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Structural Tailoring of Select Fiber Composite Structures

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SUMMARY

A multidisciplinary design process for aerospace propulsion composite structures has been formalized and embedded into computer codes. These computer codes are streamlined to obtain tailored designs for select composite structures. The codes available are briefly described with sample cases to illustrate their applications. The sample cases include aircraft engine blades, propfans (turboprops), flat and cylindrical panels. Typical results illustrate that the use of these codes enable the designer to obtain designs which meet all the design requirements with maximum benefits in efficiency, noise, weight or thermal distortions.

INTRODUCTION

Design of composite structures for aerospace propulsion systems is a multidisciplinary activity where the participating variables from each discipline are traded off in order to meet specified designer requirements for: (1) safety, (2) durability, (3) performance, (4) maintenance, and (5) cost. The observation from the above is that the multidisciplinary design is a complex activity of competing objectives which result in compromised designs. The multidisciplines that are usually associated with aerospace composite, structures are the following: (1) aerodynamics, (2) structural mechanics, (3) aeroelasticity, (4) acoustics, (5) composite mechanics, (6) mechanics for fatigue and fracture, (7) life predictions, (8) economics, and perhaps several others. Observation: there are several independent disciplines, each of which requires that seasoned expertise be utilized. In one of these disciplines there are several participating variables that define: (1) load conditions, (2) structural configuration, (3) materials, (4) aerodynamic performance, (5) structural performance, (6) durability/life, (7) safety, (8) cost, and (9) profits. Observation: these comprise a large number of variables that need to be traded off to obtain a compromised design. The present procedure is that each discipline iterates to come up with the best configuration which satisfies the specified designer requirements within that discipline. After that has been done, a compromise is achieved by one or more sequential iterations among the participating disciplines. This process is time consuming and results in inefficient use of engineering effort. In addition, there are disagreements among the engineers in the different disciplines; some people may feel that they have been offended during this iteration process and perhaps ill feelings are created which may not be resolved and continue through the next time around. An alternative to the above is to formalize this multidisciplinary design process. When the formalization is driven by structural consideration, it is appropriately called structural tailoring. The objective of the present report is to describe structural tailoring methods that have been developed for select propulsion composite components, illustrate their applications, present results obtained therefrom, and discuss their significance.

APPROACH AND FORMALIZATION

The approach to formalize the design for structural tailoring is to examine the design process, identify the participating disciplines, and cast that design process into mathematical form. This usually consists of: (1) an objective function (a dependent variable which is used to evaluate the merit of the design); (2) the design variables (those variables that the designer controls), the behavior variables (structural response variables which evaluate the adequacy of the design); for example, displacements, stresses, strains, fatigue life, frequencies, buckling loads; (3) the side constraints which are bounds (limits) on the variables that control (the design variables) or any other considerations that require the design to be within those limits; and (4) the behavior constraints which are the bounds set by design requirements on the/behavior variables mentioned previously. For example, the local stress may not exceed the strength of the material.

In the process of casting a multidisciplinary design into the formal procedure, each one of the disciplines has to contribute its part. That means that each discipline contributes its part to the objective function. The contribution is dependent on the set of design variables which define the discipline, the behavior variables associated with that discipline and the respective side and behavior constraints. In addition to these, each discipline has to provide the discipline specific analysis that relates the behavior variables to the design variables and to the overall structural configuration. The mathematical representation of the structural tailoring problem is outlined as follows:

$$\text{Min } F(\vec{D}_V) = \sum_{i=1}^{N} f(DO)_i$$

Subject to:

$$\vec{B}_V(\vec{D}_V) \geq B_C$$

$$\vec{D}_V \geq \vec{D}_C$$

where

$\vec{B}_C$ behavior variables constraints list

$\vec{B}_V$ behavior variables list

$\vec{D}_C$ design variables constraints list

$\vec{D}_V$	design variables list
$F(\vec{D}_V)$	objective of integrated design
f(DO)	design objectives of each discipline
N	number of design variables

Stated in words: minimize a function of design variables which is a combination of terms from each discipline, where the behavior variables are bound by their respective behavior constraints, and where the design variables are bound by their respective side constraints. This form of the mathematical programming problem has been streamlined and organized into a computer code, STAEBL--for structural tailoring of engine blades (refs. 1 and 2). A flow chart of the computer code is shown in figure 1.

Aircraft Engine Fan Blades

Figure 2 is an illustration of the application of STAEBL to a specific fan blade made from superhybrid composite. The objective for the design of this fan blade was to maximize the return on investment (ROI). This is a primary consideration of management. As can be seen in the figure that using current practice procedures, the multidisciplinary design team came up with a blade which weighs 17 lb. The ROI was 3 percent and took the multidisciplinary design team 52 weeks to complete the design. Using STAEBL, one engineer arrived at a design which weighs 16 lb. The ROI is 3.3, but the effort in professional man-years is reduced from 52 weeks to 1 week. At this point, it is worth noting that the weight reduction from 17 lb to 16 lb does not seem very much for a single blade; however, it multiplies rapidly since there are many fan blades in a stage. It is also important to note that an increase in ROI of 0.3 percent is a significant result. In this case, STAEBL was applied to a multidiscipline problem. Using STAEBL to tailor the blade for only minimum weight, we were able to reduce the weight from 17 lb to 9 lb, which is almost half the weight. This demonstrates the bias of one discipline against the overall design. It also demonstrates the strong interaction among the participating disciplines and the shortcoming of using a single discipline to structurally tailor complex structures. In figure 3, the results of another case study including constraints and their bounds are presented. These were obtained from the same blade as in figure 2. However, now the whole blade was assumed to be made from composites. It was further assumed that the blade is subjected to temperature, moisture, and centrifugal forces. There were nonuniform temperatures and moisture distributions over the blade as well as their gradients through the thickness. STAEBL proceeded by selecting a composite in such a way that all the design requirements (ply stresses through thicknesses, overall stresses, displacements, and frequencies) were satisfied. The solid symbols in the figure indicate the initial design while the open symbols indicate the optimum design. The following observations are of interest: (1) the stress near the root, as well as the ply stresses, did not violate the constraints, (2) there is a small change in the stresses from the initial design to the final, and (3) this change is sufficient to move the outer ply stress from negative to a small positive margin.

Turboprop (Propfan) Blades

Figure 4 schematically depicts another computer code that was developed for multidisciplinary structural tailoring. This code is identified as STAT (Structural Tailoring for Advanced Turboprops) (ref. 3). The shape of these turboprops is complex because it contains twist, sweep, camber and variable thickness in both chord and span directions. The internal structure is also complex because it consists of a metal spar, a composite shell, an adhesive layer as well as foam to fill the gaps between the spar ends and the shell. The multidisciplines that are integrated into STAT are listed in the lower left of the figure and include: (1) ADS (Automated Design System) optimizer, (2) blade model generator, (3) aerodynamic analysis, acoustic analysis, (4) stress and vibration analysis, (5) flutter analysis, and (6) forced response, where 1 P forced response means 1 excitation/revolution.

In the lower right part of the figure is a summary of results obtained for a specific design. For this case, the initial design had an efficiency of 82.9 percent, a near field noise of 144 dB and a blade weight of 41 lb. The objective function was direct operating costs (DOC) which is -0.8. The final design includes: an increase in efficiency of about 0.3, a reduction in the near field noise by approximately 7 dB, no change in weight, and a major reduction in the direct operating cost by a factor of 5.

Table I is a summary of a study in which STAT was used to select both the twist and the sweep as a continuous function of high degree polynomials assuming the shell is made from titanium. The coordinates of the midline X and Y are expressed in terms of these polynomials. With fixed exponents, however, the coefficients of the polynomials were selected as design variables which are tailored by STAT to generate a turboprop airfoil shape for the best possible design. The table lists variations in the noise level as a function of coefficient A and the exponent M. As can be seen in the table, substantial reduction in the noise level can be obtained by these variations.

In cases of large variations in A, STAT found no solution because that combination of twist and sweep was beyond the capability of the state-of-the-art of the acoustic analysis in the code. The point to be noted is that the designer can select this function with unspecified coefficients and allow STAT to adjust these coefficients during the design process in order to obtain a good design. The coefficients of this function define both the blade twist and sweep. Typical results are summarized in figure 5 where the span (X) and chord (Y) coordinates are represented by shape functions for both the twist and sweep. The constraints are plotted in terms of safety margins, that is, how much margin is in the design. All the mechanical design requirements are represented in the figure in terms of constraint safety margin percentages. The initial designs are indicated by solid symbols while the final design, by open symbols. The final design is shifted somewhat closer to the constraints compared to the initial design. The important point is that all the constraints were satisfied with substantial margins. The lower part of the figure summarizes the values of the shape functions, of the efficiencies and of the noise levels. STAT designed a propfan with an improved efficiency (5 points) and with reduced noise (18 dB) compared to the initial design.

Structural Tailoring of Composite Panels

STAEBL has been modified to STAEBL/GENCOM (General Composite) to provide the capability for this type of structural tailoring. To demonstrate this kind of application a panel is selected. The panel is depicted in figure 6 with the laminate configuration through the panel. For the purpose of this discussion, the panel is of uniform thickness, the ply angles are fixed on the outer plies of the panel; however, the ply angles (θ_1, θ_2) within the core are allowed to vary in order to minimize the distortion. Each of the ply angle thicknesses are indicated for θ_1 and θ_2 (in the figure). The design variables are the core ply angles θ_1 and θ_2. The load cases are summarized at the top right of the figure. The objective functions for each of the loading conditions were to minimize: (1) the extension in the X direction, (2) the distortion in the Y direction, and (3) the combined displacement in which both the displacements in the X and Y directions were considered simultaneously.

The results are summarized in tables II to IV for thermal load, pre-extension, and combined, respectively. The initial design is listed at the top. The final design (objective function, extension magnitudes, and ply angles are listed in the lower part. The results show different core ply angles for the different objective functions and for the different loading conditions. The results also show that the final design core ply angles are not necessarily intuitively obvious. The important point is that once a laminate is optimized for one set of conditions it is not necessarily optimum for any other load conditions.

Application of STAEBL/GENCOM is further illustrated by using it to structurally tailor two different panel shapes (fig. 7). One is a flat panel which is similar to the one discussed before and the other one is a cylindrical panel. The objective here is to see whether the structural shape has an influence on the laminate configuration where the loading conditions remain the same. Both panels are subjected to mechanical and thermal loading conditions. The mechanical loading consists of the ratio 2:1:1; 2 along the X direction; 1 the Y direction; and 1 shear. The thermal loading consists of uniform temperature through the thickness. Each panel is made from two different composite material systems: AS/epoxy and HM/epoxy with laminate configuration, shown in figure 6. The difference between the two is that the HM/epoxy has approximately one and one-half times the modulus along the fiber direction of the AS/epoxy composite.

Again, the objective function is minimum distortion. The sum of the combined X and Y displacements at each node is minimized. The results are summarized in table V. Only the core ply angles are shown here, the outer ply angles are shown in figure 4. The upper part of the table summarizes the results of the mechanical loading. The core ply angles are different from different composite systems which show a strong dependence on composite systems. These ply angles are also different for the two structural components. The final distortion is substantially different for the different structural shapes. The important observation is that different laminate configurations are optimum for different structural shapes under the same loading conditions. Stated differently: an optimum laminate configuration for one structural shape is not necessarily optimum for a different structural shape even though the loading conditions are the same.

GENERAL COMMENTS

Some general comments from these studies are as follows. In developing structural optimization codes for multidisciplinary tailoring, it is important that the design team which will perform the design participates in completing the structural tailoring code. It is also important that approximate discipline-specific analyses, with acceptable accuracy, be included in the code. The participating disciplines must provide the respective computer code modules. In other words, they are the ones who have the experience on what is important, what is not important and what kind of accuracy they will accept from an approximate analysis.

The discipline-specific modules must be integrated in the tailoring code early on once the decision has been made. The integrated tailoring code should have an executive module and a dedicated data base. The code should be made available to all members that participate in a design team. Another important point is the amount of input data. This must be kept to a minimum. Anything that can be done to expedite the input data is very helpful. The primary interest is the use of the code with minimum effort in getting the information ready for its use. If this information becomes voluminous, the likelihood to use that code is rather limited. Finally, one needs a single robust optimization algorithm which is consistent with the specificity of the code and its resident approximate analyses. A variety of optimization algorithms are not needed because most of the users will not be knowledgeable enough in the details and subtleties of mathematical programming to take advantage of the different optimization algorithms.

CONCLUSIONS

Structural tailoring methods for select fiber composite components for propulsion and related structures are available. They can also be put together quickly by knowledgeable people who are participating in the field. These methods formalize the multidiscipline procedures required during the design process. Typical results obtained from the use of such structural tailoring codes are as follows: (1) reduce the professional time spent by 80 percent, (2) improve the design objectives by reducing weight by 50 percent or more depending on specific components, (3) reduce the noise by 18 dB, (4) increase the return on investment by 4 percent, (5) increase safety margins, and (6) minimize all thermal distortions. Use of these codes expedites a given design, provides for the formalization of interdisciplinary designs and permits the practitioners to examine alternative design concepts in a timely and cost-effective manner.

REFERENCES

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3. K.W. Brown, P.R. Harvey, and C.C. Chamis, "Structural Tailoring of Advanced Turboprops," in Structures, Structural Dynamics and Materials Conference, 28th, Monterey, CA, Apr. 1987, AIAA, New York, 1987, pp. 827-837.

TABLE I. - EFFECT OF TWIST AND SWEEP ON NOISE OUTPUT

[Offsets of exponential form: $x = Az^m$; $y = Az^m$; z = span fraction ($0 \le z \le 1$).]

m	A	dB	m	A	dB
1	0.000	150.5	6	0.080	140.0
1	.025	150.4	|	.120	136.0
1	.050	(a)	|	.140	134.5
			↓	.160	(a)
2	.050	149.2	8	.100	135.5
2	.075	(a)	8	.110	(a)
3	.080	145.7	—	------	------
4	.080	143.5	10	.080	135.9
5	.080	141.6	10	.100	(a)

[a] Analysis terminated by convergence failure or runtime error. Shell made from titanium.

TABLE II. - THERMAL LOAD

[Initial extension: $\Delta X = 4.546 \times 10^{-3}$ in.; $\Delta Y = 5.324 \times 10^{-3}$ in.]

Objective function	Extension (10^{-3} in.)		Ply angles, deg.	
	ΔX	ΔY	θ_1	θ_2
ΔX	4.171	5.171	18	18
ΔY	6.826	2.380	88	88
Δr	6.535	2.497	76	76

TABLE III. - EXTENSION LOAD

[Initial extension: $\Delta X = 0.5987 \times 10^{-3}$ in.; $\Delta Y = 0.0543 \times 10^{-3}$ in.]

Objective function	Extension (10^{-3} in.)		Ply angles, deg.	
	ΔX	ΔY	θ_1	θ_2
ΔX	0.5987	0.0543	0	0
ΔY	.8056	.0338	90	90
Δr	.5987	.0543	0	0

TABLE IV. - THERMAL AND EXTENSION LOAD

[Thermal and extension loads adjusted to produce equal extension.
Initial extension: $\Delta X = 9.037\times10^{-3}$ in.
$\Delta Y = 5.285\times10^{-3}$ in.]

Objective function	Optimum extension × 10^3 in.		Ply angles, deg.	
	ΔX	ΔY	θ_1	θ_2
ΔX	8.759	4.948	59	59
ΔY	12.790	2.369	96	96
Δr	8.779	4.719	53	53

TABLE V. - STAEBL/GENCOM DISTORTION MINIMIZATION STUDIES

Geometry	Loading case	Material system	Optimal ply angles, deg.				Total distortion,[a] 10^{-3} in.	
							Initial design	Final design
Flat plate	[b]2/1/1	AS/E[c]	[d](θ_1/θ_2)				5.89	0.132
		HM/E[e]	1	53	0	2	3.97	.088
Cylindrical panel	[b]2/1/1	AS/E	-1	-42	29	9	3.64	.344
		HM/E	5	-44	23	11	4.59	.121
Flat plate	ΔT through thickness[f]	AS/E	3	-40	85	74	.88	.011
		HM/E	68	0	4	0	.11	.000
Cylindrical panel	ΔT through thickness[f]	AS/E	0	0	0	0	.009	.009
		HM/E	0	0	0	0	.009	.009

[a] Total distortion is proportional to sum of squares of displacements at each grid point.

[b] Proportional loading - x tension : y tension : shear (2:1:1) = (2000/1000/1000) lb.

[c] AS/E AS-graphite fiber/epoxy matrix.

[d] Initially all ply angles are zero; symmetric laminate about mid-plane.

[e] HM/E High-modulus graphite-fiber/epoxy matrix.

[f] Δ_T = 100 °F.

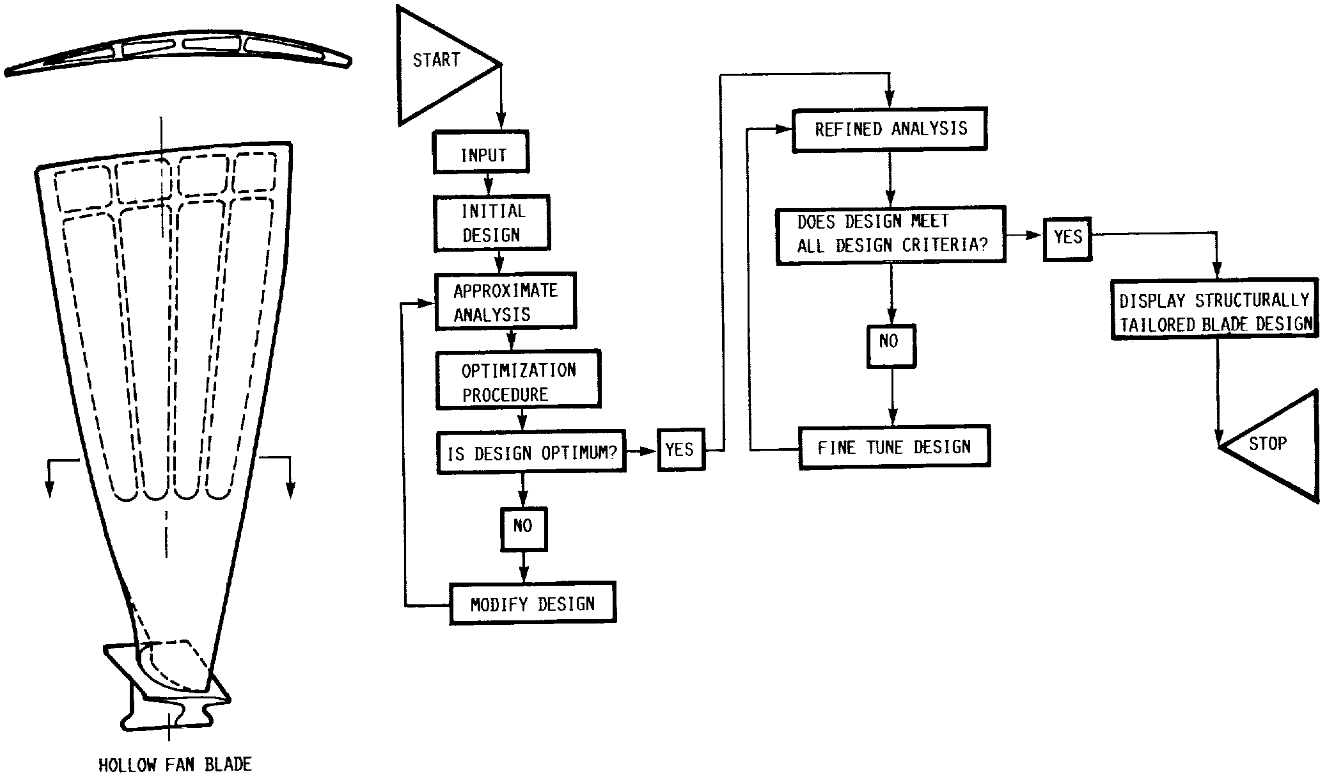
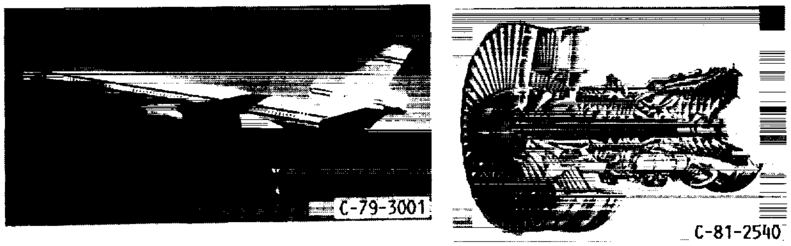
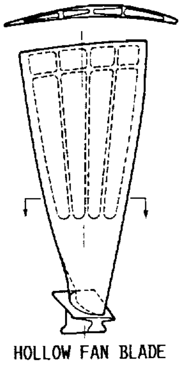


FIGURE 1. - STRUCTURAL TAILORING OF ENGINE BLADES (STAEBL).





CURRENT DESIGN PROCEDURES:

- WEIGHT 17 LB
- ROI 3.0 PERCENT
- PROF. EFFORT; 52 WEEKS

STAEBLE DERIVED DESIGN

- WEIGHT 16 LB
- ROI 3.3 PERCENT
- PROF. EFFORT; 1 WEEK

FIGURE 2. - STAEBL -- STRUCTURAL TAILORING OF ENGINE BLADES.

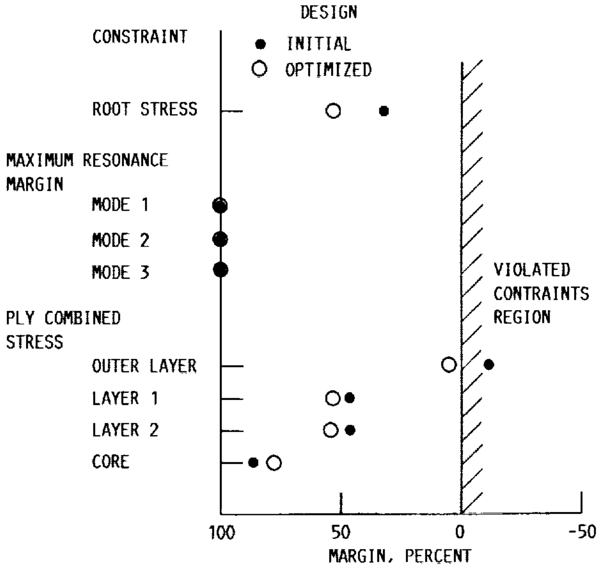
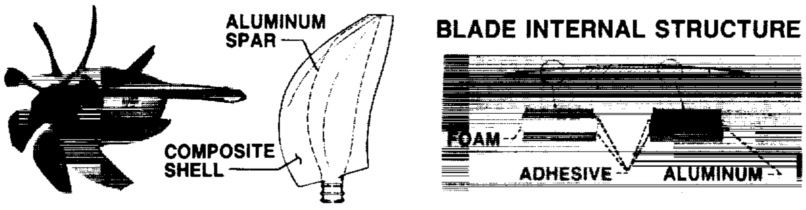


FIGURE 3. - COMPARISON BETWEEN INITIAL AND OPTIMIZED DESIGNS, THERMAL, MOISTURE, AND CENTRIFUGAL LOADS.



TURBOPROP STAGE AND PROPELLER

MULTI-DISCIPLINARY ANALYSIS MODULES

- ADS OPTIMIZER
- BLADE MODEL GENERATION
- AERODYNAMIC ANALYSIS
- ACOUSTIC ANALYSIS
- STRESS AND VIBRATIONS ANALYSIS
- FLUTTER ANALYSIS
- 1 P FORCED REPONSE

TYPICAL ANALYSIS RESULTS

	INITIAL	FINAL
EFFICIENCY, PERCENT	82.86	83.17
NEAR FIELD NOISE, DB	143.8	137.3
WEIGHT, LB	41.1	41.2
DOC	–.853	–4.201

FIGURE 4. - STAT -- STRUCTURAL TAILORING OF TURBOPROP BLADES.

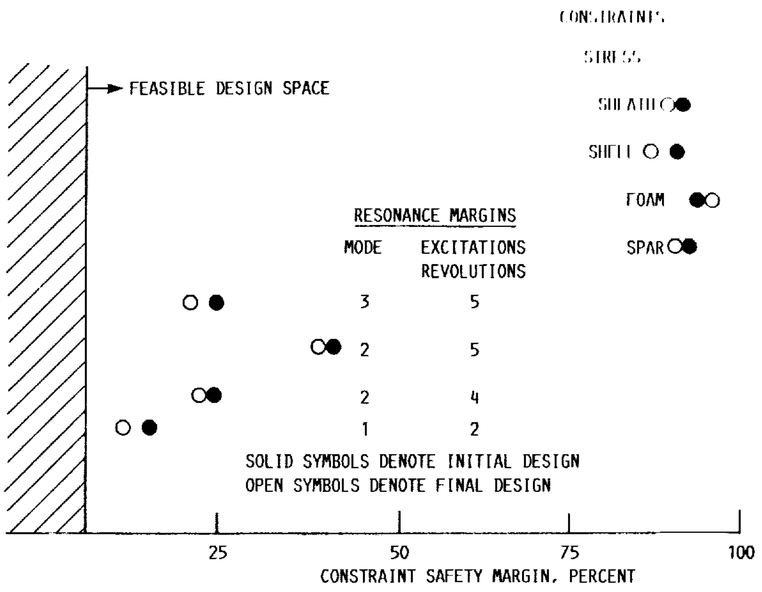


FIGURE 5. - STAT OPTIMIZATION STUDY. INITIAL DESIGN (UNSWEPT): NOISE = 152 dB; EFFICIENCY = 76 PERCENT. FINAL DESIGN: $X = .1334z^6$, $Y = .1721z^6$; NOISE = 134 dB; EFFICIENCY = 81 PERCENT.

PLY ANGLES	PERCENT THICKNESS
0^0	20
90^0	10
θ_1	10
θ_2	10
θ_2	10
θ_1	10
90^0	10
0^0	20

DESIGN VARIABLES: PLY ANGLES θ_1 AND θ_2

LOADS:
- (1) THERMAL LOAD (UNIFORM TEMPERATURE)
- (2) PRE EXTENSION
- (3) THERMAL AND EXTENSION LOADS

OBJECTIVE FUNCTIONS*
- (1) X EXTENSION ΔX
- (2) Y EXTENSION ΔY
- (3) MAXIMUM TOTAL DISPLACEMENT

$$\Delta r^2 = \sqrt{\Delta x^2 + \Delta y^2}$$

*UNCONSTRAINED

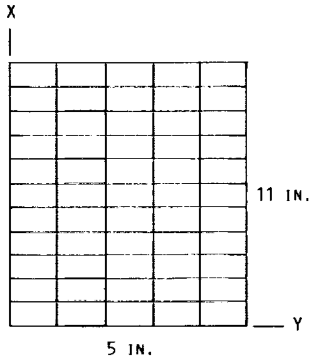
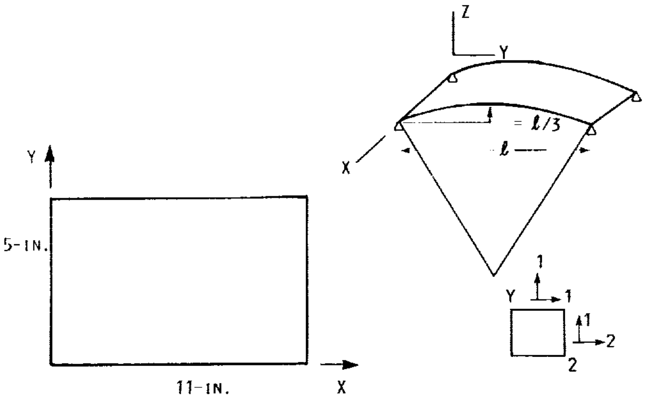


PLATE FINITE ELEMENT MODEL

FIGURE 6. - COMPOSITE PLATE STRUCTURAL TAILORING.



FLAT PANEL CYLINDRICAL PANEL

STAEBL/GENCOM	FLAT	CYLINDRICAL PANEL	OBJECTIVE FUNCTION
BIAXIAL LOAD 2/1/1	(1) AS/E (2) HM/E	(1) AS/E (2) HM/E	MINIMUM DISTORTION
ΔT THROUGH THICKNESS	(1) AS/E (2) HM/E	(1) AS/E (2) HM/E	MINIMUM DISTORTION

AS/E - AS-GRAPHITE-FIBER/EPOXY-MATRIX; HM - GRAPHITE FIBER/EPOXY-MATRIX

FIGURE 7. - STRUCTURAL TAILORING OF SELECT COMPOSITE PANELS.

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16. Abstract

A multidisciplinary design process for aerospace propulsion composite structures has been formalized and embedded into computer codes. These computer codes are streamlined to obtain tailored designs for select composite structures. The codes available are briefly described with sample cases to illustrate their applications. The sample cases include aircraft engine blades, propfans (turboprops), flat and cylindrical panels. Typical results illustrate that the use of these codes enable the designer to obtain designs which meet all the design requirements with maximum benefits in efficiency, noise, weight or thermal distortions.

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