item was the F-111 horizontal stabilizer as shown in Fig. 10.[13] This structure was fairly simple in construction and was a nontrivial item in that its function was flight-critical. This item passed the static, fatigue, and ground vibration tests. It achieved the anticipated weight savings of 25% and has been flown by the Air Force and has accrued 250 flying hours. As the experience in substitution of metals by composites accumulates, more complex structures were made. One of these was the F-5 fuselage shown in Fig. 11. Not only did the size, weight (approximately 800 lb), and

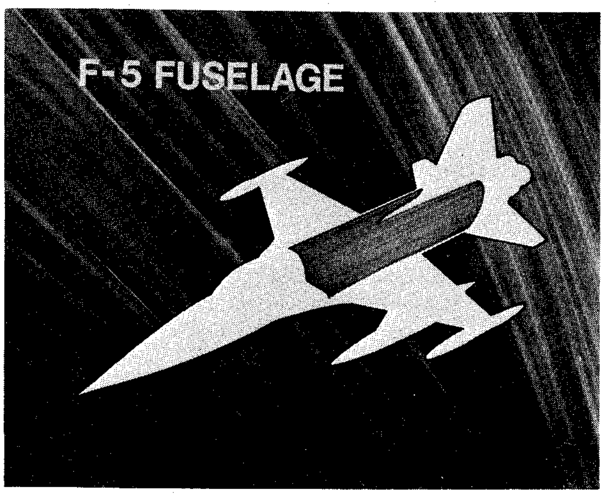

Fig. 11 One of the most complex components for the purpose of demonstration to date was achieved through novel manufacturing methods similar to those used for building boats. Fail-safe features could be achieved by reinvesting some of the weight savings.

complexity became significantly higher than that of the F-111 stabilizer; there were many novel manufacturing methods developed for this item. Fail-safe features were also exploited. On direct substitution basis, 26% weight reduction was achieved. The savings in weight could be reinvested in fail-safe features, resulting in a reduction in weight savings from 26 to 15%.

As a direct result of the technology demonstrated by the F-111 empennage structure, composite stabilizers were adopted for F-14 and F-15 for production use, to solve weight problems in the tails of these airplanes, even though the cost at the time of decision was higher than metal structure. Subsequent production costs have proved to be lower than titanium alloy stabilizer, which would have been the alternative. The critical design problem was achieving stiffness without excessive weight and advanced composites solved this problem. Later, advanced composite empennage was also adopted for YF-16 and extensive composite secondary structure was adopted for the YF-17. Now technology feasibility of wings and fuselage primary structure has been demonstrated, but there are no applications yet adopted for production use.

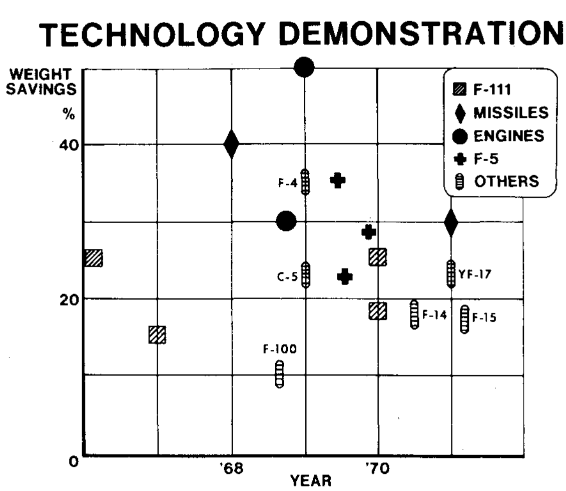

Fig. 12 Using weight savings as a comparator, various components made for technology demonstration since the 1960's are shown. The weight savings alone, however, do not tell the whole story. The basis on which weight savings were achieved must be carefully scrutinized. The improvement on the systems performance and cost is more meaningful than weight savings alone. The approach of composites in the 1970's are following the balance between performance and cost on absolute basis.

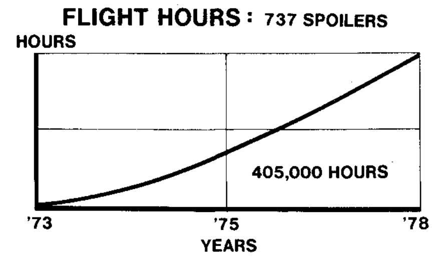

Fig. 13 This NASA-sponsored flight program of Boeing 737 Spoilers can rapidly accrue large numbers of hours over different operating conditions offered by participating airlines. Validation of composite components through extensive usage is necessary to establish confidence and to uncover possible problems of operation and maintenance.

Since the beginning of the Air Force program in the development of composites, a summary of the weight savings achieved for various components is shown in Fig. 12. A uniform ground rule for weight savings is difficult to establish. A turbine fan blade that achieved 50% weight savings was based on the weight of the fan blade only. The lower bound case of the F-100 wing was based on the total wing of the composites covers with metal substructure. The composites designed were constrained to include the existing method of fastening. The summary in Fig. 12 is only intended to show that a 20% weight savings can be conservatively expected. Again, the savings were based on direct substitution. No iteration to achieve a fully integrated design was attempted.

VII. Composites Recast

In late 1972, I decided that an evaluation of the advanced composites technology was necessary, not only to examine the progress since Project Forecast, but more importantly to set the course for the future. While this study, labeled "Composites Recast" was initiated by the Air Force and cosponsored by NASA, the primary input to the study was made by representatives of the materials and aerospace industries. Of the many recommendations that this study provided, confidence and cost were identified as the two primary barriers which must be overcome if composites were to mature as an engineering material. Composites Recast furnished a midcourse correction in the sense that Project Forecast provided the initial impetus.

One factor in gaining confidence that was clearly brought out was that extensive service testing, or accumulation of large amounts of flight hours, was desired, in order to: 1) confirm conclusively the anticipated environmental resistance of composites, and 2) to see if any unpredicted problems of any kind developed such as might possibly arise in handling in service, etc. Significant number of flight hours have been accumulated to date in military aircrafts with a variety of composite components. In civil aviation the program sponsored by NASA on the Boeing 737 spoilers, shown in Fig. 13, includes six participating airlines with diversified routes.[14] It is anticipated that 405,000 hr will be accrued. Also, environmental factors which must be better understood throughout the entire life cycle include moisture, lightning, and impact. Finally, confidence can be enhanced by in-depth technology-oriented data base. Design criteria, new methods of materials evaluation, quality assurance, and life prediction must be developed more fully and more rationally than the methodology and data base now available. While composites have been shown to have truly outstanding fatigue properties, the implication of such properties has not been fully characterized and effectively utilized.

In the area of cost, the other uppermost concern cited by Composites Recast, it is a volume-sensitive item. Unit

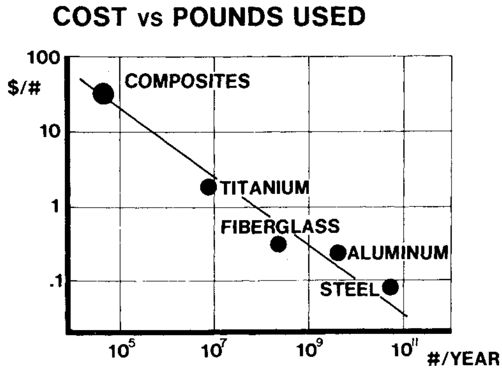

Fig. 14 Cost relates more directly to volume used than structural properties like modulus and strength. Direct comparison of metals with advanced composites here is based on the material cost only. Difference in the fabrication process that converts raw materials to structures is not reflected here. Composites have less wastage than metals for many aerospace applications.

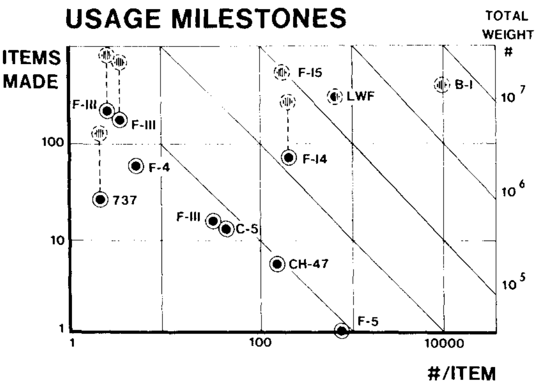

Fig. 15 Examples of past and anticipated usage of advanced composites for various components are shown in solid and dashed circles, respectively. The total weight used in each program is measured by the slanted lines, the product of the ordinate and abiscissa. One obvious way to increase usage is to introduce advanced composites to large aircraft.

cost of raw materials compared with usage is estimated in Fig. 14. The cost and volume do not reflect the finished product cost, which would make advanced composites even more attractive costwise than most metals. The advanced composites point shown in Fig. 14 corresponds to $50 per pound at 80,000 pounds per year usage. The usage of advanced composites for various aerospace applications is shown in Fig. 15, where the number of items made is plotted against the weight of each item; for example, one F-5 fuselage was made at a weight of 800 lb. The 45° lines represent the products of the coordinates or the total weight used by any given program. Through the technology demonstration, many of the items made, tested and flown are included in this figure. Projected use of F-14, F-15, and future systems will result in significant increase in total usage of composites.

VIII. Future

If the composites technology is to be fully utilized, it must be exercised across the interfaces of materials, structures, aerodynamics, and others. While cost and weight savings are achievable, the immediate future will evolve from the following:

a) Some few particular parts are already cost competitive with aluminum. This is not generally true for most primary structures, like wings and fuselages. However, projections based on development of improved manufacturing methods, plus fewer parts, and tools due to simpler, lower cost designs possible with composites, plus lower future materials costs, all together show that composites will, in a few years, become cost competitive on an absolute basis with aluminum for these structures.

b) Production composite stabilizers are now lower cost than equivalent titanium alloy stabilizers which would have been used otherwise.

c) Composite materials costs, mainly the reinforcing fibers, are going down, and will continue to go down, whereas metals are going up in cost.

The use of innovative design that can be seen in Fig. 16, where the prototype model for the YF-16 shown on the left is an improved version of the original F-111 composite stabilizer. If we are to identify the composites for the F-111 as the first generation, this item on the left is second generation which still retains some key metallic members at highly loaded points. The third-generation design is seen on the right of this figure which becomes a truly all-composite stabilizer that can be competitive both in cost and weight. This latter design, labeled "Clam Shell," can be generalized to other aerospace structures.

The future of composites demands greater integration of several technologies. Significant benefits of such integration in terms of performance parameters are derivable. Weight savings due to composites can be translated into significant maneuverability and range. This is an example of the evolution from the direct substitution in the middle of the 1960's to an integrated design approach of the 1970's.

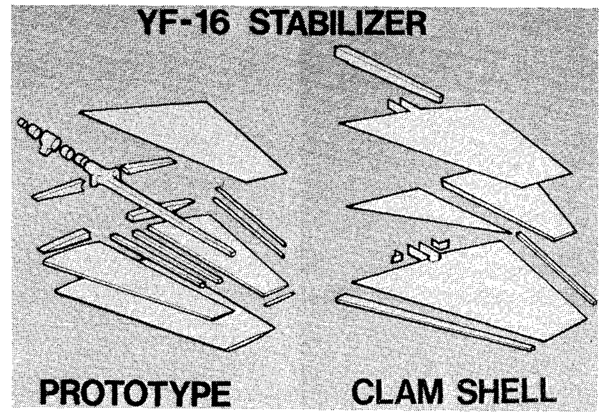

Fig. 16 The evolution of empennage structures made of advanced composites can be traced from the first-generation design of F-111 stabilizer shown in Fig. 10 to the second- and third-generation designs shown in this figure. The prototype design of YF-16 still retains key parts made of metals. The clam shell design is all composites and features an innovative design that utilizes composites to the fullest extent and efficiency.

Fig. 17 Current commercial airline flight programs of composites components to be installed on Lockheed TriStars and McDonnell-Douglas DC-10's. Such flight experience may pave the way for usage of advanced composites for primary and secondary structures on large aircrafts in competition with existing metallic and nonmetallic materials.

Planned applications of composites to civil aviation is seen in Fig. 17. Under NASA programs, major air carriers are involved in flying components on the TriStars and DC-10's with the objective of accumulating flight experience, thus confidence.[14] In addition, composites have found their way in sporting goods such as golf clubs, fishing rods, skies, and tennis rackets.

IX. Conclusions

In retrospect, the development of advanced composites to date has fulfilled the original predicted destiny. Cost and weight advantages of composites have been demonstrated. As the usage of composites broadens, increase in volume and decrease in cost will come as a matter of course. The use of composites in large aircrafts will be the next giant step in the growth of composites. Just as the use of fiber glass in Boeing 747's, for example, have expanded by a geometric proportion, it is anticipated that advanced composites will follow the same pattern in the years to come. The pacing problems which we now face are still numerous but they do not appear to be insurmountable. In addition to the environmental problems cited earlier, the foreign object damage to fan blades or initial stages of compressors is another specific problem. Guaranteed life is a challenge that must be addressed through reinvestment of weight savings or other advanced technologies. Cost of raw materials must also be reduced. Graphite fibers made from pitch and the use of hybrid composites will reduce cost.

Although the coverage of this paper has been primarily on the airframe, opportunities of composites for spacecrafts, aeropropulsions, rotors, and numerous other military and civil applications are equally promising and may make as great an impact on this growing technology as the airframe. But the basic philosophy of materials, design, and manufacturing that are related to the airframe is, in general, closely related to others as well.

This being a von Kármán lecture, it is fitting to project our focus from advanced composites to science and technology in general. Dr. von Kármán was instrumental in fostering science and technology from the very birth of the Air Force. Flashes of genius that seem to come to him so naturally and frequently can only be achieved through his intellectual capacity, inquisitive mind, and ability to communicate. This combination of attributes was needed 25 years ago at the birth of the Air Force as it is today. I have been supporting the need of a strong technology base in order to insure the future of the Air Force. I also recognize the importance of timely transition of theory to practice. As a fitting tribute to von Kármán, we should rededicate ourselves to achieve a rational balance between research and applications as multitudes of pressures surround us.

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