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ABSTRACT

A detailed stress analysis is performed using NASTRAN to demonstrate theoretically the adequacy of composite hubs for low cost turbine engine applications. The results show that composite hubs are adequate for this application from the steady state stress view point.

INTRODUCTION

Low cost gas turbine engines for general aviation are of considerable interest and an extensive investigation towards this end is discussed in reference 1. During the course of the investigation of reference 1, it was decided to study the suitability of composites for hubs for low cost engine applications. This study resulted in a composite hub concept. The adequacy of this composite hub concept from the stress view point is the subject of the investigation reported herein.

The present investigation had two objectives: (1) carry out a detailed stress analysis to theoretically prove the composite hub concept for low cost gas turbine engines; and (2) demonstrate that NASTRAN ring elements can be used to carry out the stress analysis of such composite hubs. The major low cost engine design conditions, the composite hub concept, the NASTRAN stress analysis that was conducted, and results obtained are described in the report.

LOW COST ENGINE DESCRIPTION

The low cost engine considered in this investigation is described in considerable detail in reference 1. Briefly, the major design conditions of this engine are:

1. 1500° F turbine inlet temperature

2. 4.0 to 1 pressure ratio

3. 650 lbs sea level static (SLS) thrust

4. 1.3 lb/hr per pound thrust fuel consumption

STAR Category 39

5. 570 mph flight cruising speed

6. 11.5 in external diameter

7. 100 lb weight

8. 36960 revolutions per minute engine speed

A cross section schematic of the low cost engine is shown in figure 1.

COMPOSITE HUB

A photograph of the metal hub which the composite hub was intended to replace is shown in figure 2. The conceptual design for the composite hub proposed by Fiber Science, Inc., Gardina, CA is shown in figure 3. As can be seen in the side view of this figure, the composite hub is an assemblage of four parts, namely: hub-core, load bar, keeper, and hoop wraps or overwraps. The fan blades are made from 17-4-PH steel alloy in pairs (12-pairs or 24-blades).

The essential features of the composite hub concept shown in figure 3 are as follows: The hub core is to be made from random graphite/epoxy composite (fibers oriented randomly in the hub core plane) in order to obtain uniformly low thermal growth and it has a groove at its circumference. The load bar is to be made from unidirectional S-glass/epoxy composite with an outside diameter equal to the bend diameter of the blade pair. The load bar keeps the blade pair in the hub. The keeper is to be made from random S-glass/epoxy composite and is designed to fill the space between the load bar and the outer diameter of the hub with provisions for the hoop wraps. The hoop wraps (unidirectional graphite/epoxy) are applied to the keeper and react to the centrifugal force of the blades. In this fashion, the hoop wraps resist the blade centrifugal force in tension which is the most efficient use of fiber composites. The hoop wraps are to be made from graphite/epoxy. This was done to minimize the thermal stresses (residual and those induced by the operational temperature) which would result from unequal thermal coefficients of expansion of the random composite hub core and the unidirectional hoop wraps.

Since the hoop wraps are the main load members and since they hold the hub together, it is imperative to obtain an accurate assessment of the hoop stresses in these wraps.

STRESS ANALYSIS METHOD

A schematic of the composite hub for analysis purposes is shown in figure 4. Note in this figure that the various parts of the composite hub are identified (designated) and numbered. The materials to be used for the various parts of the composite hub and their respective orientation are listed in table 1. The corresponding elastic and thermal properties used in the stress analysis are given in table 2 (see fig. 4 for coordinate directions). Because the hub is a three-dimensional solid, the three dimensional elastic and thermal properties are required. The properties for the unidirectional composites were generated using the computer code described in references 2 and 3. Those for the random composite were determined using the "pseudoisotropic equivalence" concept described in reference 4. Those for the steel alloy were obtained from reference 5.

The stresses in the various parts of the composite hub were determined using NASTRAN (NASA STRUCTURAL ANALYSIS, via finite element) reference 6. The composite hub was modeled using ring elements with trapezoidal (quadrilateral) and triangular cross sections. These elements are identified respectively, as CTRAPRG and CTRIARG in the NASTRAN finite element library. These elements are axisymmetric and need nine elastic constants and three coefficients of thermal expansion to simulate the composite materials used in the hub. The use of these elements simplifies the analysis of the hub considerably because only one element is needed around the circumference instead of several if regular 3-D elements were used.

The finite element model of the hub is shown in figure 5. The model consists of 128 elements and 143 nodes (grid points). Note that the load bars and the keepers are not continuous along the circumference. This is easily simulated in the ring elements by assuming very low stiffness in the hoop (θ) direction ($E_{\theta\theta} \rightarrow 0$) and zero values for the Poisson's ratio $\nu_{r\theta}$ and $\nu_{\theta z}$. Note also that the gap is simulated by a material which can transfer load in the z direction but not in the r and θ directions (fig. 4).

The metal blades were simulated by increasing the mass of the elements representing the blades to account for the total blade centrifugal force induced in the load bars. This increase in mass was determined from the following equation:

$$F = V\Omega^2 r\rho/g \tag{1}$$

and

$$\rho/g = F/V_e\Omega^2 r \tag{2}$$

where ρ/g is the equivalent mass, F is the centrifugal force of a blade pair induced at the load bar per unit circumference, V_e is the volume of the blade elements per unit circumference, Ω is the fan stage rotational speed and r is the location of the blade elements in the finite element model.

The centrifugal force induced at the load bar by one blade pair is determined from the following equation:

$$F = 2\rho V\Omega^2 R \tag{3}$$

where ρ is the blade (steel density), V is the volume of one blade, Ω is the rotational speed in rad/sec, and R is a mean radius. Using the following numerical values for this hub

$$\rho = 0.282 \text{ lb/in.}^3$$

$$V = 0.261 \text{ in}^3$$

$$\Omega = 36960 \text{ rpm} = 3870.4 \text{ rad/sec}$$

$$R = 2.53 \text{ in.}$$

equation (3) yields:

$$F = 14438 \text{ lb per blade pair}$$

Using the additional numerical value,

$$V_e = 0.008 \text{ in}^3\text{/in.}$$

$$r = 1.225 \text{ in.}$$

equation (2) yields

$$\rho/g = 3.88 \ \frac{\text{lb/sec}^2}{\text{in}^3\text{/in.}}$$

as the equivalent blade element mass to induce the same centrifugal force at the load bars using NASTRAN.

The stress analysis was performed using rigid format 1 of NASTRAN with the R force card to represent the centrifugal forces generated by the rotational speed. The boundary conditions used were: "zero" z displacements (no hub axial growth) along the nodal line connecting nodes 1 and 129, figure 5. These boundary conditions permit: radial and circumferential growth, and axial growth about the nodal line connecting nodes 1 and 129, figure 5.

STRESS ANALYSIS RESULTS AND DISCUSSION

Four types of stresses are induced in the composite hub by the rotational speed. Referring to figure 4, these stresses are radial (σ_{rr}), circumferential ($\sigma_{\theta\theta}$), axial (σ_{zz}), and shear (σ_{rz}). Because the hub consists of several parts the best way to present the NASTRAN predicted stresses is in terms of the average stress at the center of each element. This method provides a good assessment of the stress gradients in each of the parts of the hub.

The NASTRAN predicted stress distribution for the radial stress is shown in figure 6. As can be observed from the values in this figure, the radial stresses are very small. The maximum radial stress in the hub-core is approximately 2400 psi in the vicinity of the blade. This value is about 10 percent of the ultimate of this material (24000 psi Hercules Data). The maximum stress (average of 4 triangular elements) in the hoop wraps is 2000 psi which is about 20-percent of the transverse tensile strength of Graphite T300/epoxy. Note that the radial stresses in the gap elements are "zero" as they should be.

The circumferential stresses in the elements are shown in figure 7. The maximum circumferential stress in the hub-core is 2.6 ksi which again is about 10-percent of the material strength. The maximum circumferential stress in the hoop wraps is 14.4 ksi which is about 7-percent of the unidirectional longitudinal strength of Graphite T300/epoxy (200 ksi). The circumferential stresses in the blade elements, keeper elements, and gap are "zero" as they should be.

The axial stress distribution is shown in figure 8. The maximum stress in the hub-core elements is 2.1 ksi compared to about 8 to 10 ksi for the transverse tensile strength of this material. The axial stress in the hoop wraps is 1 ksi or less which is about 12-percent of the transverse tensile strength of the Graphite T300/epoxy composite. Note the small compressive axial stress in the gap elements indicating the transfer of axial stress from the hub-core to the other parts.

The shear stress distribution is shown in figure 9. As can be seen in this figure, the shear stresses are negligible in all the composite parts.

The important conclusion from the above discussion is that the composite hub design concept investigated herein should be satisfactory from the steady state stress view point. Although the results are not presented here, including a thermal change of 400° F in the calculations to simulate hub extreme operational conditions had little effect on the stress distribution described. This was expected because the random graphite composite in the hub and the hoop wraps do not have sufficiently different thermal coefficients of expansion. Because the radial stresses are very small, the hub radial growth is also negligible (less than 0.003 in.). Therefore, this composite hub design concept appears to be adequate from all steady state analysis considerations. These results lead to the recommendation that composite hubs of this type be made and tested to verify fabrication practicality and operational requirements of the composite hub concept for low cost gas turbine engines.

CONCLUSIONS

The results of this investigation lead to the conclusion that composite hubs are suitable for low cost engines from the steady state stress analysis view point. The concept appears sufficiently promising to warrant verification by actual fabrication and test. It is also concluded that use of the NASTRAN ring elements simplifies the stress analysis of composite hubs of the type considered in this investigation.

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2. C. C. Chamis, "Computer Code for the Analysis of Multilayered Fiber Composites - Users Manual," NASA Technical Note D-7013 (1971).

3. C. C. Chamis, Composite & Structures 3, 467-482 (1973).

4. C. C. Chamis, "Design Properties of Randomly Reinforced Fiber Composites," NASA Technical Note D-6696 (1972).

5. V. Weiss and J. G. Sessler, ed., Aerospace Structural Metals Handbook. Volume 1: Ferrous Alloys, Code 1501, Syracuse Univ. Press (1963); revised.

6. C. W. McCormic, "NASTRAN User's Manual (Level 15)," NASA Special Publication 222 (01) (1972).

TABLE 1. MATERIAL DESIGNATION AND ORIENTATION

[Refer to fig. 4]

Material Designation	Description
1	Graphite T300/epoxy (random)
2	Blade material steel alloy 17-4-PH
3	Load bar S-glass/epoxy (unidirectional)
4	Keeper bar S-glass/epoxy (random)
5	Hoop windings graphite T300/epoxy (unidirectional)
6	Low stiffness material to represent possible gap

Material	Fiber Direction
1	Random r-z plane of lamination
2	Isotropic. Assume low hoop modulus and close to "0" Poisson's ratio values
3	Fiber direction parallel to z-axis. Low hoop properties and "0" Poisson's ratio values
4	Random θ-z plane
5	Fiber direction parallel to θ-direction
6	Low stiffness material to prevent load transfer from load bar and keeper to hub-core in the radial and hoop directions

TABLE 2. MATERIAL PROPERTIES AT ROOM TEMPERATURE

[Refer to fig. 4 for direction]

Property		Units	Material: T300/ep Random 1	Steel 2	S-G/ep Unidirectional 3	S-G/ep Random 4	S-G/ep Unidirectional 5
Elastic Modulus,	E_{rr}	10^6 lb/in^2	6.438	28.0	1.495	1.745	1.428
"	$E_{\theta\theta}$	"	1.874	28.0	1.495	3.205	16.17
"	E_{zz}	"	6.438	28.0	6.450	3.205	1.428
Poisson's Ratio,	$\nu_{r\theta}$	Ratio	.332	.3	.500	.332	.257
"	$\nu_{\theta z}$	"	.332	.3	.257	.276	.257
"	ν_{rz}	"	.302	.3	.257	.332	.542
Density,	ρ	lb/in^3	.0563	.282	.065	.065	.0563
Shear Modulus,	$G_{r\theta}$	10^6 lb/in^2	.463	10.77	.498	.249	.703
"	$G_{\theta z}$	"	.463	10.77	.690	1.256	.703
"	G_{rz}	"	2.472	10.77	.690	.249	.463
Thermal Coeff. of Exp.,	α_{rr}	10^{-6} in/in/^{o}F	2.745	6.0	16.0	20.02	26.06
"	$\alpha_{\theta\theta}$	"	37.90	6.0	16.0	6.55	.216
"	α_{zz}	"	2.745	6.0	3.932	6.55	26.06

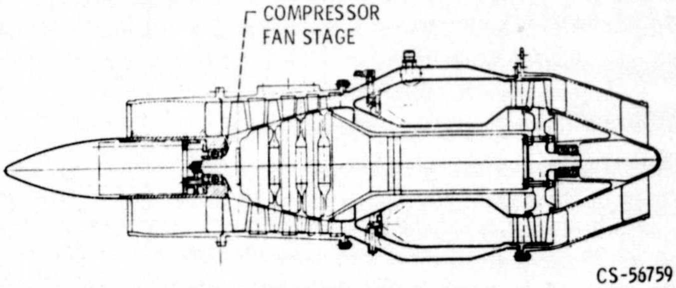

Figure 1. - Low cost engine schematic (650 lb. sea level static thrust ref. 1).

E-9038

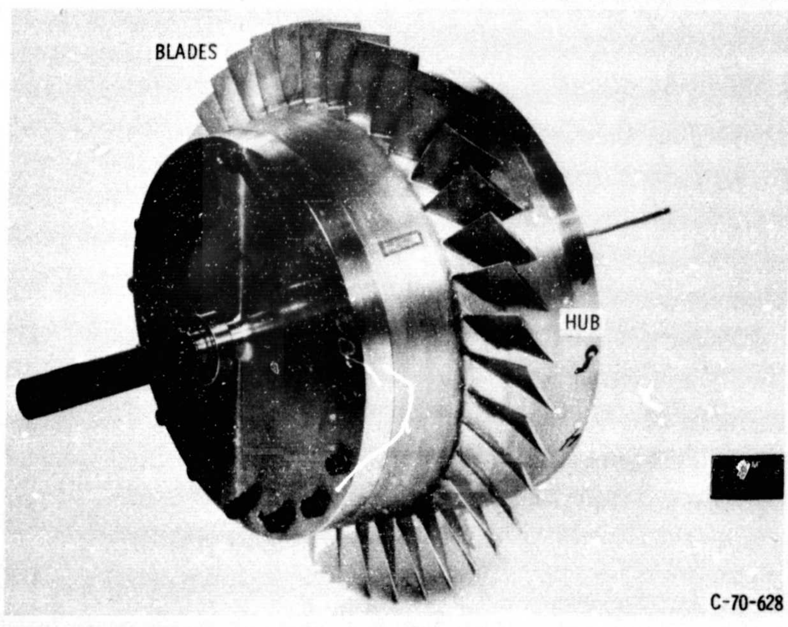

Figure 2. - Metal compressor rotor fan stage hub and blades (ref. 1).

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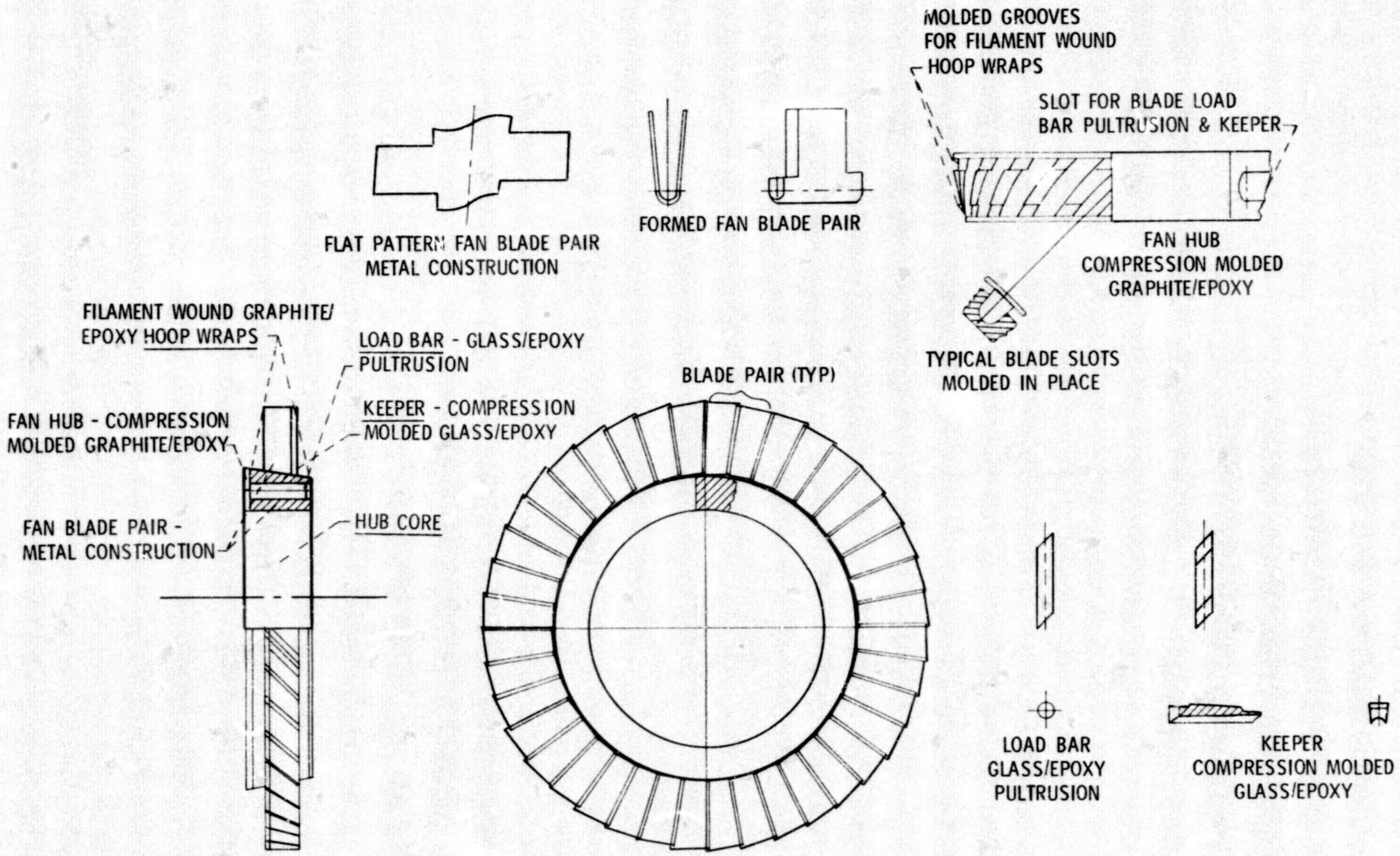

Figure 3. - Representative low cost jet engine compressor stage fan (full scale).

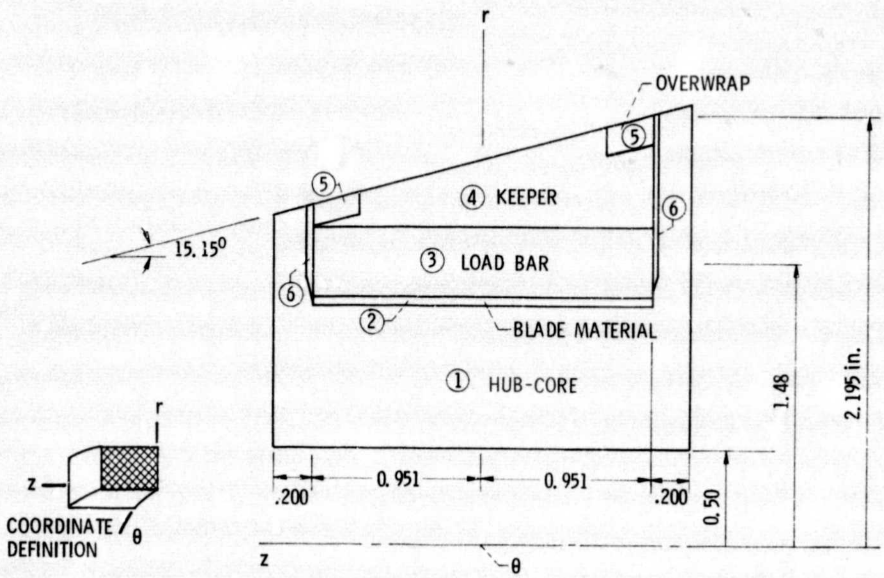

Figure 4. - Hub cross section, coordinates and material regions.

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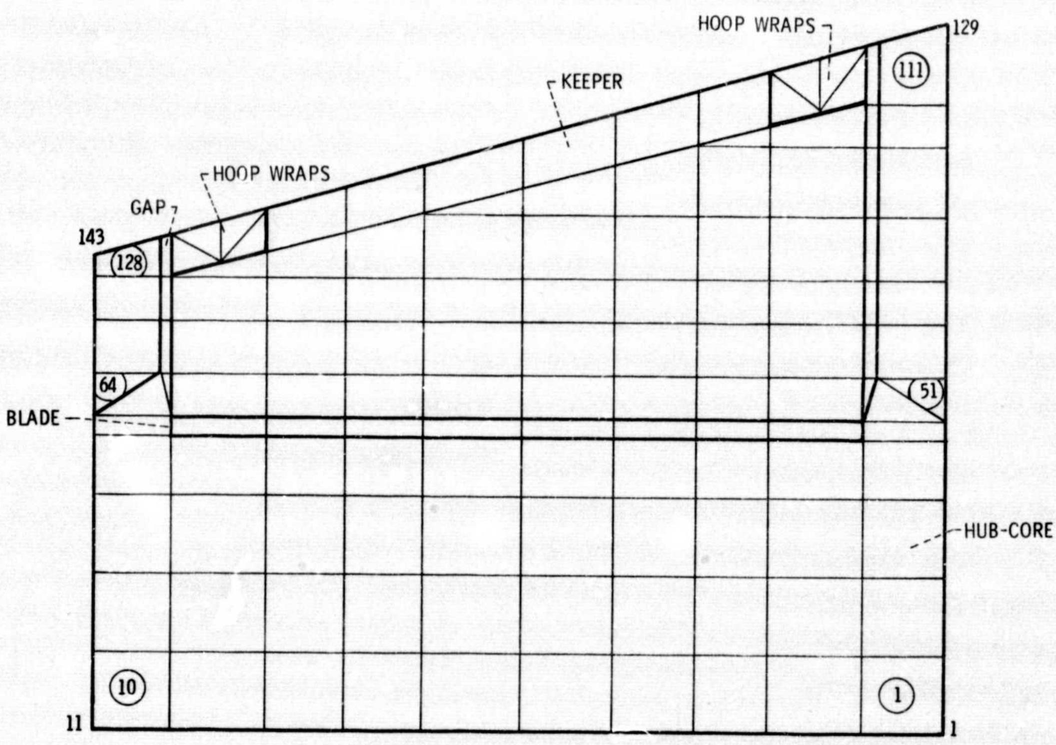

Figure 5. - Finite element model (143 nodes, 128 ring elements)

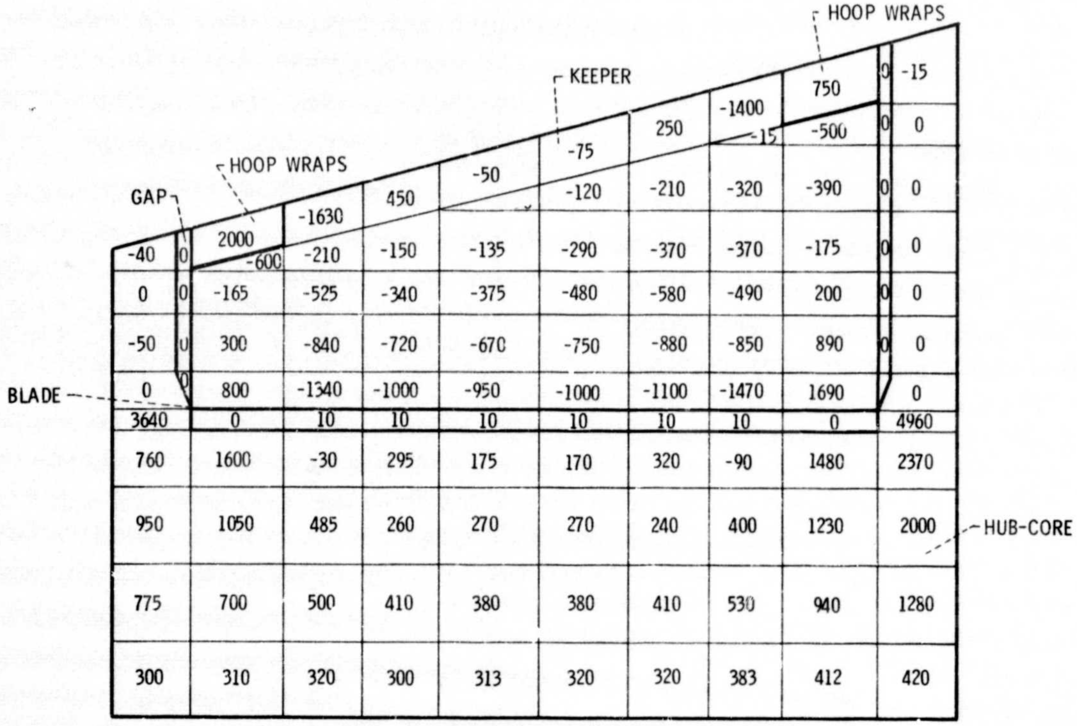

Figure 6. - NASTRAN predicted radial stress (psi).

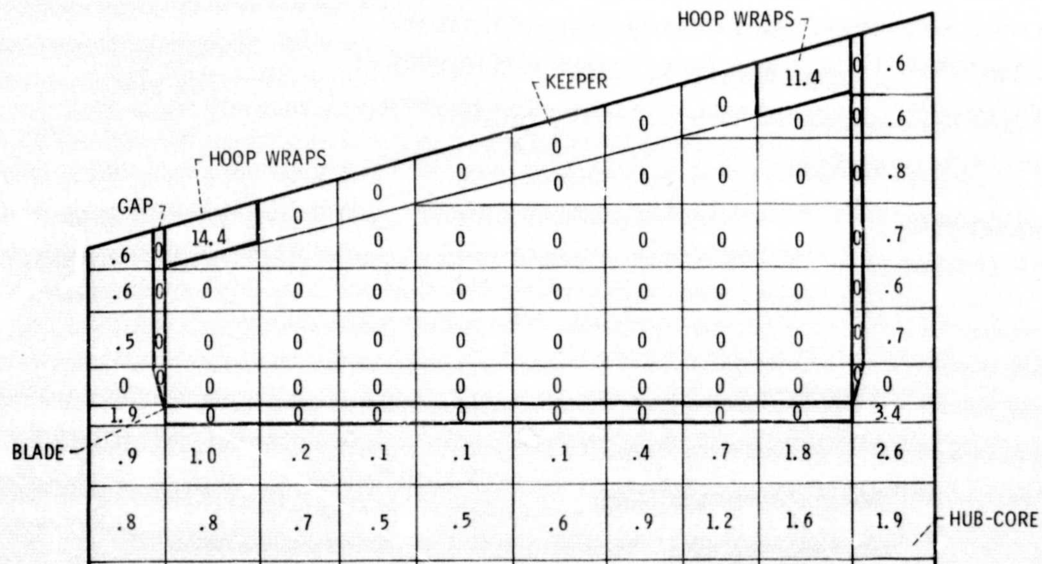

Figure 7. - NASTRAN predicted circumferential stress (ksi).

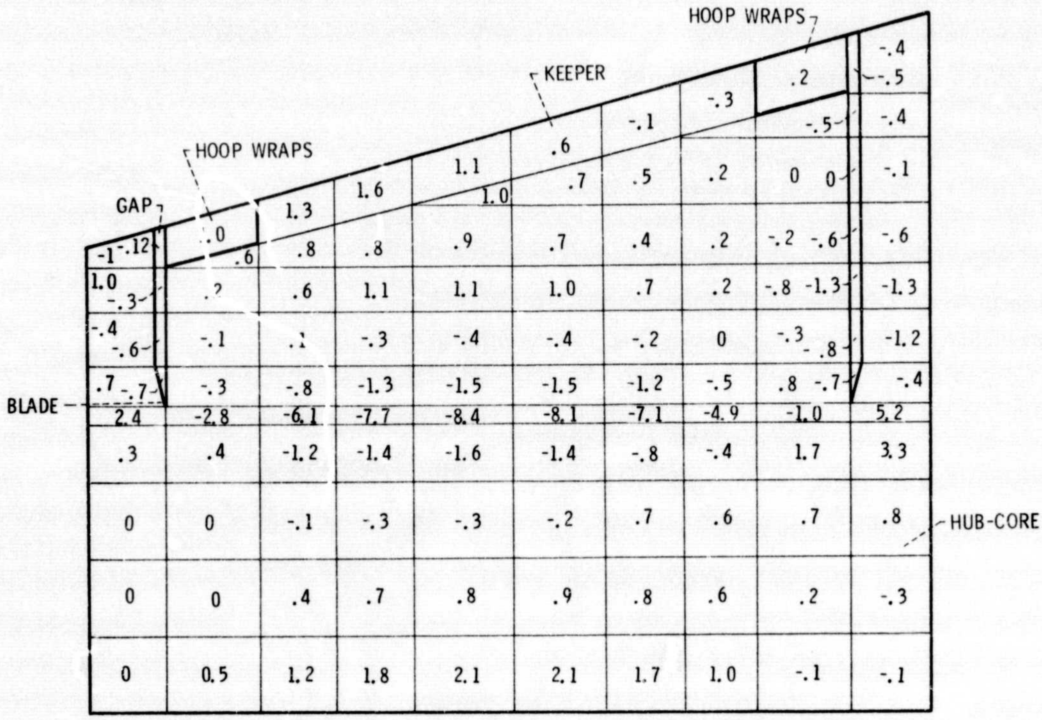

Figure 8. - NASTRAN predicted axial stress (ksi).

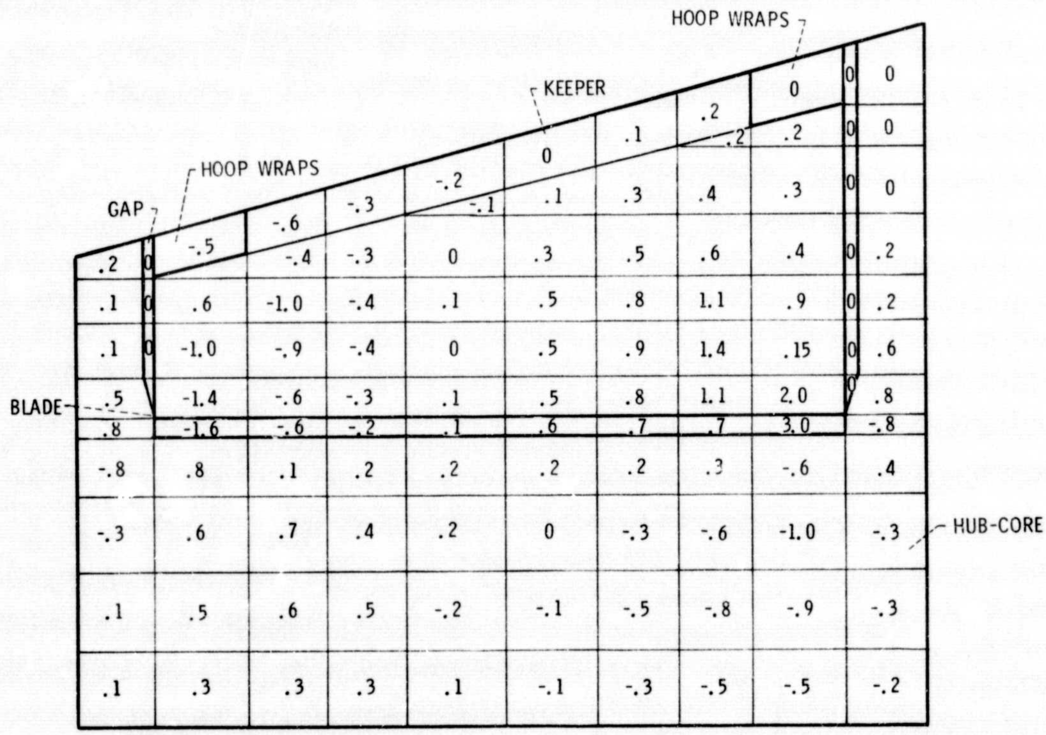

Figure 9. - NASTRAN predicted shear stress (ksi) (σ_{rz}, fig. 4).

E-9038

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