Evaluation of the Cost Effectiveness of Hybrid Composite Laminates

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Theme

IN this paper, a methodology is presented for the evaluation of cost performance of hybrid composite laminates. The optimum cost and weight configurations are obtained for simple structural configurations which are representative of "real world" structures, over a practical range of loadings. Aluminum and hybrid and single-fiber laminates are the candidate materials. Measures of the optimum weight and cost for the representative structural elements are compared for these various candidate materials. Weight differences are incorporated into the cost comparisons through the use of a premium cost to quantify the value of weight savings. Material costs, manufacturing costs, and premiums are all treated as variables in this design study. Hence, the results can be applied to a broad range of problems of interest for the dual purposes of 1) establishing cost-performance ranking of a particular hybrid system in a preliminary fashion for a specific structural application and loading and 2) providing guidance for developing additional improved material systems and hybrid laminate configurations.

Contents

An examination of the available fiber-reinforced composites clearly suggests that the higher stiffness and strength materials such as boron and graphite have higher price levels than the lower stiffness and strength materials such as Kevlar-49 and S-Glass. A logical outcome of this observation is to blend the two categories of fibers into hybrids so that the price levels can be brought down, probably at the expense of some strength and stiffness properties. This will make composite materials more competitive with metals such as aluminum and titanium. Also, studies of impact behavior of hybrid laminates have indicated that the impact strength is considerably enhanced because of 1) the high strain capability of the lower modulus fibers and 2) the introduction of additional failure modes such as interply delaminations.

The concept of "hybridization" in fiber-reinforced materials can be explored in different ways. Figure 1 illustrates the possible combinations. Starting from a filament (such as Boron)/filament yarn (e.g., S-Glass, Kevlar-49, Graphite, Kevlar-49/Graphite), hybrids may be classified as 1) intraply hybrids in a "zebra" ("discrete") pattern or in an "intimate" pattern, 2) intra-interply or interspersed hybrids, and 3) interply hybrids. Only the interply hybrids have been considered in the present study. Such a hybridization can be achieved by replacing the off-axis layers with lower cost prepregs to yield the greatest cost advantage with the least weight penalty. Among the various possible hybrid laminate families, particular emphasis is placed on the $[0_i^A/\pm45_j^B]_s$ laminates.

Economics and performance are two factors that are of primary importance to aircraft designers. There is obviously a need for a tradeoff between these two factors in design. The objective of the present study is to perform an initial screening of hybrid composite laminates with cost and weight minimization as the dual objectives without actually performing a detailed design or a costing thereof. The method of structural efficiency analysis as outlined in Ref. 1 provides a means to do this. In this approach, the optimum values of weight or cost index (measure of weight or cost) are obtained as a function of structural index (measure of loading intensity) for some design constraints, and a parametric study is performed to assess the cost effectiveness of various hybrid laminate configurations.

Every design task is governed by certain optimality criteria. In structural analysis, optimal design is synonymous with "minimum weight" design. However, it is important to realize that the minimum weight design is not the minimum cost design for all configurations (see Fig. 2), and the weight and cost of a component depend on many factors other than the basic design. Hence, the weight index as a measure of structural efficiency may not be an appropriate yardstick for economic efficiency. Whether a designer should follow the "minimum weight" approach or the "minimum cost" approach is entirely a function of objectives.

Replacement of single-fiber systems with hybrids will result in lower raw material costs and changes in other performance characteristics. While thus perturbing the performance, it must always be borne in mind that the basic advantages (such as weight savings) of advanced composite materials over metals are not lost. Hence a realistic cost-effectiveness study can be performed only by the consideration of relative merits (such as structural efficiency, which is a measure of weight as

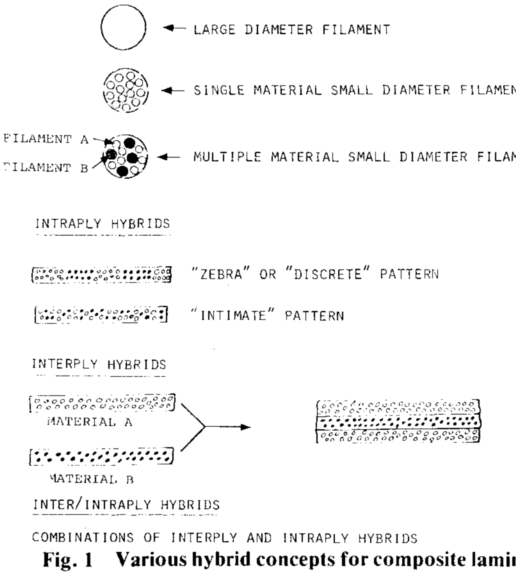

Fig. 1 Various hybrid concepts for composite laminates.

Presented at the AIAA/ASME/SAE 17th Structures, Structural Dynamics, and Materials Conference, King of Prussia, Pa., May 5-7, 1976 (in bound volume of Conference papers, no paper number); submitted June 21, 1976; synoptic received May 6, 1977; revision received Aug. 16, 1977. Full paper available from AIAA Library, 750 Third Avenue, New York, N. Y. 10017. Price: microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Structural Composite Materials; Structural Design.

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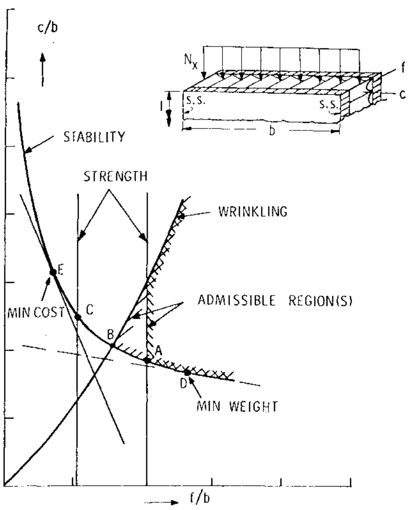

Fig. 2 Design space for a sandwich plate subjected to uniaxial compression.

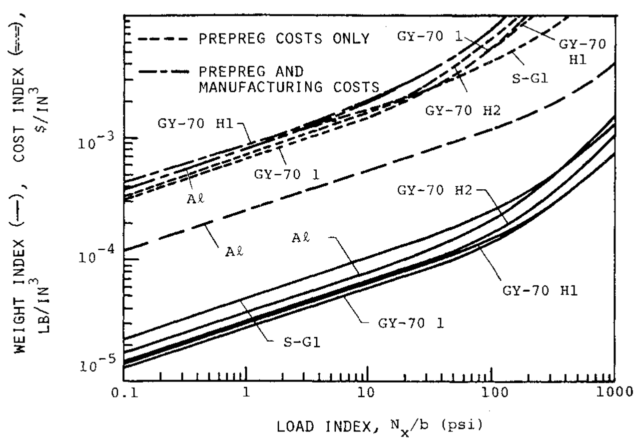

Fig. 3 Structural efficiency chart for a sandwich plate subjected to uniaxial compression.

related to performance) and costs, not only for the single-fiber system and hybrid but also for a baseline metal. A tradeoff study also needs to reflect a potential payoff value for improvement in performance. Hence, the concept of a premium. The premium reflects in dollars the saving in life-cycle cost per pound of weight saved with respect to a baseline case such as aluminum.

The raw material and manufacturing costs for some unidirectional prepregs utilized in this study are itemized in Table 1. These numbers represent average costs during the time period Aug.-Oct., 1974 (these numbers are volume sensitive). Note that the manufacturing costs are a function of volume rather than weight.

The optimum weight and cost configurations are obtained here by utilizing the Simultaneous Mode Design approach. Salient features of this approach are outlined in Ref. 2, and the design space for a sandwich plate subjected to uniaxial compression, for example, is shown in Fig. 2.

Parametric design studies were performed for the representative structural configurations with hybrid laminate properties, load index, manufacturing cost, and premium as variables. The dependent variables in the optimization of the sandwich beam (Fig. 2) are the weight and cost indices. Hybridization of four advanced composite materials (Boron, GY-70, Hercules 3002M, Thornel T-300) was investigated. The three graphite prepregs essentially reflect the three gradations of the materials based on modulus and strength. The lower modulus, lower cost prepregs were S-Glass, Kevlar-49, and their cloths.

Referring to Fig. 2, the primary design constraints for the sandwich plate subjected to uniaxial compression are strength, overall instability, and wrinkling. As a result, the moduli (longitudinal, transverse, and shear) and compressive strength of the hybrids will significantly affect their ranking. So, using a hybrid laminate which has a high compressive strength and good resistance to wrinkling may not yield an efficient structure in terms of the overall instability constraint. In fact, for the plate buckling case, the quasi-isotropic laminates $[0/\pm 60]_s$ and $[0/\pm 45/90]_s$ are less efficient than the $[\pm 45]_s$ laminate. Based on strength considerations, however, the $[\pm 45]_s$ laminate is a poor choice, and a compromise has to be made. Therefore, the $[0_i^A/\pm 45_j^B]_s$ hybrids are a fair choice for this structural configuration.

Figure 3 shows a typical structural efficiency plot for the sandwich plate with GY-70/GY-70-hybrid laminates as face sheets. S-G1‡ (S-Glass) is the heaviest material at lower load indices mainly because of its lower modulus. The GY-70 H2 laminate is heavier than the GY-70 H1 laminate because an increase in the transverse and shear moduli is accompanied by a decrease in the longitudinal modulus.

Because of its higher weight at lower load indices, the S-G1 laminate is costlier than the GY-70 H1, H2 laminates (on the basis of prepreg costs) in spite of the fact that S-G is considerably cheaper than GY-70. For higher load indices, the S-G1 construction is certainly more attractive from a cost standpoint, but is much heavier than GY-70 1 or GY-70 H1, H2. The GY-70 1 laminate is also cheaper than the GY-70 H1, H2 hybrids, once again because the reduction in the cost factor of hybrids is offset by an adverse effect on the transverse and shear moduli. For the same reason, GY-70 H2 costs more than GY-70 H1. If manufacturing costs ($40/lb for Al and $2.5/in.^{3} for the composite) are considered, the GY-70 hybrid cost index is comparable to that of Al. Since there is a weight saving with respect to Al, the GY-70 H1 laminates will be more cost effective when a premium is attached to the weight savings.

In summary, a simplified rational approach has been formulated to arrive at minimum cost/weight designs of structural configurations representative of "real world" structures. The possible advantages resulting from decreased weight have been incorporated into the cost evaluation via the concept of premium. The results of this conceptual study are straightforward enough for utilization by a designer/engineer to make a preliminary design evaluation of hybrid composite laminates for a specific design problem.

Acknowledgment

This investigation was supported by Air Force Materials Laboratory Contract F33615-74-C-5174.

Table 1 Raw material and manufacturing costs[a]

Material	$/lb
Celanese GY-70 prepreg	60.00
S-Glass prepreg	18.00
Aluminum	2.00
Al honeycomb (0.0029 lb/in.^{3})	5.20

[a]Manufacturing cost 2.50 $/in.^{3} (based on average prepreg density of 0.06 lb/in.^{3}).

References

[1]Shanley, F. R., *Weight-Strength Analysis of Aircraft Structures*, Dover Publications, New York, 1960.

[2]Kulkarni, S. V., Rosen, B. W., and Boehm, H. C., "Evaluation of Hybrid Composite Materials," Air Force Materials Laboratory, AFML-TR-75-92, April 1975.

‡Suffix 1 represents a $[0/\pm 45]_s$ 75%/25% laminate; suffix 2 represents a $[0/\pm 45]_s$ 50%/50% laminate; suffix H represents a hybrid laminate $[0_i^A/\pm 45_j^B]_s$.