Advanced Composites and Their Application to Hydrofoils

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Following a brief review of the advanced composites and their application to structural components of aircraft, missiles, and space vehicles, studies are presented on potential applications of composites to various structural components of hydrofoils, including decking, hull, foils, and strut. It is shown that application of various composites to the hull and decking of a hydrofoil can yield a weight saving of 16-51% whereas application of composites to struts and foils shows potential weight savings of approximately 60% compared to steel counterparts. Results are also presented on cost effectiveness of composites as applied to hydrofoils.

Introduction

OVER the past 10 years, significant progress has been made in the development of advanced composite materials possessing high strength, high modulus, and low density. Composites such as boron-epoxy and graphite-epoxy have been successfully employed as structural materials in aircraft, missiles, and space vehicles and have performed satisfactorily as demonstrated through extensive ground testing and through in-flight performance. Moreover, the application of these composite materials to various structural components of aircraft, missiles, and space vehicles has demonstrated significant weight savings over comparable components made of conventional metals. Table 1 shows some typical examples and identifies the system, and structural component, and the weight savings resulting from application of composites in lieu of metals. Use of composites has resulted in weight savings of 11-44%.

These weight savings were achieved through substitution of composites for metals. Greater weight savings may be realized through the use of new design concepts employing composites—concepts whereby advantage is taken of the superior properties of composites and the great design flexibility inherent in these materials. In contrast to metals, where a designer is given a material and from it designs a structure, in composites the designer has the freedom to design both the material and the structure. Thus, the composite can be tailored to precisely fit the structural requirements of a given component. For structural components of high-performance Naval vehicles such as patrol craft hydrofoils,[1,2] weight savings similar to those shown in Table 1 can be achieved as a result of using advanced composites for various structural components such as foils, struts, decking, and hull.

To establish the magnitude of weight savings resulting from possible application of composites to Patrol Craft Hydrofoil (PCH) structural components, as well as the cost effectiveness of these materials, the study described herein was conducted. The primary emphasis was on material-structural aspects of composites as applied to PCH.

Because of the availability of information for the existing PCH-1, such as design loads, safety factors, weight breakdowns, operational characteristics, and other requirements, the various tradeoff studies presented were based on, or the results of these studies compared to, the existing PCH-1 design. In the case of required strength, stiffness, and safety factors, these were either met or exceeded. Even though the results presented are for PCH-1, they can be used to make preliminary estimates of the benefits resulting from using composites in more advanced hydrofoils.

General Description and Weight Breakdown for PCH and Basis for the Design of Composite Structural Components

The overall view of the PCH vehicle under consideration is shown in Fig. 1. Table 2 shows the PCH weight breakdown. The hull structure and foil system constitute approximately 50% of the light ship weight. Materials used for various components of the present PCH are aluminum for the hull structure and HY80/HY130 steel for the foils and struts. The documents used in studies on application of composites to PCH are Refs. 1 and 2; additional information required for the studies presented herein was obtained from NAVSHIPS.

The various composite structural components investigated were designed to meet or exceed the load, strength, and stiffness requirements of the all-metal components on the existing PCH. The minimum factor of safety used for composite components was taken to be 1.5 which exceeds the minimum specification value for metals. Section 522-1 of the specification[1] states that the maximum combined stresses arising from design limit loads shall be limited to provide a factor of safety of at least 1.25 on the yield point of the materials, or on the critical buckling stress. The critical load is defined[2] as the limit load increased by the factor of safety, this load being matched with the material yield or buckling stress, whichever is the lesser. A more detailed discussion of the basis for designing the various PCH structural components is presented in Refs. 4 and 5.

Composite Materials for PCH Applications

A survey was made of various reinforcing fibers and composite materials, as well as their mechanical properties, cost, and projected long-range developments. Materials on which

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Table 1 Typical application of advanced composites in aircraft, missiles, and space vehicles

System	Structural component[a]	Material[b]	Actual weight savings (%)	In-service experience (flight hr)
Aircraft				
F-111	Horizontal stabilizer (LPI)	Al-B/E	27	>300
	Wing trailing edge panel (LPI)	Al-B/E	11	>1000
	Airflow deflector door	Al-B/E	16	...
	Aft main landing gear door (TI)	Al/B/E	17	...
F-15	Horizontal stabilizer (FH)	(Ti)-B/E[c]	(20-25)	>500
	Vertical stabilizer (FH)	(Al)-B/E	(30-35)	>500
	Rudder (FH)	(Al)-B/E, G/E	(50-60)	>500
F-14	Horizontal stabilizer (FH)	Ti-B/E	19	>2000
F-4	Rudder (FH)	Al-B/E	44	>1000
A-4	Wing flap (TI)	Al-B/E	20	...
	Wing flap (TI)	Al-G/E	30	...
	Horizontal stabilizer (TI)	Al-G/E	30	...
F-5	Main landing gear strut door	Al-G/E	36	...
Typical Aircraft	Airframe fuselage (subscale) (TI)	Al-G/E	27	...
Aircraft	Wing-box component (TI)	Al-B/E	20	...
Missiles and Space Vehicles				
Atlas/Centaur	Interstage and payload adapted (TI)	Al-B/Al	40	...
Minuteman	Interstage (TI)	Al-G/E	27	...
Model 36 Spacecraft	Struts with joints (TI)	Al-B/E	30	...

[a] LPI denotes limited production item (up to 20 ship sets). TI denotes test item (1-5 items fabricated and tested). FH denotes flight hardware used on production aircraft. In the case of the F-15 only composite components have been fabricated.

[b] First symbol denotes conventional material from which component is made. Second symbol denotes composite material, B/E, G/E, and B/Al denoting boron-epoxy, graphite-epoxy, and boron-aluminum, respectively.

[c] Items in parentheses denote that these metals could be used for component fabrication; the components are being fabricated from composites only.

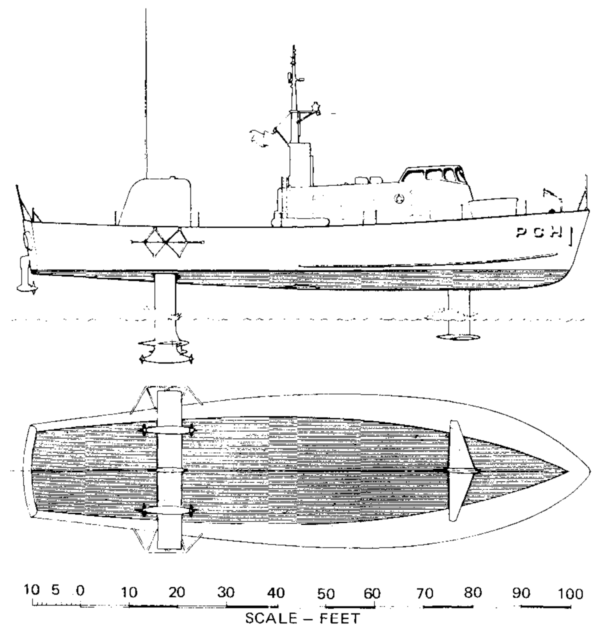


Fig. 1 Overall view of PCH.

data were compiled included glass fibers, boron fibers, PRD 49 III fibers, various graphite fibers, and composites made with these reinforcing materials. Table 3 summarizes the range of properties of various reinforcing materials. Of the various fibers available, graphite fibers are the most numerous. In general, except for cost, for each reinforcement material shown in Table 3 there is an equivalent graphite fiber which has similar or better properties. The present and projected costs of several reinforcing fibers are shown in Fig. 2. The latter shows that by 1980 a number of the reinforcing fibers are expected to cost ≈ \$10/lb and up. Not shown in Fig. 2 are the prices of glass fibers. Their prices now range from \$0.7-\$6/lb (see Table 3) and, in contrast to graphite and boron fibers, are expected to increase by 1980. Even though the number and variety of available reinforcing fibers are great, the number and variety of composites that can be made from these fibers are even greater, since the latter can be made with different resins the variety of which is even greater than that of the reinforcing fibers.

Although a thorough review was made of the various composites, only some typical results pertinent to this paper are presented herein (Tables 4 and 5). Table 4 gives the experimental properties of unidirectional composites that are best suited for any given simple application (for structures designed by simple tension, compression, shear, stiffness, etc.).

From the results shown in Table 4, it is readily seen that the choice of the composite material for a given structural application is strongly dependent on the type of loads that the structure has to resist. No one composite has a set of properties that is superior to properties of all other composites. Typical properties of various bidirectional composites are shown in Table 5. The results shown were calculated from measured properties of unidirectional composites.

To narrow the large number of potential candidate composites for PCH applications, the cost effectiveness of the various types of unidirectional composites was estimated and compared. For a given composite the cost effectiveness

Table 2 Weight estimate for PHC-1

Item	Weight $\times 10^{-3}$ lb	% of full load	Remarks
Hull structure	71.28	25.5	Includes: hull plating, web frames, buklheads, longitudinal stiffeners, deck house, external and internal decking, etc.
Foil system	40.05	14.3	65% of this weight is for aft foil and struts; 35% is for forward foils and strut.
Propulsion	40.92	14.6	
Other items	69.89	25.0	Electrical plant, communication and control, nonstructural auxiliary systems, outfits and furnishing, fixed armaments and miscellaneous.
Total (light ship)	222.14	79.4	
Payload	57.66	20.6	Fuel, arms, personnel.
Total (full load)	279.80	100.0	

Table 3 Range of properties of fiber materials

		Range of properties			
Fiber material	Variety of fiber available	Tensile strength (ksi)	Young's modulus (msi)	Density (lb/in.^{3})	Cost[a] ($/lb)
Glass	4	500-600	10-12	0.092	0.7-6
Boron	2	400-500	55	0.092-0.098	180-225
PRD49-III	3	400-430	12-19	0.05	50
Graphite	26	200-470	20-75	0.054-0.071	30-275

[a]For 100 lb quantities in 1972.

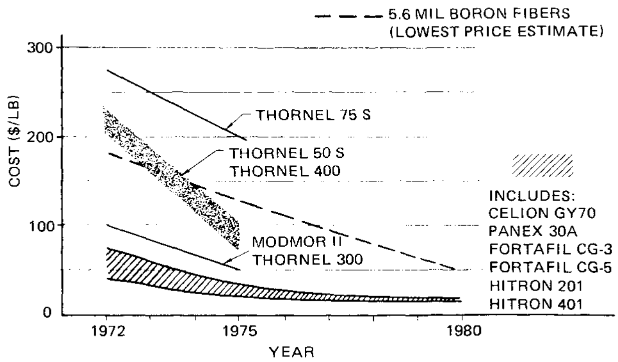


Fig. 2 Present and projected cost of fibers (for orders above 100 lb).

associated with tensile loading, compressive loading, and stiffness can be defined as

$$S_t = (\rho c/\sigma_t) \quad (1)$$

$$S_c = (\rho c/\sigma_c) \quad (2)$$

$$M = (\rho c/E) \quad (3)$$

respectively, where ρ is the density of composite, c is the cost /lb of composite, E is the Young's modulus, σ_t is the tensile strength, and σ_c is the compressive strength. Using the data such as given in Table 5 in combination with Eqs. (1,2, and 3), the various composites shown in Table 5 were rated for cost effectiveness in designs governed by strength and stiffness. Using this approach it was possible to narrow down the candidate composite materials for application to PCH to the following: *S*-glass/epoxy, Courtaulds type *A*/epoxy, Thornel 300/epoxy, Courtaulds HTS/epoxy, and Celion GY70/epoxy.

It is noted here that because of the rapidly changing prices of the various composites and improvements in composite properties, the material ratings can change rapidly. The material ratings used here were based on August 1972 properties and cost data for various composites.

Table 4 Optimum composites for simple structures (unidirectional properties)

Property	Best composite	Value
Highest axial tensile strength	*S*-glass epoxy	289 ksi
Highest axial compressive strength	Boron-epoxy	338.6 ksi
Highest transverse tensile strength	Boron-epoxy	13.3 ksi
Highest transverse compressive strength	Boron-epoxy	34.5 ksi
Highest interlaminar shear strength	Modmor II/epoxy	16.0 ksi
Highest flexure strength	Thornel 400/epoxy	278 ksi
Highest axial Young's modulus	Thornel 75/epoxy	44×10^6 psi
Lowest density	PRD49-III/epoxy	0.050 lb/in.^{3}
Lowest cost	*E*-glass/epoxy	$5/lb

Application of Composites to External Decking

Geometry and Design Criteria

Figure 3 shows the overall view of the external deck. For clarity, design details such as access openings, joints, etc. have been omitted in the figure. The external deck on the existing PCH consists of integrally stiffened aluminum extrusions, a cross section of which is shown in Fig. 3. The deck area covered by these extrusions is approximately 3000 square ft. The total weight of the external deck is 8654 lb, or 2.88 psf of deck.

In studying the application of composites to external decking, design loads given in Ref. 1 were used. Additional constraints were placed on various composite designs by specifying that: a) bending stiffness of the composite design be equal to or greater than that of metal design; b) deflection of the composite design be equal to or less than that of metal design; c) the in-plane tension and compression load-carrying ability of the composite design be equal to or greater than that of metal design; d) extensional stiffness of the composite design be equal to or greater than that of metal design; and that e) total thickness of the deck made of composites not ex-

Table 5 Typical properties of bidirectional composites

Composite	Strength (ksi) Tensile	Strength (ksi) Compressive	Young's modulus (msi)	Density (lb/in.^{3})	Prepreg cost (1972) ($/lb)
S-glass	150	62	5.6	0.075	12
PRD49-III	94	22	5.9	0.050	75
Boron	113	186	16.7	0.075	285
High σ graphite[a]	91-132	85-108	9.7-11.7	0.054-0.057	75-205
High *E* graphite[b]	62-74	52-67	15.6-17	0.054-0.058	145-205
Thornel 75	109	49	22.4	0.057	275
GY 70	46	46	21.4	0.061	75

[a] Includes: Thornel 300, Thornel 400, Courtaulds HTS, Courtaulds A; Modomor II.
[b] Includes: Thornel 50; Courtaulds HMS; Modmor I.

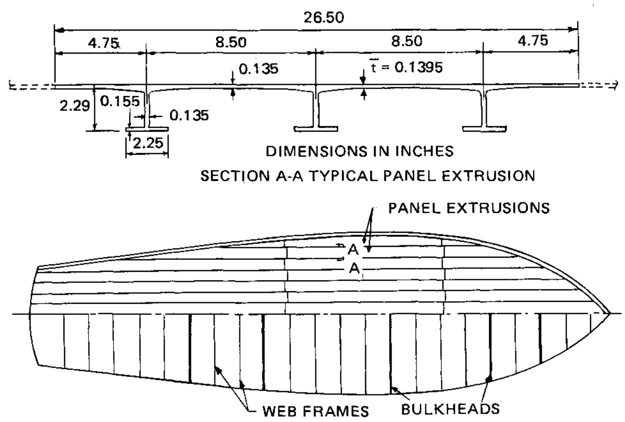


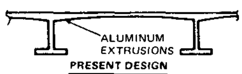
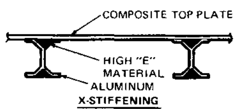
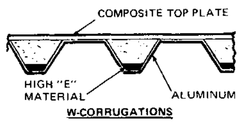
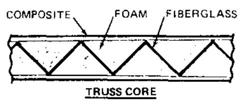
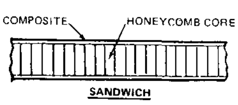
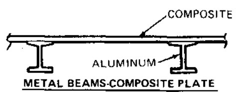
Fig. 3 External decking.

ceed the thickness of the metal deck. Thus, the detailed specifications for the various designs of composite decking were chosen so as to be equal to or superior to the design of metal decking. The working stress for composites was taken as ⅔ of the ultimate strength (tensile or compressive) of a bidirectional composite.

Composite Decking Concepts

A number of structural concepts for PCH decking were investigated. The more conventional structural concepts that were investigated included: composite plates stiffened with metal extrusions, composite plates stiffened with composite stiffeners; honeycomb sandwich with composite faces; and truss core sandwich. Some of the more advanced design concepts that were investigated were: composite plates stiffened with fiber-reinforced *x*-stiffeners; composite plate stiffened

Table 6 1973-74 cost effectiveness of various design concepts for decking

Design	Weight savings (%)	Top plate Material	Top plate Weight (lb/ft^2)	High E matl Type	High E matl Weight (lb/ft^2)	Total cost[a] ($/ft^2) 1973-74	Total cost[a] ($/ft^2) 1980	Cost of weight saved ($/lb) 1973-74	Cost of weight saved ($/lb) 1980
	0	All aluminum construction 2.88 lb/ft^2 weight				28.80	38.60		
	53.1	Courtaulds A	0.396	GY-70	0.237	99.50	40.73	65.00	26.60
	45.2	S-glass	0.540	GY-70	0.274	78.81	44.71	60.60	34.40
	51.3	Courtaulds A	0.396	GY-70	0.216	77.21	35.14	52.10	23.80
	44.1	S-glass	0.540	GY-70	0.283	57.62	38.70	45.50	30.40
	40.0	GY-70	0.88			106.17	50.30	92.20	43.60
	27.1	Courtaulds A	0.97			106.39	41.51	136.40	53.20
	53.1	GY-70	0.88			104.02	47.45	68.10	31.0
	45.1	Courtaulds A	0.97			104.27	38.66	80.20	29.80
	24.3	PRD 49	1.60			57.93	30.54	82.60	43.70
	25.0	GY-70	0.94			106.18	45.26	147.70	62.90
	19.4	Courtaulds A	1.11			112.98	37.61	202.00	67.30
	16.3	PRD-49	1.21			69.54	30.12	148.00	64.10

[a] Includes cost of all materials, tooling, labor and scrap; cost of assembling panels into final PCH deck not included in the total cost for metal or composite panels.

with fiber-reinforced *w*-corrugations; and isogrid-stiffened composite plates. Several of the structural concepts are shown schematically later in Table 6. The advanced design concepts employed various combinations of materials, including combinations of composites, and combinations of composites and metals. It was felt that by using the hybrid material approach both weight and cost would be minimuzed. In the case of the more conventional design concepts, the applicability of 10 different composites to the PCH decking was investigated.

The studies of the advanced design concepts involved only 3 composites (*S*-glass/epoxy, Courtaulds type *A*/epoxy, and Celion GY70/epoxy) which were shown to be efficient from the standpoint of structural efficiency and cost effectiveness. To arrive at efficient designs for the various concepts, and especially for the advanced design concepts, extensive analytical tradeoff studies were performed on the influence of the material and geometric parameters in any given design on the structural efficiency of the design. Typical results from these studies are presented in Figs. 4 and 5. Figure 4 shows the influence of cover plate thickness (made of Courtaulds type-*A*) and stiffener spacing on the extensional stiffness, total deflection, and weight of the panel. From the results such as shown in Fig. 4 cross-plots such as shown in Fig. 5 were made of W and V_2 for various values of L_1 and b_2. By plotting also the curve of constant deflection δ and a curve of constant extensional stiffness, B corresponding to different values of L_1 and b_2, it was possible to establish the minimum weight design that simultaneously satisfies the required δ and B. The latter design was then checked to ensure that the strength and other requirements were also satisfied. A similar approach was employed to arrive at efficient designs for other decking concepts.

Cost Effectiveness of Composite Decking Concepts

In addition to conducting the tradeoff studies on the structural efficiency of the various composite designs for PCH decking, preliminary estimates were made of the fabrication costs for the various configurations, as well as total costs of fabricated panels. The cost estimates were made for the 1973-74 and 1980 time periods. In making the estimates for the fabrication costs of various composite panel design concepts, the following were considered: a) cost of all raw materials; b) cost of tooling; c) labor costs to fabricate the panels; d) 5% cost increase per year for labor and materials (other than advanced composites); e) cost decrease of advanced composite materials in 1980 as well as cost changes for these materials vs volume of material purchased; and f) cost of excess material (waste).

The labor costs included such items as composite layup, in-process quality control, bagging and curing of the part, trimming and cleanup operations, adhesive bonding, and nondestructive testing. Material costs included advanced composites, adhesive, metal stiffeners or corrugations (if used in a given design), and foam. A factor of 1.30 was applied to the amount of raw materials required in any given design as an allowance for waste and for making quality control specimens.

In estimating the fabrication costs, it was assumed that a total of 40 panels measuring 5-15 ft would be fabricated. This number of panels is sufficient to cover the external deck of the PCH. All tooling costs were therefore amortized over the 40 panels. A learning curve was applied to labor hours to estimate the cost reduction per panel if 40 panels were fabricated.

In arriving at the fabrication cost in 1973-74, it was assumed that the panels would be fabricated by semiskilled labor, costing $11.50 per man-hour. To this figure a 30% factor was added for supervision and other miscellaneous items giving a total rate of $15.00 per man-hour.

In making the 1980 cost estimate for various types of composite panel designs, it was assumed that the costs of various raw materials (other than advanced composites) and labor costs increase at 5% per year. It was also assumed that 12-in.

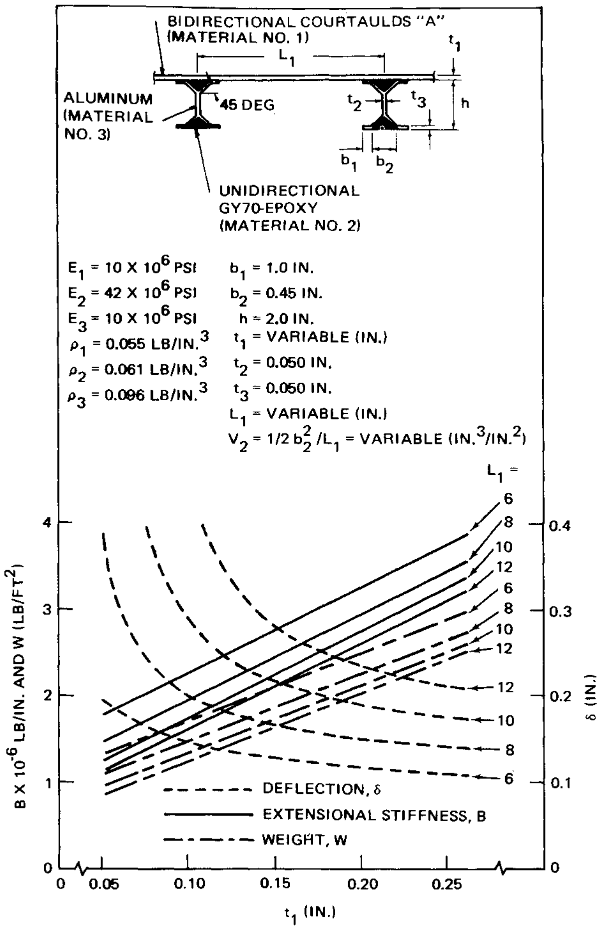


Fig. 4 Influence of top plate thickness and stiffener spacing on extensional stiffness, panel deflection, and panel weight (top panel made of Courtaulds).

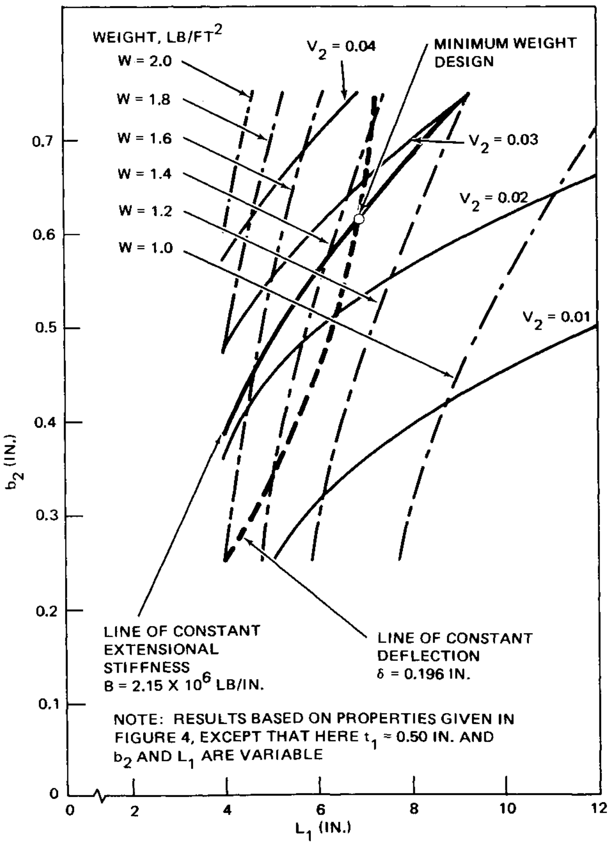


Fig. 5 Optimum design of Courtaulds type A composite panel stiffened with GY70 composite reinforced aluminum X-stiffeners.

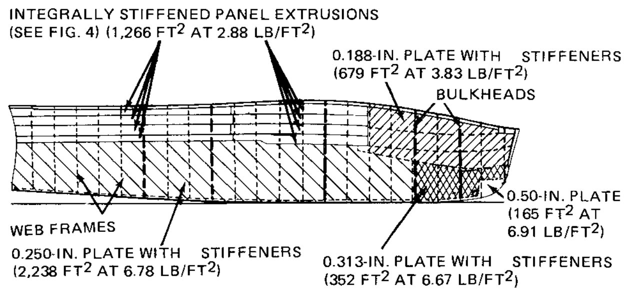


Fig. 6 Expanded view of PCH hull shell plating.

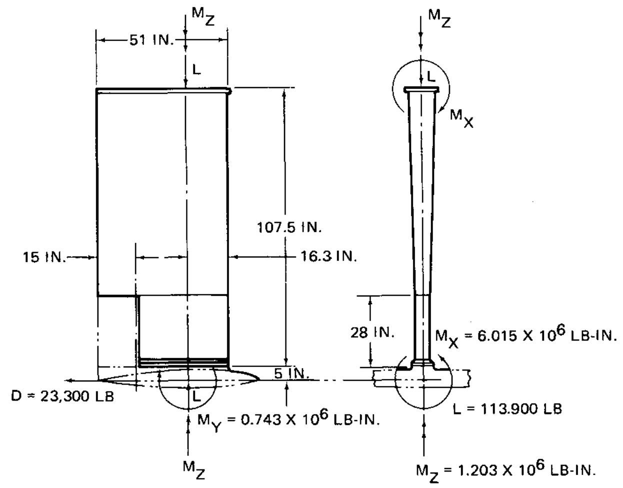


Fig. 7 Strut geometry and critical loads.

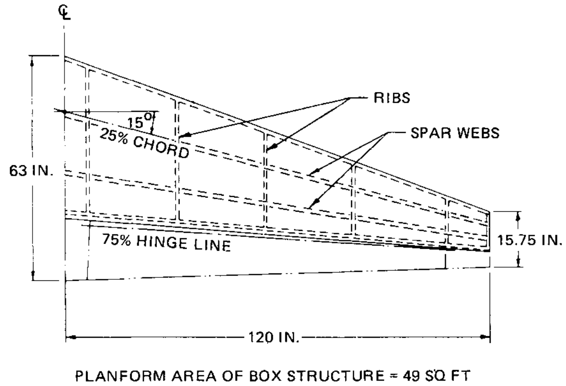


Fig. 8 Forward foil geometry.

wide composite prepregs (just now becoming available) will be used instead of the 3-in. wide prepregs used in arriving at the results for 1973-74. This will reduce the layup time by an estimated two-thirds. For 1980, further reduction of layup time is expected due to use of semiautomatic and automatic layup machines. A grossly conservative estimate was made that when using the semiautomatic layup machines, the layup time would be one-half of what it is for hand layup.

The 1980 prices of advanced composite materials were estimated to be[4]: $20 /lb for prepreg made with intermediate-modulus graphite fibers, and $30/lb for prepreg made with high-modulus graphite fibers. Since fiber glass is now produced in multibillion-pound quantities per year, no price reduction was applied to glass prepregs. On the contrary, their price was assumed to increase by the same amount as the more conventional raw materials. The 1980 price of PRD 49 prepregs was assumed to be the same as of the prepregs made with *S*-glass fibers ($\approx$$15/lb). This is in general agreement with the projections given in the literature.

The weight savings, cost, and cost effectiveness of the various decking designs are summarized in Table 6. It is noted here that the final assembly costs (assembling panels into PCH decking) are not included in the data given in Table 6 for either the existing all-metal design or for the various types of composite designs. The cost psf of the existing nonassembled metal decking (aluminum extrusions) is comparable to the cost psf of the nonassembled composite decking because the former represents vendor estimate for the cost of materials, tooling (dies for making non-standard extrusions), and labor cost of making the extrusions, which items are similar to those considered in estimating the cost of composite decking. Although the final assembly costs for composite panels would be expected to be somewhat higher than for metal panels, if in both cases the same number of panels were to be assembled into PCH deck, it is noted here that the assembly cost for decking made of composite panels can be reduced by using 75-100-in.-wide panels rather than 26.5-in.-wide panels. Fabrication of wide composite deck panels is both feasible and economical, whereas in the case of metal extrusions the 26.5-in. width is near the upper limit for the present day capability of making extrusions. From the cost comparison of nonassembled panels shown in Table 6, it is seen that by 1980 at least 6 different composite design concepts are expected to be less expensive than the all-metal design, with an additional benefit of weight savings of 45-53%.

Application of Composites to PCH Hull

An expanded view of the PCH hull is shown in Fig. 6, with specific details such as openings and locations of stiffeners omitted. The upper aft portion of the hull is made of the same type of aluminum extrusions as the external decking . The remainder of the hull is made of stiffened aluminum plates. The plating size used on various portions of the PCH hull, the areas covered, and weight psf are shown in Fig. 6.

Since the upper portion of the hull and external decking are of similar construction, the results presented in the previous sections can be used for making preliminary estimates of the weight savings resulting from the application of various composites and design concepts to PCH hull structure. Thus, maximum application of composites to PCH hull shell plating could result in weight savings of 25-53%, or, assuming a 10% allowance for joints and connections, a total weight reduction of between 5,600-11,900 lb. The cost-effectiveness of using composites in the PCH hull is expected to be similar to the external deck.

It is noted here, that to make an accurate assessment of the feasibility of using composites in various portions of the hull and an accurate estimate of weight savings resulting from application of composites to the PCH hull, would require further consideration of the environment and requirements dictating the hull design. For example, aluminum plating as a result of its ductility frequently sustains overloads without loss of water-tight integrity. How composite constructions would perform under such circumstances is an important question to be answered before these materials are used in hull construction, and so is a question of degradation, if any, of composite properties as a result of exposure to marine environment. Since detailed studies on application of composites to the hull were not conducted, the range of weight reduction given should be considered only as a preliminary estimate.

Application of Composites to Forward Foil and Strut

Design studies were conducted on the forward strut and foil of the PCH to determine the feasibility of replacing the existing welded steel structure with components utilizing advanced filamentary composite materials. The composite designs were constrained to have the same external geometries as the existing parts and to be fully interchangeable with them. No changes were made to control surfaces or their operating mechanism, the investigation being confined to the fixed structural portions only. Configuration studies considered the selection and orientation of the shell material, and the arrangement of the internal supporting structure. The final designs were selected on the basis of their weight and cost advantages.

Geometry and Design Criteria for the Strut and Foil

The geometry of the strut is shown in Fig. 7. The lower portion of the strut on which the rudder is mounted has a 12% thickness-to-chord ratio increasing to 20% at the upper end. The foil is mounted at the base of the strut, its geometry being shown in Fig. 8. The foil surface area and aspect ratio are 65.6 ft^2 and 6.1, respectively. The sweepback measured on the 25% chordline is 15° and the flap hinge line is on the 75% chordline. The hydrofoil has a 9%-thick NACA 16-309 section with a maximum thickness of 5.67 in. The critical loads acting on the strut and the foil are shown in Fig. 7. They correspond to the worse condition and were derived from Ref. 2.

Apart from meeting the strength requirements dictated by the design limit and critical load conditions, it was found necessary to meet certain bending and torsional stiffness requirements. In particular, it has to be shown that the flutter, divergence, and flap reversal speeds have an adequate margin over the PCH-1 operating speed, which was assumed to be 50 knots. In the absence of full dynamic calculations, approximate methods were adapted from the information given in Refs. 6-8. Thus, the bases for the foil design were as follows: a) strength requirements; b) hydroelastic flutter; c) divergence; and d) flap reversal speed.

Items b, c, and d were expressed in terms of the foil geometry and torsional and bending rigidities at the root. The analyses that were performed and the results of the more rigorous dynamic calculations reported in Ref. 2 for the steel foil showed that torsional rigidity of the composite foils should be equal to or greater than that for the steel foil because the flutter speed for the steel foil given in Ref. 2 was only marginally satisfactory. Because of the known difficulties in accurately predicting the flutter speed, the torsional rigidity of composite foil was therefore kept the same as that for the steel foil.

The reduction in bending rigidity, on the other hand, was found to have no effect on the flutter speed and would have been beneficial to divergence speed, if the latter had not already been evaluated to be infinite. Since the steel foil design was dictated by bending strength and its flexural rigidity was approximately twice the required value, the composite foil was designed to have 100% of the torsional stiffness, but only 50% of the bending stiffness of the existing steel foil.[4] The design criteria and stiffness requirements for the composite strut were obtained in a similar manner.

Analytical Approach

To make a rapid convergence on the optimum material combination, orientation, and thickness for the shell structure, a simplified analysis procedure was devised. Critical cross-sections were selected for each of the two components. For the strut, the base section was used since this was the most highly stressed portion. It was assumed that strut shell thickness was kept constant for the whole surface to agree with the constant plate thickness of the steel strut. Although it was realized that this was not the most efficient distribution of shell material, it did enable a simple comparison with the steel strut to be made on the basis of the single selected cross-section.

For the foil, a datum centerline section was derived by assuming a smooth variation of shell material, taking no account of local discontinuities arising from the attachment to the strut. A skin thickness distribution proportional to the foil chord was selected to give a near approximation to the taper on the metal skins, and to simplify calculations of shell volume and weight.

The shell, consisting of the skin and the rear spar, was considered to be of uniform thickness for each cross section. Again, this was not necessarily the most effective distribution,

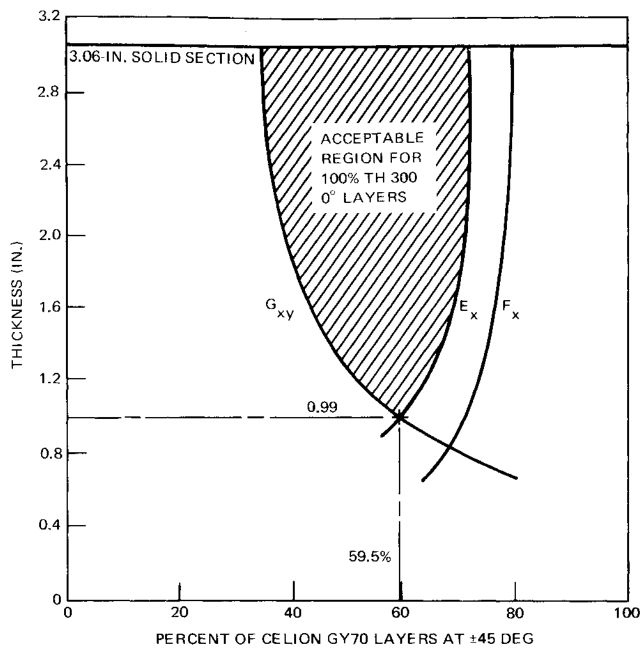


Fig. 9 Required wall thickness of GY70/Thornel 300 hybrid composite strut.

although it did offer advantages in layup simplicity. Furthermore, it enabled certain basic section properties to be expressed as functions of wall thickness. These included the moment of inertia I; the torsional constant K; the shell volume V; and, in the case of the unsymmetrical foil, the neutral axis location y. Knowing the required bending and torsional stiffness EI and GK, and the critical bending moment, it was then possible to plot the required values of E and G, and also the extreme tensile and compressive stresses, against wall thickness.

It was assumed that only spanwise (°) material and ±45° layers would be used, since these were the directions which would best satisfy the bending and torsional stiffness requirements. For each material combination, the modulus values E_x and G_{xy} and the tensile and compressive strengths F_{xT} and F_{xc} were plotted against the percentage of layers at ±45°. A sufficient accuracy was provided by assuming a straight-line variation between the end values at 0-100%. It was found that the in-plane shear strength was not critical and this property was not included in the investigation.

By combining this material information with the previously derived E, G, and stress charts, it was possible to plot the acceptable region of wall thickness against percent of layers at ±45° for each material combination. The typical chart shown in Fig. 9 represents the optimum material arrangement for the strut, and consists of Thornal 300 material at 0° and Celion GY70 at ±45°. A minimum wall thickness of 0.99 in. with 59.5% of the layers at ±45° is indicated. In practice, the optimum point cannot always be obtained, and in this case the thickness and percentage selected for further study were 1.00 in. and 60%, respectively.

Figure 9 shows that bending stress is less critical than the modulus E_x. It was thought that a more optimum arrangement could be achieved by mixing in some GY70 layers in the 0° direction. This material, having a higher modulus, but lower strength, than the Thornel 300 material, was expected, by its addition to the 0° material, to bring the E_x and F_x curves closer together, thereby resulting in a lower required wall thickness. This proved not to be the case, because the low failure strain of the GY70 material actually prevented the Thornel 300 layers from working to their full capacity.

It is interesting to note that the GY70 proved to be the best ±45° material because its ultra-high modulus was best suited to the requirement for high torsional stiffness. Since torsional

Table 7 Weight and cost comparison of strut shell materials

	Thickness (in.)	Layer direction (deg)	Percentage of layers	Volume (cu in.)	Weight (lb)	Weight saving (%)	Cost ($) 1974	Cost ($) 1980
Steel	0.50			5,000	1,420	...	14,200	19,100
Boron	1.18	0/±45	24.3/75.7	11,600	836	41.1	237,500	117,000
Thornel 75	1.23	0/±45	48.5/51.5	12,100	678	52.2	268,600	95,000
Celion GY-70	1.51	0/±45	54.4/45.6	14,600	818	42.4	114,400	81,800
Boron	0.86	0	34.0	2,920	210	62.8	59,600	29,400
Celion GY-70		±45	66.0	5,680	318		44,500	31,800
				8,600	528		104,100	61,200
Narmco 5206	0.99	0	40.5	3,970	222	61.4	34,600	19,300
Celion GY-70		±45	59.5	5,830	327		45,800	32,700
				9,800	549		80,400	52,000
Thornel 300	0.99	0	40.5	3,970	222	61.4	34,600	19,300
Celion GY-70		±45	59.5	5,830	327		45,800	32,700
				9,800	549		80,400	52,000

shear stress was not critical, the material was not penalized by its rather poor strength capability. Thornel 300, on the other hand, provided the best combination of the bending strength and stiffness as required by the 0° material. It has been shown that the two materials will behave most effectively together when they are interspersed throughout the thickness in an approximately homogeneous fashion.

Cost-Effectiveness of the Composite Strut and Foil

Initial cost comparisons were based on the assumption that the only significant variable costs were those associated with the quantity of composite material used. Other costs such as tooling, machining, and autoclave operation and preparation were considered to be constant items, and were not included in the comparison. Total layup and inspection costs were assumed to be $60/lb of finished composite and, taking total material wastage to be 60%, the following equation was derived:

$$\text{Total variable cost} = \$(60 + 1.6C)W$$

where W is the weight of finished laminate material and, C is the cost/lb of prepreg.

To make a comparison with the existing steel components, an equivalent cost was required for the fabrication of these parts. This was difficult to assess, but was fixed at $10/lb for 1974 rising to $13.5/lb in 1980 due to increasing material and labor prices. Based on these assumptions, comparative costs for the different materials were tabulated for the strut (Table 7) , together with the appropriate weight information. It can be seen that steel, although the heaviest, is by far the cheapest. The boron/GY70 arrangement shows the largest weight saving, but Narmco 5206/GY70 and Thornel 300/GY70 are practically as light and have the lowest cost. Results similar to those shown in Table 7 were obtained for the foil.

Internal Structure and Foil-Strut Joints for the All-Composite Designs

The analysis of the shell took no account of the internal support structure since it was assumed that this would have a secondary effect of the total weight and cost estimates. Because the composite shells were thicker than their steel counterparts, less stabilization against buckling was required. In the case of the foil, it was found that no spanwise members were required other than the rear spar on which the flap hinges were mounted. A transverse rib was provided at each of the hinge stations to redistribute the hinge loads into the structural box.

The essential internal members in the strut were a spar web on which the rudder hinges were mounted, and a transverse rib at the intersection of the tapered and constant section. In addition, provision was required for the mounting of 2 control-rod bearings. Two configurations were considered for the substructure, the first being a conventional arrangement of spar and rib webs. The alternate configuration was the truss-web design (Fig. 10) which, although heavier, was selected for fabrication reasons.

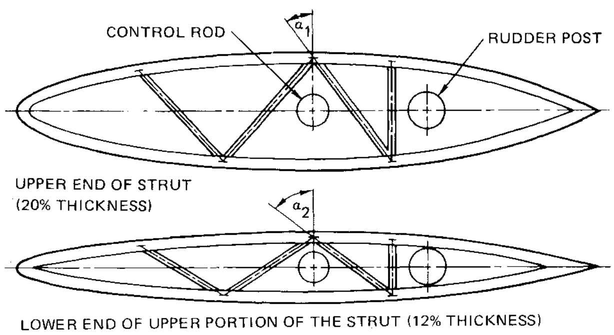


Fig. 10 Truss-web geometry for all-composite strut design.

Preliminary engineering drawings were prepared for both the strut and the foil to enable more detailed estimates of weight, cost, and strength. Both the strut and the foil were designed to be fully interchangeable with the existing metal parts. This requirement imposed the constraint that existing joint geometry had to be maintained. However, if both the strut and the foil are considered as a single replacement item, the joint between them is no longer bound by this constraint. Although this possibility was considered, no advantage could be obtained by changing the basic joint design, so the 2 components were designed to be independently interchangeable. The joint on the strut consisted of metal flanges at each end of the strut. The flanges were welded to tapered plates (running in the direction of strut axis) which formed a scarf joint between the composite and the metal. The joint on the foil consisted of an external metal plate which tapered to a feather edge from center of the foil outward. The design of the joints was based on the analytical methods given in Ref. 9 and took into account the stiffness imbalance and thermal mismatch of materials.

Composite-Reinforced Metal Designs of the Strut and Foil

As shown in Table 7 for the strut, the all-composite design was over 60% lighter than the steel structure, but at a considerable cost penalty. A study was conducted to see if the advantages of each material could be combined to provide a mutual benefit. The concept was to use a steel skeleton, constructed in a way similar to the existing components, over which composite layers were added. The analysis procedure was similar to that used for the all-composite design, but the extra complexity necessitated the use of a computer to make a rapid assessment of the thickness required for strength and stiffness. The thickness of the steel shell was varied to cover the complete range from all-composite to all-steel structures.

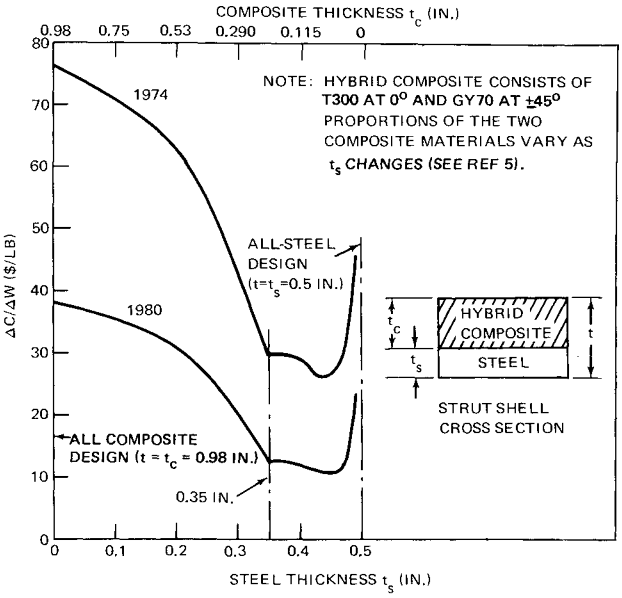


Fig. 11 Cost/weight ratio for composite-reinforced steel strut.

For both the strut and the foil, weight increased and cost decreased with increasing steel thickness. To make an assessment of cost effectiveness, curves were drawn to show the cost of saving a lb of weight, the chart for the strut being illustrated in Fig. 11. A discontinuity was evident in the curves at a steel thickness of 0.35 in., where the critical stressed material changes from the steel to the composite. The incremental costs per pound at the transition points were very close to the minimum values shown in the curves. A similar result was obtained for the foil. For this reason, it was decided to make a further study of configurations for the strut and the foil to represent these conditions, and preliminary engineering drawings were prepared for the resulting steel skeleton designs.

Weight and Cost Comparison of the Steel, Composite, and Composite-Reinforced Steel Strut and Foil Designs

The engineering drawings of the all-composite and steel-skeleton designs are given in Refs. 4 and 5. These are not sufficiently detailed to enable fabrication of the components, but allow a more accurate assessment of strengths, stiffnesses, weights, and costs. Moreover, these drawings were sufficient to establish required tooling and estimate their cost, as well as the fabrication sequence and the cost of fabricating the various strut and foil designs. The final designs were checked to ensure that the strength and stiffness requirements, as well as other requirements and constraints, were met.

A weight and cost summary for the final designs of the strut and the foil is given in Table 8. Compared with the existing steel design, the weight savings for the all-composite and the steel-skeleton designs were 60.9 and 22.7%, respectively, for the strut, and 61.6 and 29.2% for the foil. The costs indicated that for the production of 100 ship sets, the all-composite design should become less expensive than either the all-steel or the steel-skeleton designs before 1980.

A number of potential problem areas relative to the application of advanced composites to the various structural components of the PCH have been identified and briefly considered.[4] None of the problems appears to be insuperable to the extent that the results and conclusions presented herein would be changed significantly.

Influence of Weight Savings on Hydrofoil Performance

As discussed in Ref. 4, the payoff resulting from the reduction in structural weight of the hydrofoil can be in terms of increased speed, range, endurance, or payload. Nominal increases in hydrofoil performance can be achieved by accepting the weight savings without making any changes in engine, payload, or fuel volume. Significantly higher improvements in performance can be achieved by converting the weight savings into extra fuel to increase the range or endurance, higher horsepower engine to increase speed, or additional payload.[3,4]

Table 8 Cost comparison for forward strut and foil[d]

Design		Composite reinforced steel		All-composite	
Item	All-steel	100[a]	10[a]	100[a]	10[a]
Strut					
Total weight (lb)	2,173	1,680		848	
Weight saved (lb)	...	493		1,325	
Weight Savings (%)	...	22.7		60.9	
1974 total cost ($)[b]	54,400[c]	50,580	204,880	58,710	138,500
1980 total cost ($)[b]	72,800	63,320	270,020	48,750	155,450
Foil					
Total weight (lb)	2,714	1,924		1,044.7	
Weight saved (lb)	...	795		1,674.3	
Weight savings (%)	...	29.2		61.6	
1974 total cost ($)[b]	68,000	64,300	241,200	82,200	181,800
1980 total cost ($)[b]	91,100[c]	76,500	314,100	63,900	197,100

[a]Number of ship sets on which cost was based.
[b]Includes cost of composite materials, HY130 steel, scrap (waste), and all costs associated with fabrication and assembly, quality control, tooling, and planning. Labor rate taken as $20 per hour in 1974; increase in labor cost assumed as 5% per year.
[c]Based on cost of $25/lb of fabricated structure in 1974. Material and labor cost assumed to increase at 5% per year to obtain 1980 cost figures.
[d]Note: Detailed cost estimates are for 100 ship sets; cost of 10 ship sets was extrapolated from the latter figures using the learning curve obtained on F-4 composite rudder.

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