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STRESS ANALYSIS OF A FULLY INFLATED RIBLESS GUIDE SURFACE PARACHUTE

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UNIVERSITY OF MINNESOTA

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FOREWORD

This report was prepared by the Department of Aeronautics and Engineering Mechanics of the University of Minnesota in compliance with U. S. Air Force Contract No. AF 33(657)-11184, "Theoretical Deployable Aerodynamic Decelerator Investigations," Task 606503, "Parachute Aerodynamics and Structures," Project 6065, "Performance and Design of Deployable Aerodynamic Decelerators."

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AF Flight Dynamics Laboratory

ABSTRACT

A stress analysis of a fully inflated ribless guide surface parachute is presented. The method is an extension of an earlier publication, which is applicable to the transient state of inflation. However, in view of the normal use of ribless guide surface parachutes, the transient phase is considered to be less important since for the so-called infinite mass cases, the maximum force is considered to occur when full inflation is reached.

In general, this analysis can be applied to most canopies having non-triangular gore patterns. A numerical calculation is made for a 12-gore ribless guide surface parachute over a range of pressure loadings, canopy sizes, and cloth types representing practical application.

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SYMBOLS

a	a length (see Fig 10)
b	a length (see Fig 10)
b_o	a length (see Fig 2)
C_p	pressure coefficient
d_o	a length (see Figs 4 and 5)
D	diameter
D_c	constructed diameter
D_v	vent diameter
E	cloth modulus of elasticity (lb/ft)
f_1	circumferential stress (lb/ft; see Fig 3)
f_2	meridional stress (lb/ft; see Fig 3)
N	number of gores
Plane Q	(illustrated in Fig 2)
ΔP	pressure differential across cloth (see Figs 4 and 5)
q	dynamic pressure $\equiv \frac{1}{2}\rho V^2$
r_b	bulge radius (see Figs 4 and 5)
s	a length (see Fig 2)
x	a length (see Fig 9)
y	a length (see Fig 1)
y'	a length (see Fig 6)
z	a length (see Fig 9)
α	gore half angle (see Figs 4 and 5)
ϵ	strain
ϕ	an angle (see Fig 2)
θ	suspension line angle (see Fig 2)

SYMBOLS (CONT.)

Superscripts

*	quantities made dimensionless by D_c

Subscripts

c	referred to cord line
g	referred to gore centerline
o	initial or unstretched condition
∞	free stream conditions

I. INTRODUCTION

A method for calculating the cloth stresses in a ribless guide surface parachute during steady state is presented. In general, the approach is similar to the one of Refs 1 and 2, which analyzes the stresses in a parachute constructed of triangular gores. In the following the method is extended to encompass the stresses in canopies with irregular gore patterns such as ribless guide surface parachutes.

The presented method is based upon the known gore centerline or the cord-line profile and the gore pattern of the canopy. With this information established, the span between the suspension lines and the bulge radius of the gore can be calculated. If the bulge radius is known, the stresses in the cloth merely depend upon the differential pressure.

For the steady state, or fully inflated condition, the characteristic profiles and the pressure distribution are well known, and therefore, it appears that the stress distribution for a ribless guide surface parachute can be determined quite accurately.

Furthermore, the period of inflation for guide surface parachutes under infinite mass conditions is usually very short, and the magnitude of pressure during inflation remains about the same. In addition, the bulge radii of the gores are probably largest when fully inflated. Therefore, in view of these two reasons, the stresses in the canopy cloth are probably highest when full inflation is first achieved, and the following analysis is carried out for this case.

II. THE CANOPY GEOMETRY

The orientation of the individual gore and the related geometric terms are shown in Figs 1 through 3. With the following simplifying assumptions, one can then establish the geometry and thus the stresses occurring in an elementary gore section.

1. The pressure distribution over the canopy varies in the meridional direction but is constant circumferentially.

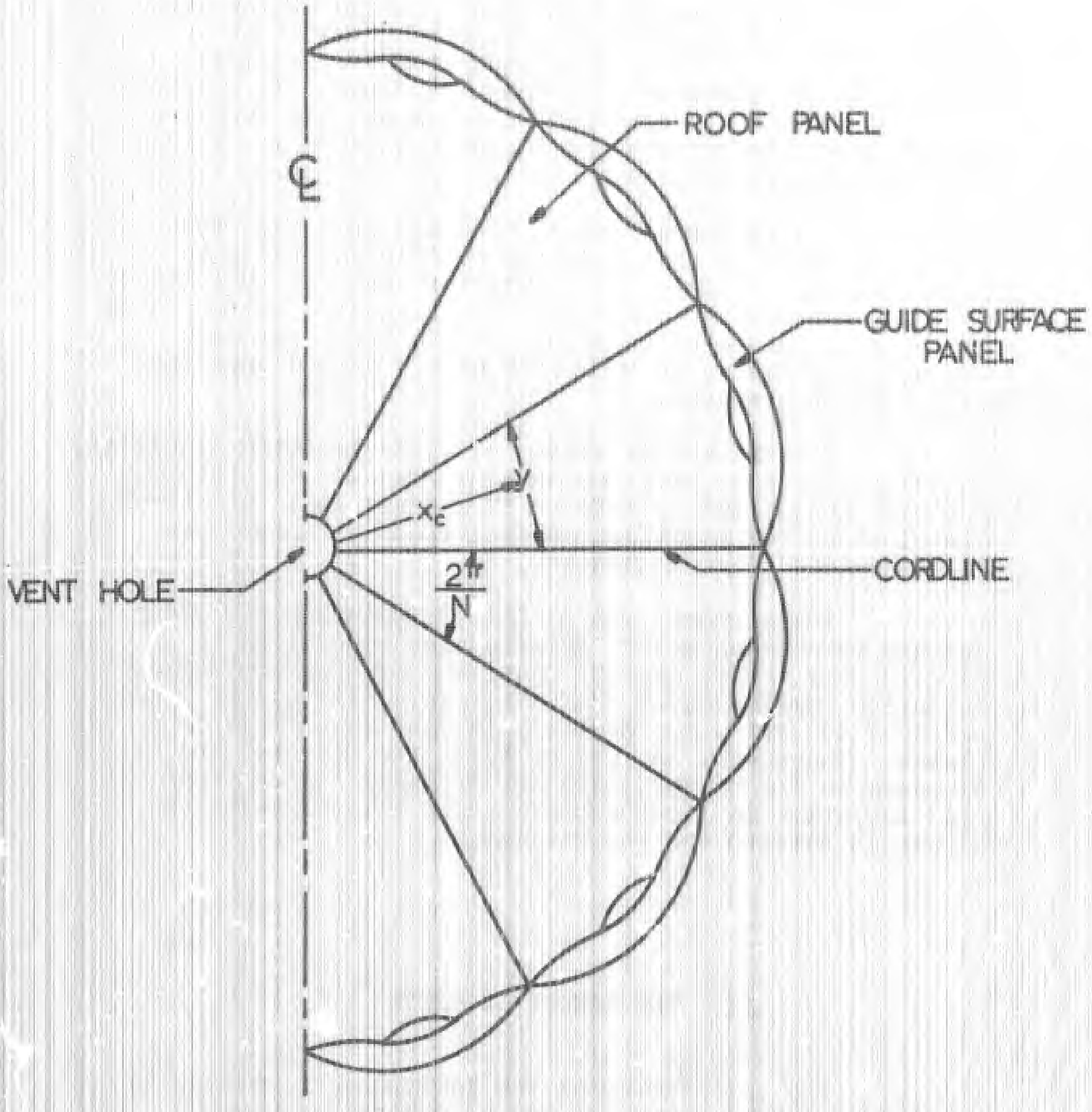


Fig 1 Top View of Inflated Ribless Guide Surface Canopy

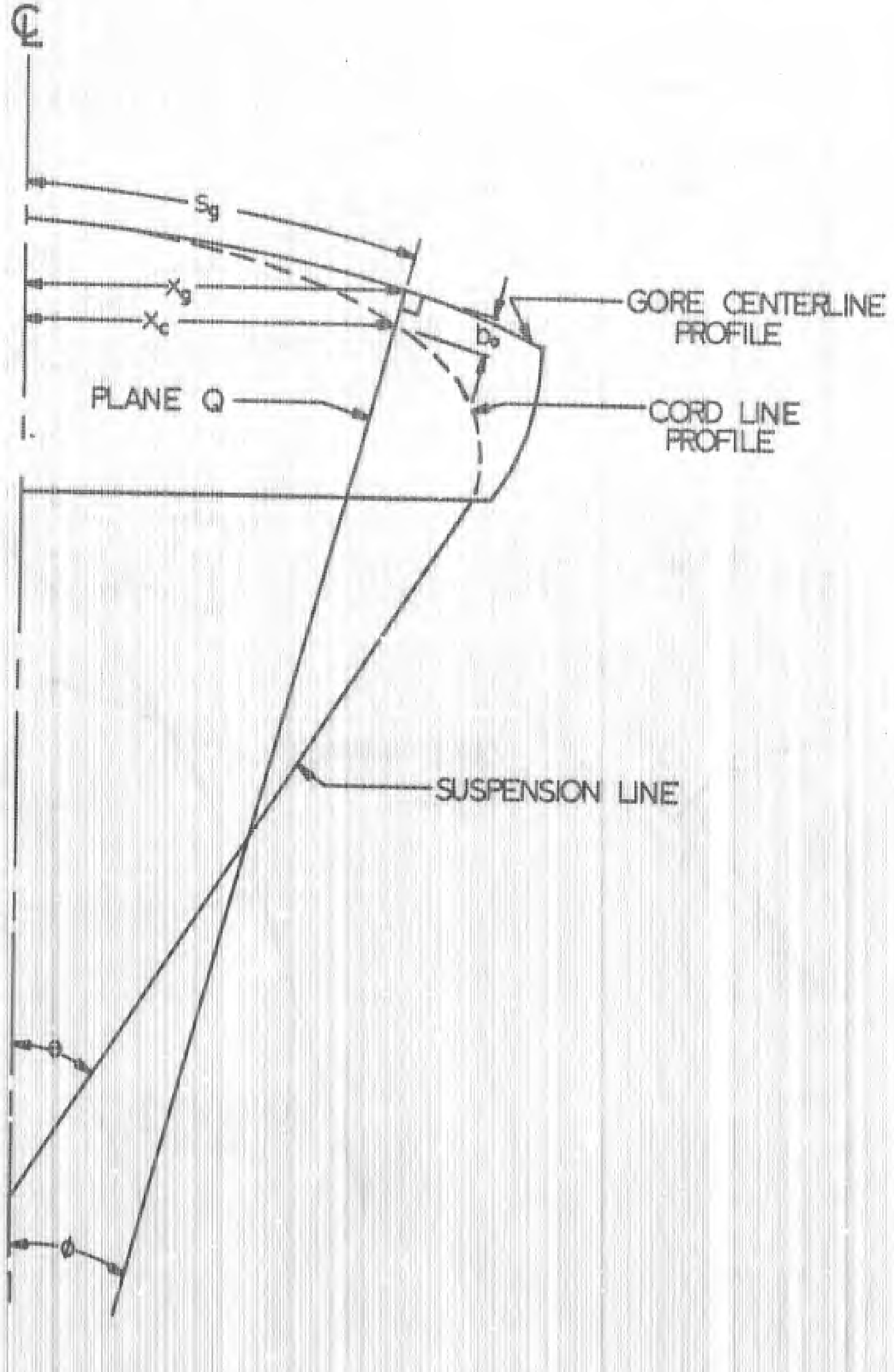


Fig 2 Profile View of an Inflated Ribless Guide Surface Canopy

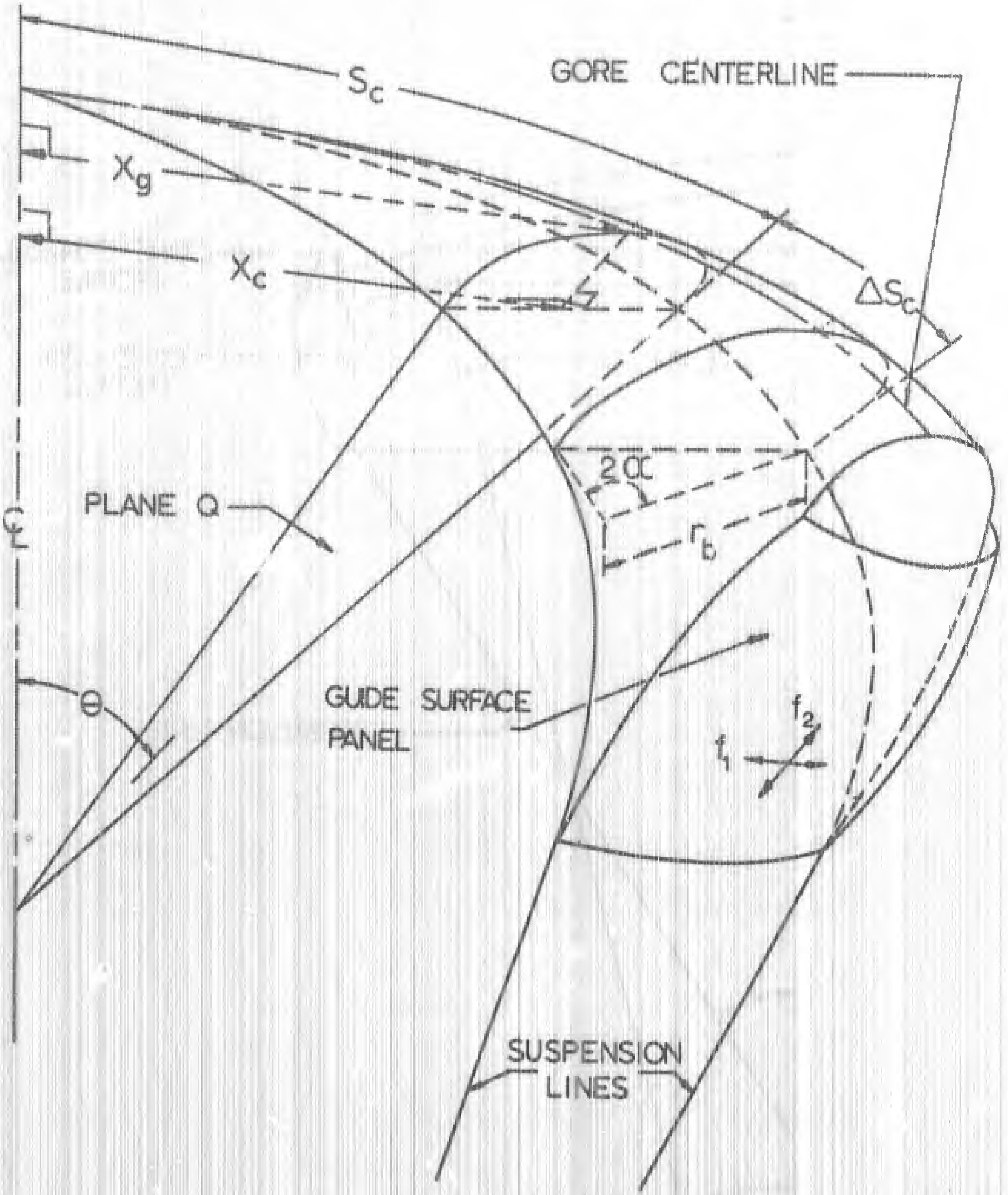


Fig. 3 Orientation of a Gore Element

2. The stresses, f_2 (Fig 3), occurring in the meridional direction are considered small compared with the resultant stress in the circumferential direction, f_1.

3. The cross-sectional shape in a plane Q (Fig 2) of any gore element is a circular arc because of uniform pressure distribution over the element. This arc cannot exceed a semicircle. In case of excess cloth the cross section of the gore element becomes merely a semicircle with parallel extensions to the cord.

4. Determining the canopy geometry, the cloth and cords are first considered to be inextensible. However, once the basic geometry is established, this assumption is dropped and the elasticity of the cloth is introducad into the equations.

In view of these basic assumptions, Figs 4 and 5 show the geometry and the force loading of a typical gore element for the case of $\alpha < 90°$ and $\alpha = 90°$ respectively.

In the following treatment, it is assumed that the gore centerline profile is known, either from photographs or other methods. This profile, combined with the gore pattern, determines the cord-line profile. This is just one approach, for one could certainly use the same method if the cord profile were given.

It is convenient to calculate first the length b_o^* as shown in Fig 2 in terms of known quantities. Then the cord-line profile can be determined by measuring b_o^* inward from the gore centerline. Combining simple geometric relationships illustrated in Figs 1 through 3, as done in Refs 1 and 2, an expression for b_o^* for the two cases represented in Figs 4 and 5 can be derived,

$$b_o^* = \frac{\sqrt{6}}{4} \left[\frac{d_o^{*2}}{4} + \frac{1}{2}\tan\frac{\pi}{N}\, d_o^*\, x_c^* - \tan^2\frac{\pi}{N}\, x_c^{*2} - 2\tan^3\frac{\pi}{N}\,\frac{x_c^{*3}}{d_o^*}\right]^{\frac{1}{2}} \qquad (1)$$

and

$$b_o^* = \frac{d_o^*}{2} + \left(1 - \frac{\pi}{2}\right) \tan\frac{\pi}{N}\, x_c^* \quad . \qquad (2)$$

Equations 1 and 2 are then to be used for the case $\alpha < 90°$ and $\alpha = 90°$, respectively.

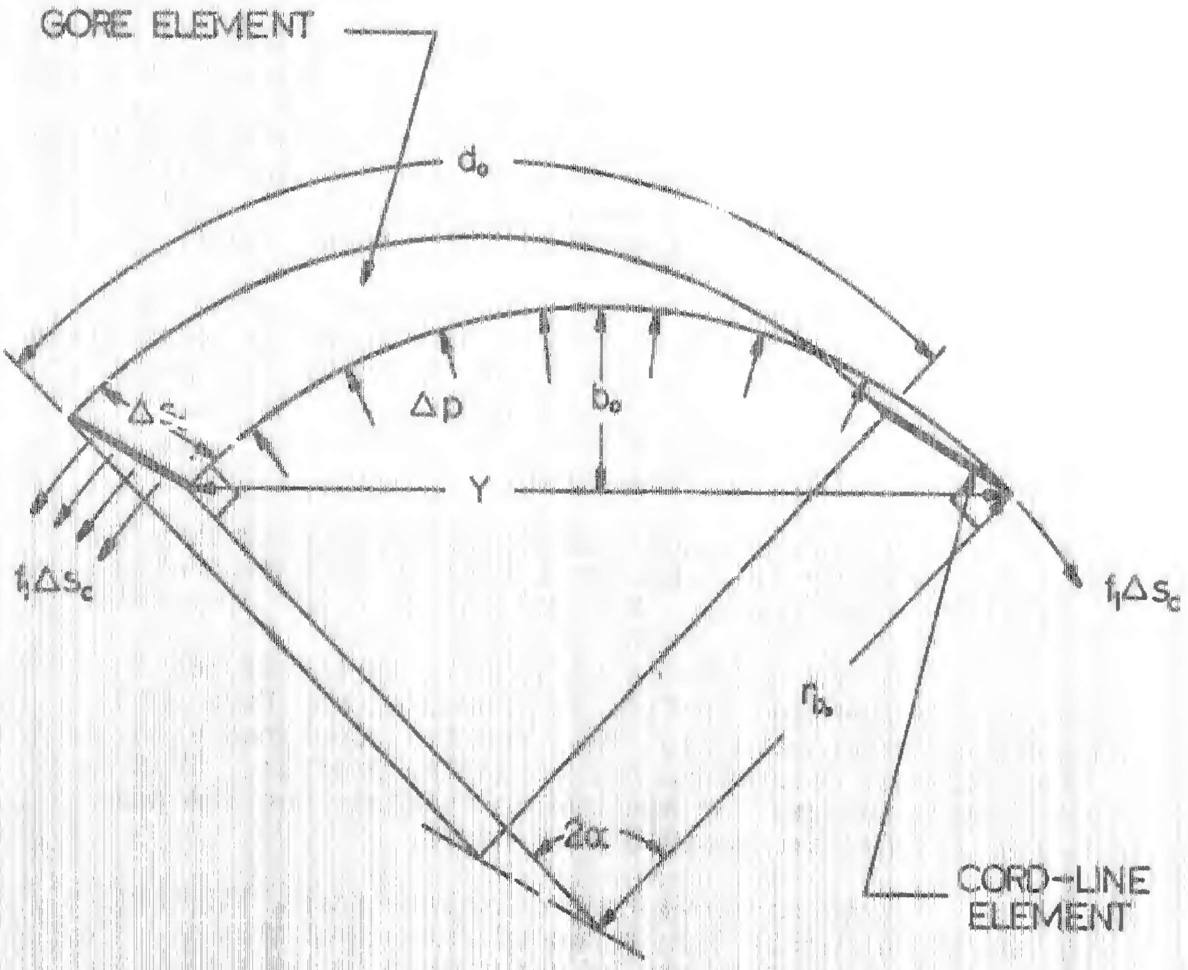


Fig 4 Typical Gore Element For the Case $\alpha < 90°$ Showing the Applied Forces

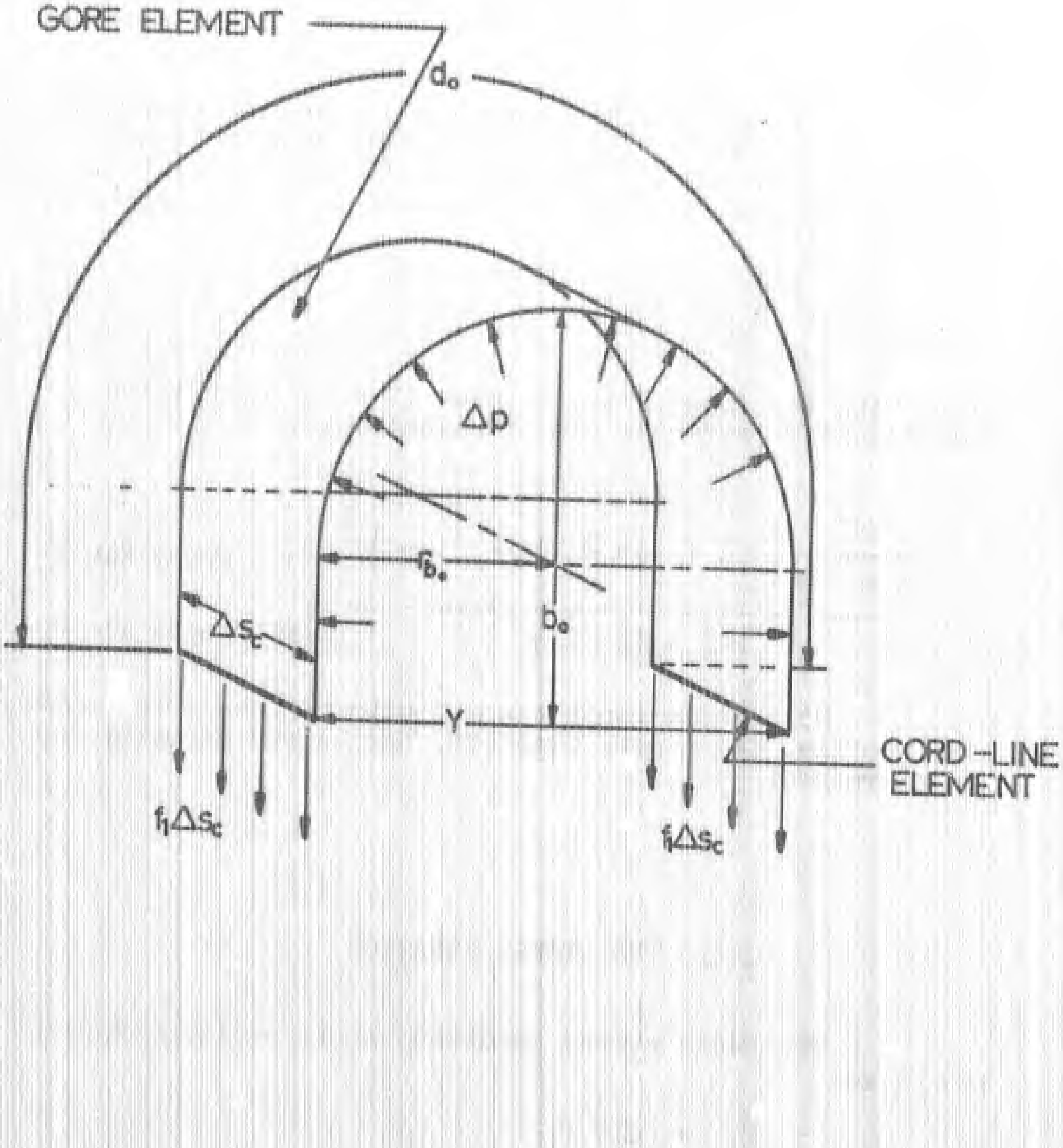


Fig 5 Typical Gore Element For the Case $\alpha=90°$ Showing the Applied Forces

These two equations contain the unknown term x_c^* which in view of Fig 2 can be expressed as

$$x_c^* = x_g^* - h_o^* \sin \phi \tag{3}$$

In many cases where the gore planform angle $\frac{2\pi}{N}$ is small enough x_c^* can be replaced by x_g^*. However, if better accuracy is necessary an iteration process using Eqns 1, 2, and 3 can be applied until the appropriate equations have been satisfied.

Before the cord-line profile can be determined, one must determine if Eqn 1 or 2 should be used for b_o^*. For this purpose the following criteria shall be established. From Fig 5 it can be seen that the arc forms a complete semicircle if

$$d_o^* \geq \frac{\pi}{2} y^* \tag{4}$$

Expressing the inequality in terms of known quantities, the following criterion can be established:

$$\left. \frac{\dfrac{2d_o^*}{\pi \tan \frac{\pi}{N}} \left[1 + \tan \frac{\pi}{N} \sin \phi \; (1 - \frac{\pi}{2}) \right]}{2x_g^* - d_o^* \sin \phi} \right| \begin{array}{l} < 1 \text{ apply Eqn 1} \\ \geq 1 \text{ apply Eqn 2} \end{array} \tag{5}$$

With these equations and with a given gore center-line profile, and a gore planform, the canopy geometry can be determined.

III. THE STRESS EQUATION

The basic stress equation can be written (Refs 1 and 2) as:

$$f_1 = \Delta P \, r_b \tag{6}$$

If perfect elasticity is assumed and if the stress is constant over any gore element, then with the geometry from Chapter II, and the algebraic method shown in Ref 1, the equation for cloth stresses for $\alpha < 90°$ is:

$$f_1^3 + \left[\frac{24E^3(d_o^* - y^*) - 3E\Delta P^2 d_o^{*3} D_c^2}{24E^2 d_o^* - \Delta P^2 d_o^{*3} D_c^2}\right] f_1^2 - \left[\frac{3E^2 \Delta P^2 d_o^{*3} D_c^2}{24E^2 d_o^* - \Delta P^2 d_o^{*3} D_c^2}\right] f_1$$

$$- \left[\frac{E^3 \Delta P^2 d_o^{*3} D_c^2}{24E^2 d_o^* - \Delta P^2 d_o^{*3} D_c^2}\right] = 0 \quad . \tag{7}$$

For the case where the gore forms an arc of a semicircle with parallel extensions as illustrated in Fig 5, the geometry and the stresses can be presented in simpler expressions and the stress equation merely becomes

$$f_1 = \tfrac{1}{2} \Delta P \, y^* D_c . \tag{8}$$

In the stress equations, Eqns 7 and 8, the pressure differential term ΔP must be established. Generally the pressure pressure distribution is determined experimentally and is given in the form of the pressure coefficient, C_p, which is is defined as

$$C_p = \frac{P_{local} - P_\infty}{q_\infty} \tag{9}$$

Introducing Eqn 9 into Eqns 7 and 8 provides after algebraic manipulation:

$$\varepsilon^3 + \left[\frac{24(1 - \frac{y^*}{d_o^*}) - 3C_p^2 \left(\frac{qD_c}{E}\right)^2 d_o^{*2}}{24 - C_p^2\left(\frac{qD_c}{E}\right)^2 d_o^{*2}}\right] \varepsilon^2$$

$$- \left[\frac{3C_p^2 \left(\frac{qD_c}{E}\right)^2 d_o^*}{24 - C_p^2\left(\frac{qD_c}{E}\right)^2 d_o^{*2}}\right] \varepsilon - \left[\frac{C_p^2 \left(\frac{qD_c}{E}\right)^2 d_o^{*2}}{24 - C_p^2\left(\frac{qD_c}{E}\right)^2 d_o^{*2}}\right] = 0 \tag{10}$$

$$\varepsilon = \tfrac{1}{2} C_p \left(\frac{qD_c}{E}\right) y^* . \tag{11}$$

In these equations the strain, ε, has been introduced through the equation

$$f_1 = \varepsilon E . \tag{12}$$

With the established geometry and with the average elasticity of the cloth obtained from static stress-strain measurements, Eqns 10 and 11, together with the criterion established in Eqn 5, can be used to calculate the cloth stresses. A more detailed presentation of the steps that should be followed in this calculation is given in Refs 1 and 2.

IV. NUMERICAL EXAMPLE

In order to exemplify how the method in the preceding sections is applied, the stress distribution in a 12-gore ribless guide surface parachute is calculated. The specifications of this particular parachute are given below:

Number of gores, N = 12

Constructed diameter, D_c = 1.08 ft

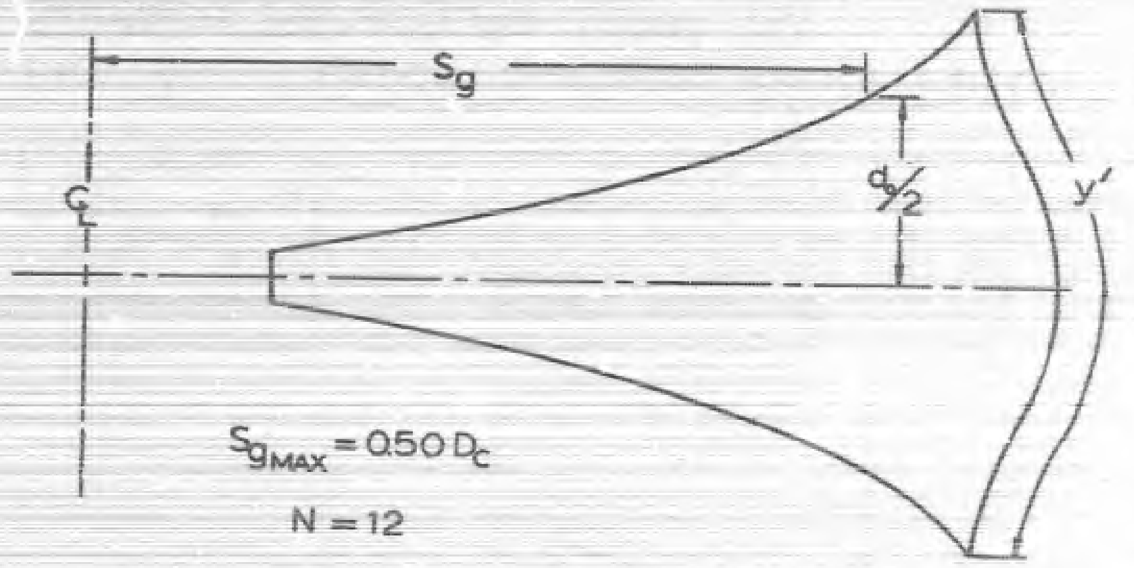
Canopy material = 1.1 oz nylon, MIL-C-7020B

Vent diameter, D_v/D_c = 0.10.

The gore patterns and the associated dimensions for the roof panel and the guide surface panel are shown in Figs 6 and 7 (Ref 3). From wind tunnel experiments the inflated profile of the canopy was determined as shown in Fig 8. From Fig 8 the dimensionless gore centerline profile for the roof panel and the guide surface panel was found and is shown in Figs 9 and 10.

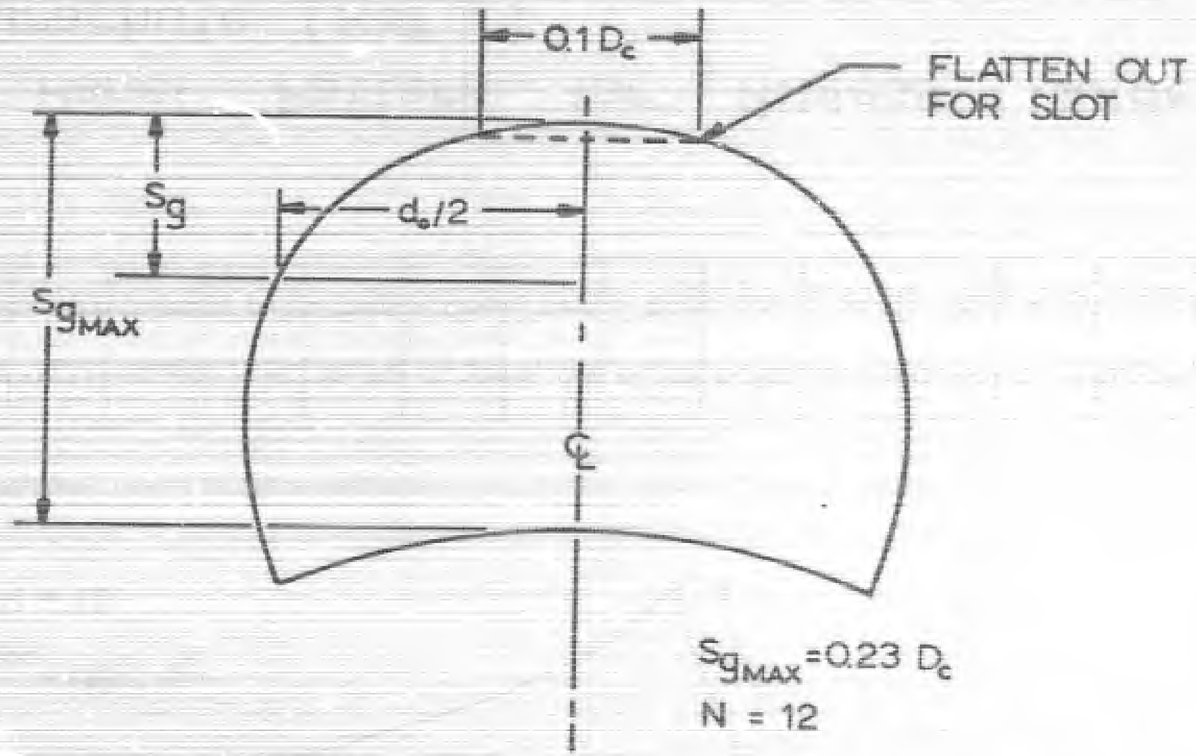
Using the equations developed in Chapter 2, the cord-line profile for the roof panel was determined and is shown in Fig 9.

The cord profile for the guide surface panel cannot be determined in the conventional manner. The span of the gore element for the guide surface panel can not be represented as the distance between adjacent cordlines. Rather, the span now becomes the distance between the seam joining the roof and guide surface panels. Thus, an end view of the guide surface panel is necessary to calculate the span. This view and the calculated cord line for the guide surface panel are shown in Figs 9 and 10.



$S_g/S_{g_{MAX}}$	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.875	0.90	0.95	0.975	1.0
$d_e/S_{g_{MAX}}$	0.788	0.788	0.788	0.814	0.820	0.832	0.856	0.882	0.990	1.352	1.054	0.522	0.325	0.0

Fig. 6 Roof Panel Pattern for Ribless Guide Surface Parachute (Ref 3)



$S_g/S_{g_{MAX}}$	0.05	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.93	0.95	1.00
$d_e/S_{g_{MAX}}$	8.66	6.42	5.16	4.26	3.16	2.50	2.06	1.72	1.444	1.22	1.030	0.00 0.982	0.452 0.944	.860

Fig 7 Guide Surface Panel Pattern for Ribless Guide Surface Parachute (Ref 3)

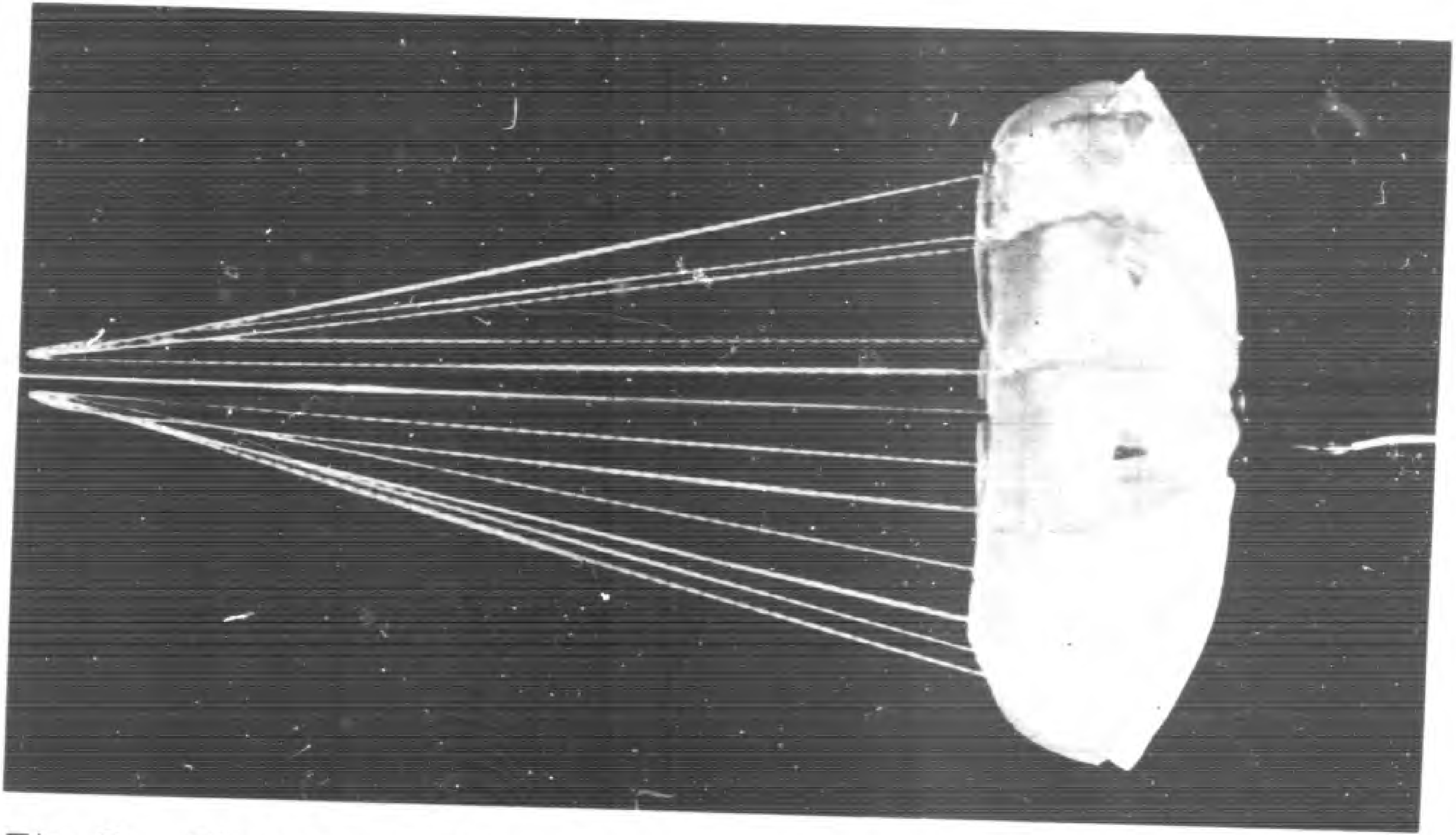


Fig. 8. Ribless Guide Surface Parachute in Wind Tunnel (D_C =13 in., N=12)

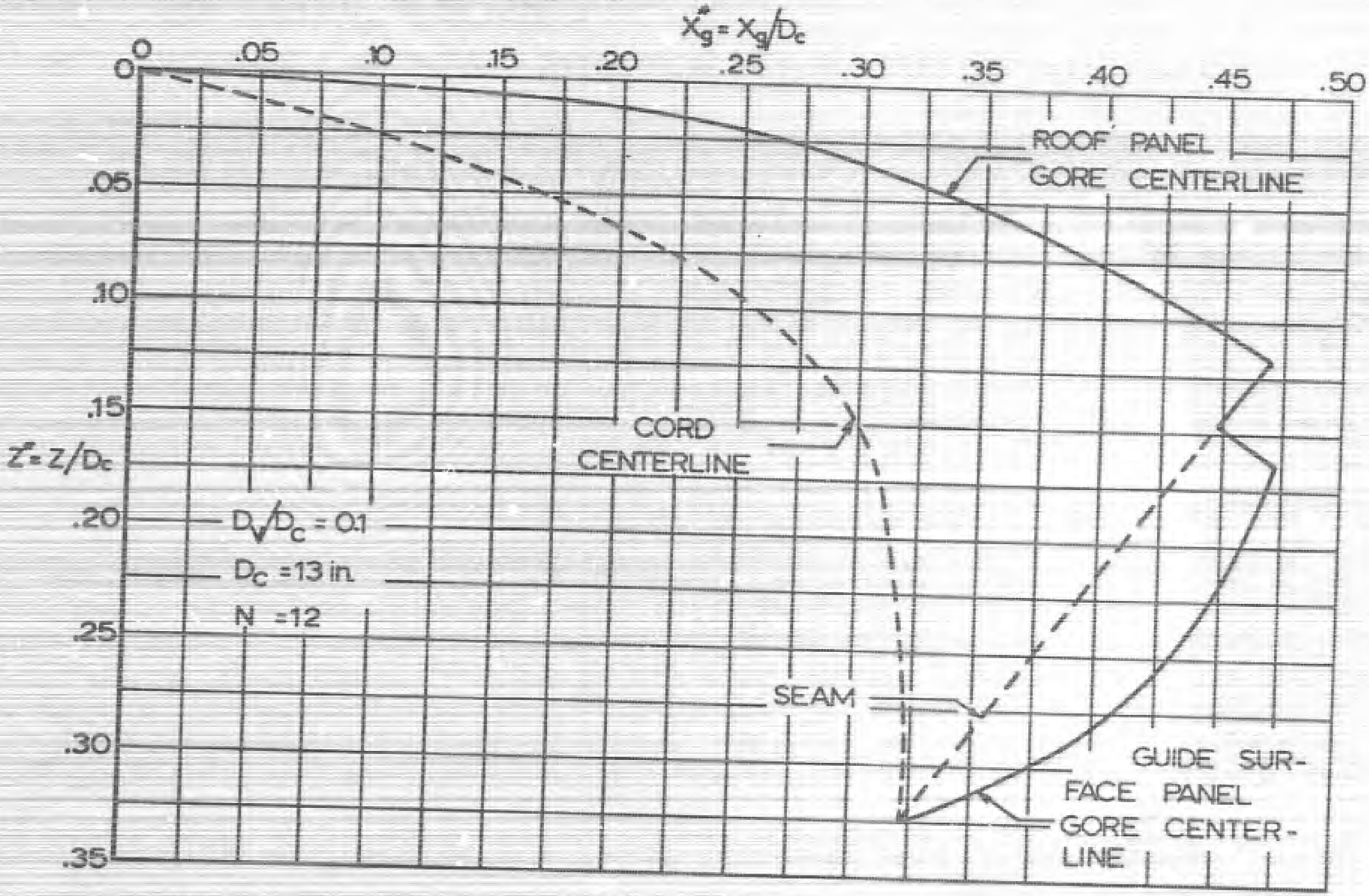


Fig 9 Profile Shape of the Ribless Guide Surface Parachute

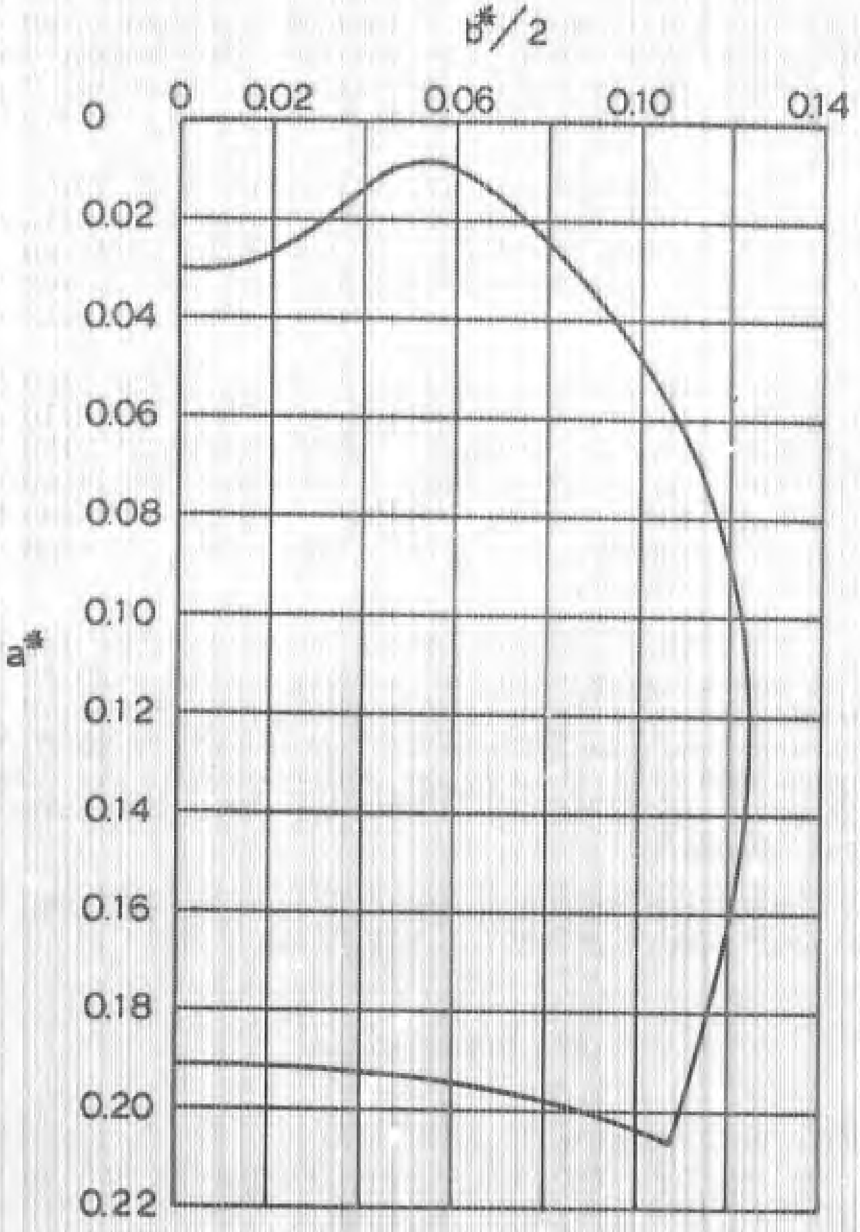


Fig 10 End View of Inflated Guide Surface Panel for Ribless Guide Surface Parachute

The pressure coefficient, C_p, over the canopy was measured, Ref 4, and the values were plotted versus the gore centerline length for the two gore panels in Fig 11. These values have been extracted from Ref 4 and were measured at a free stream Mach number $M_\infty = 0.61$.

In an attempt to make the results of this calculation applicable for various size parachutes built of different cloths and for different pressure loadings, values for the parameter qD_c/E ranging from 0.01 to 5.0 were selected. These values represent a wide range of application.

In applying the results of the stress calculation in this manner, it must be assumed that the dimensionless inflated shape and the pressure coefficient distribution over the canopy remains the same regardless of canopy material, size and pressure loading. In view of known experimental evidence, as a first approximation these assumptions are valid.

To better understand the dimensionless parameter qD_c/E, it can be seen that for a canopy with a 20 ft constructed diameter, a free stream dynamic pressure of 10 psf, which at sea level conditions is approximately 90 ft/sec and constructed of 1.1 oz nylon, MIL-C-7020B, the dimensionless parameter qD_c/E is 0.1. This is about the lowest practical boundary.

With the cord-line profile determined, the span for the roof panel was calculated from

$$y^* = 2x_c^* \tan \frac{\pi}{N} . \tag{13}$$

Since this relationship is not valid for the guide surface panel, the related span was determined photographically from Fig 10. With the geometry and pressure distribution established, Eqns 10 or 11, whichever is applicable, were applied to calculate the strain. The results of this calculation are shown in Figs 12 and 13 for the roof and guide surface panels, respectively.

With the assumption of perfect elasticity the stress is merely a multiple of the strain. Thus, the representation of the strain is characteristic of the stress as well.

With the strain calculated, it is now possible to review the strain magnitude and distribution for the two panels. In this manner several interesting observations are apparent. First, for both the roof and guide surface panels the strain increases as one approaches the skirt region. Second, the magnitude of the strain at the end

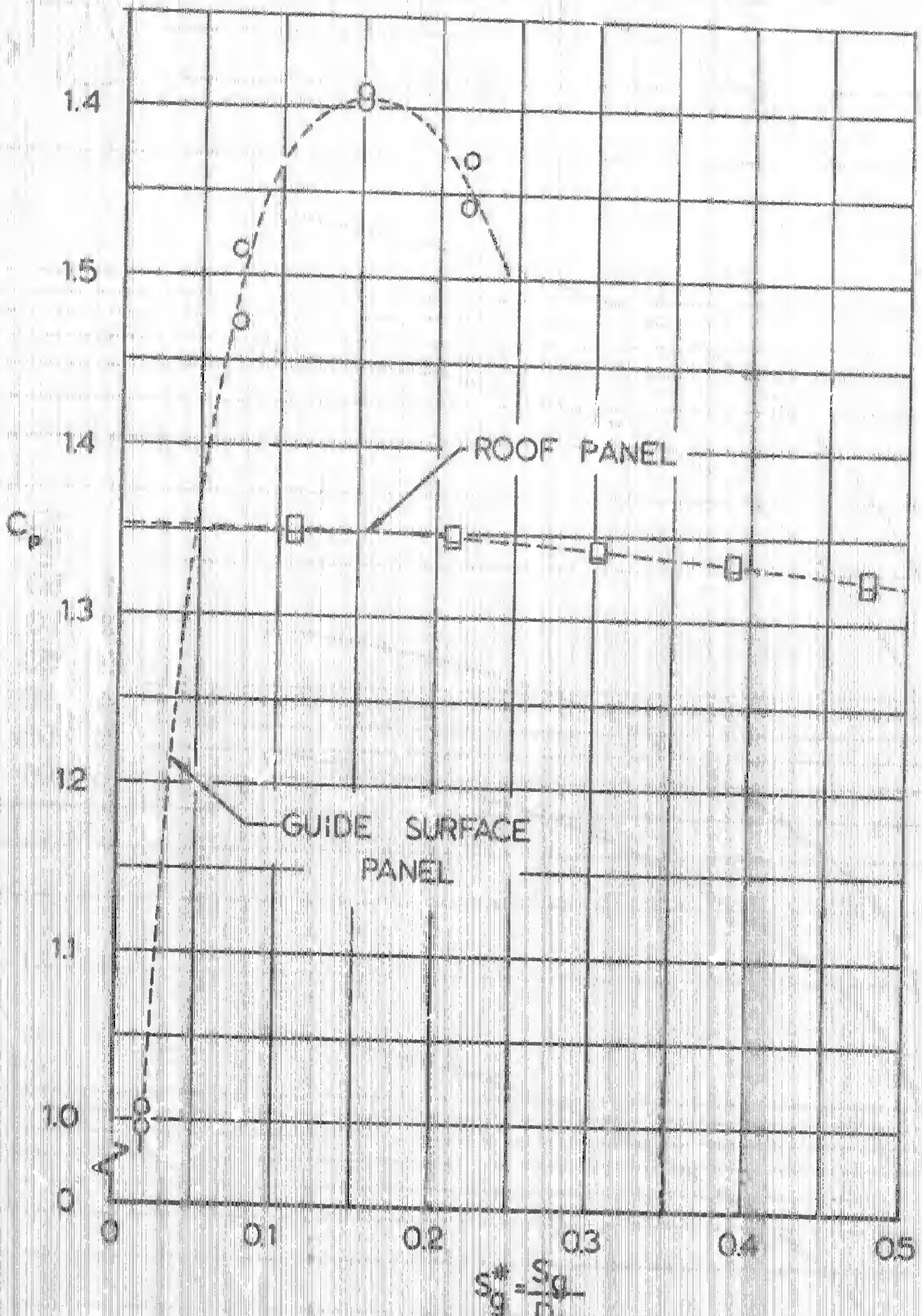


Fig. 11 Pressure Coefficient vs. Canopy Location for a Ribless Guide Surface Parachute (Ref 4)

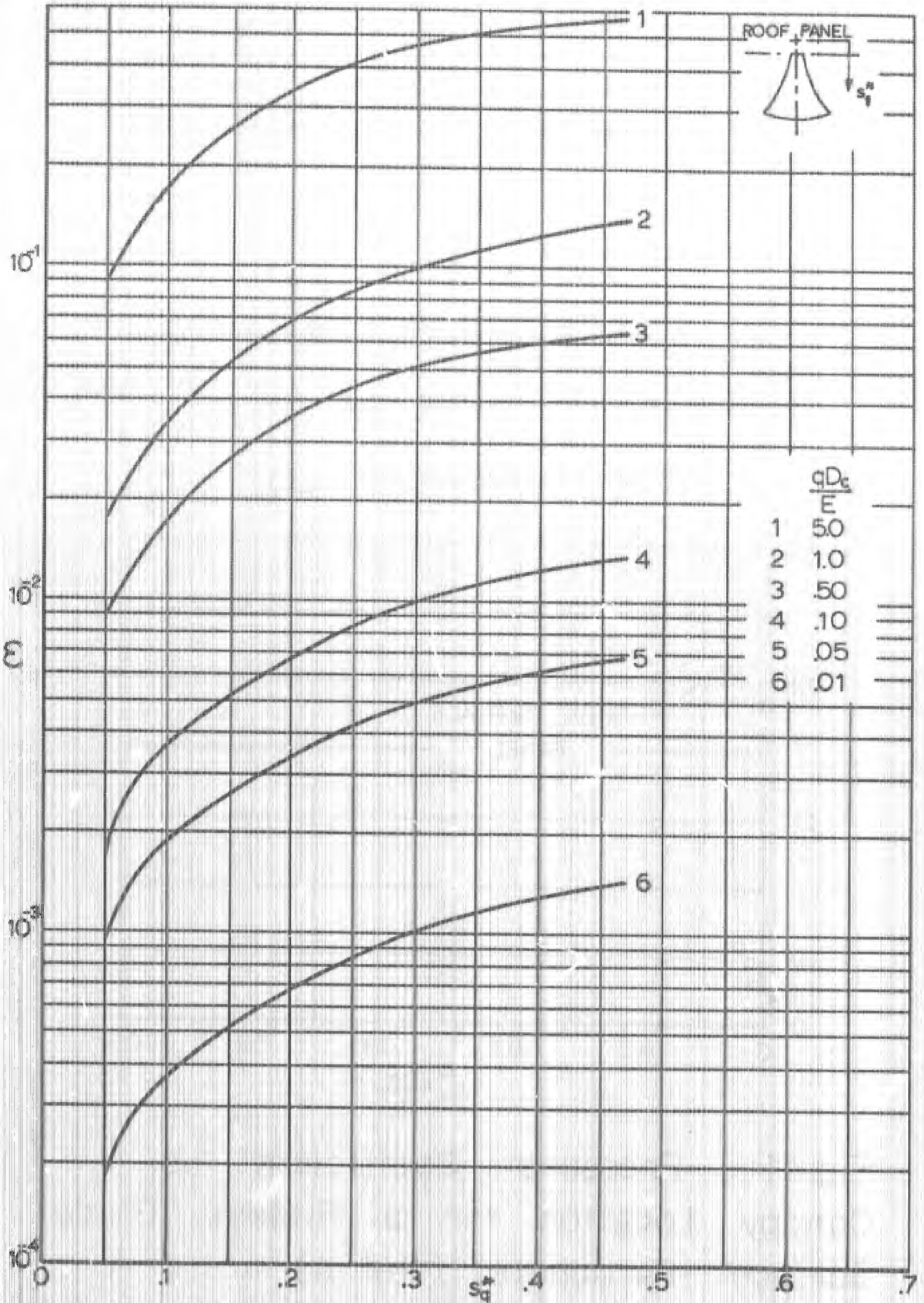


Fig 12 Strain Versus Canopy Location for the Roof Panel (N=12)

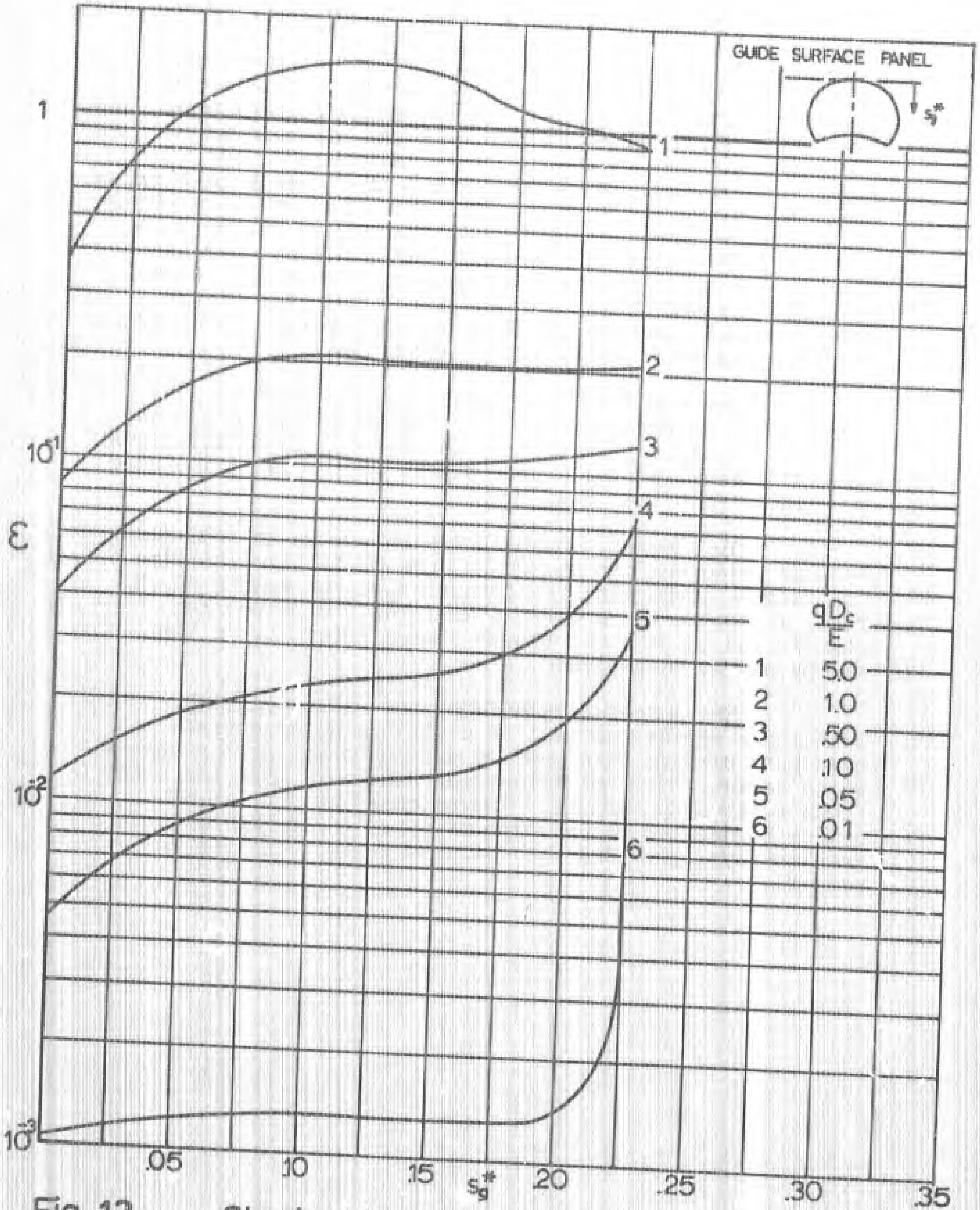


Fig 13 Strain Versus Canopy Location for the Guide Surface Panel (N=12)

and the beginning of the roof and guide surface panels, respectively, is approximately the same. This indicates a continuous strain distribution over the entire canopy. Third, for any given value of the dimensionless parameter qD_c/E, the strain is highest in the guide surface panel. Thus, as a first approximation only the stresses in the guide surface panel may need to be calculated. For if the strain in this region of the canopy is below failure, then the strain level in the roof panel is certainly within safety limitations. In addition, the strain in the guide surface panel should be correspondingly higher, for the roof gore pattern has been designed to produce at least a semicircle and in many regions it forms a semicircle with parallel extensions. This design concept was verified in the independent calculations shown above.

The guide surface panel does not achieve this condition of minimum stress, for its shape has been determined by aerodynamic reasons. In view of the calculations, the guide surface panels have at all locations an included gore angle much less than 90°.

In summary, to apply these results to a 12-gore ribless guide surface parachute, one need only determine the failure strain and the dimensionless parameter qD_c/E. Then, selecting the proper values from the respective Figs 12 and 13, the structural design integrity of the canopy can be established.

The proposed method has been illustrated by means of a stress analysis of a ribless guide surface parachute because this type of parachute has gore patterns which deviate from the triangular form more than any other known subsonic parachute. The proposed method can of course be applied to any type of gore, including the triangular form, provided the characteristic terms are inserted.

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13. ABSTRACT

A stress analysis of a fully inflated ribless guide surface parachute is presented. The method is an extension of an earlier publication, which is applicable to the transient state of inflation. However, in view of the normal use of ribless guide surface parachutes, the transient phase is considered to be less important since for the so-called infinite mass cases, the maximum force is considered to occur when full inflation is reached.

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