TRANSFER OF STRESS FROM MAIN BEAMS TO INTERMEDIATE STIFFENERS IN METAL SHEET COVERED BOX BEAMS

Thesis by

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I. ACKNOWLEDGMENTS:

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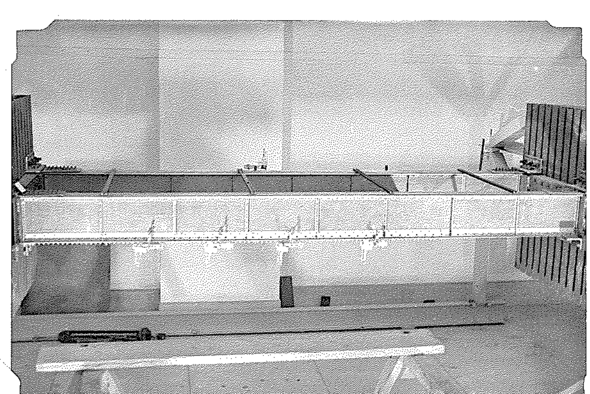
II. SUMMARY:

The authors have obtained by experimental methods an effective shear modulus for the sheet in a stiffened plane sheet beam combination under bending loads. For the combinations tested it was found that the modulus decreases rapidly under light loadings from the elastic value to some asymptotic value depending upon the sheet thickness. The thick sheet combination gave higher values of the effective shear modulus than the thin sheet.

III. INTRODUCTION:

As a part of the investigation of the stress distribution in metal covered wings leading to the most efficient distribution of materials, experiments are being made in the Guggenheim Aeronautics Laboratory with flat plates reenforced with stiffeners. White and Antz (Ref. I) investigated reenforced flat plates under concentrated end loads. The work covered by this paper has extended the investigation to include the case of two built-up beam sections, connected by a stiffened plane sheet, and subjected to a uniform bending moment. The transfer of compressive stress from the main spars to the intermediate stiffeners has been studied with the idea of finding a rational method of calculating the load in the stiffeners. Two cover sheet sizes were tested, one of which was heavy enough to stay out of the wave state under moderate loading, while the other was light enough to go into the wave state early in the loading. The stiffener size and arrangement on the two panels were the same.



IV. EXPERIMENTAL INVESTIGATION:

The test specimen consisted of two main spars 96" long and 8" deep spaced 26" apart, and a bottom cover sheet 26" X 72" secured to the flange angles by 8-32 bolts spaced $\frac{3}{4}$" apart. The four stiffeners consisted of extruded bulb angles spaced 5" apart and riveted with 3/32" rivets spaced at 1" intervals. Both ends of the spars were rigidly attached to the testing machine as was also one end of the cover sheet. The other end of the cover panel (and its reenforcing stiffeners) was free corresponding to an infinitely weak rib system near the tip of a wing. At intervals along the span chordwise spacers were used to prevent rotation of main spars. (See Fig. I)

FIG. 1

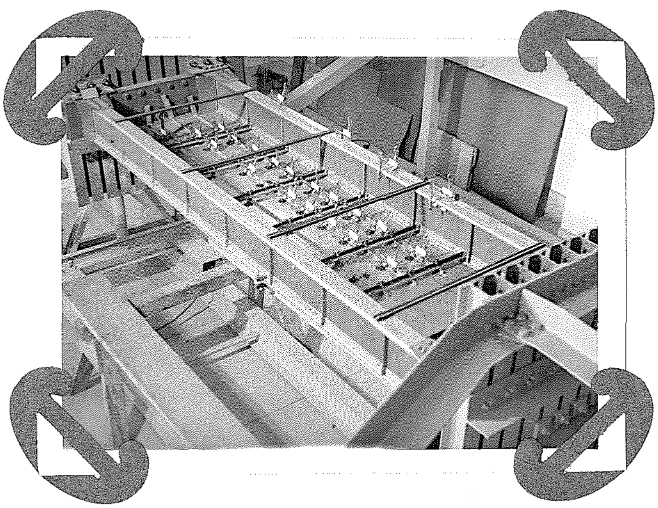
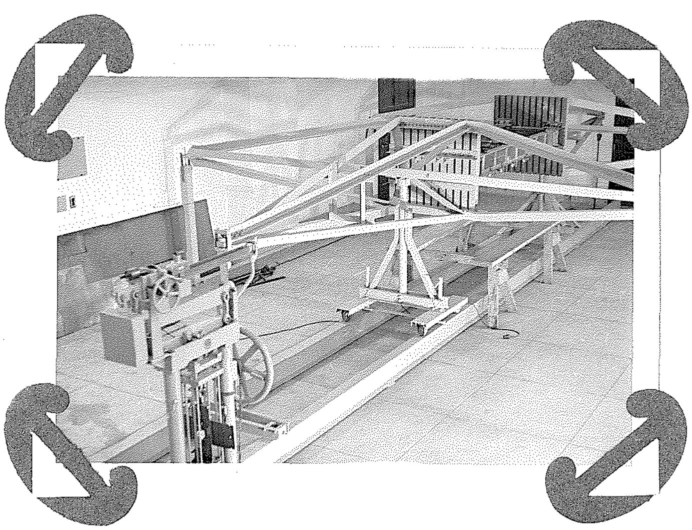
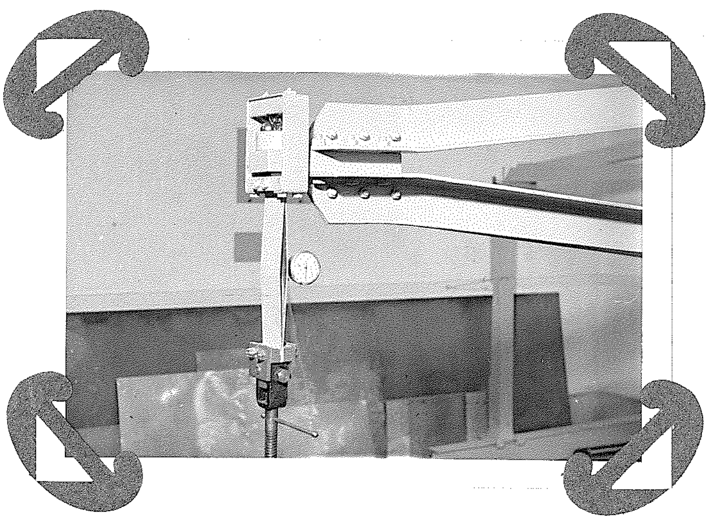


FIG. 2



The beam was mounted in the 500,000 in. lbs. Torsion-Bending Testing Machine shown in figure 2*. The machine "floated" laterally, ie, with no lateral restraint, thus eliminating torsional loads.

The bending moments were obtained by applying forces on the end of each of the testing machine lever arms. The amount of force applied was indicated by an Ames Dial Gauge measuring the lateral deflection of initially bent steel springs. (See Fig. 3). Calibration curves of pounds force versus gauge reading were obtained by calibrating the gauges in an ordinary tensile testing machine.



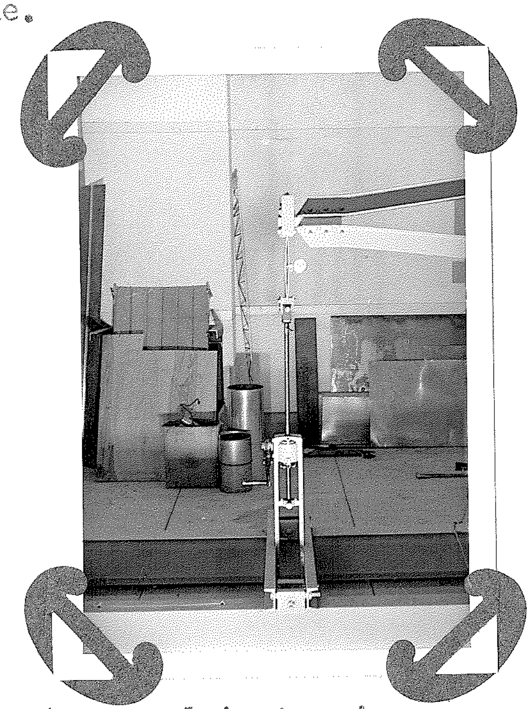


FIG. 3.

*For a description of this apparatus used in torsion see Reference 2.

The stress distribution was obtained by measuring deformations with Huggenberger Tensometers on the beam caps and stiffener legs. The gauge length was 8 cm. These Tensometers, whose scale readings are approximately 1200 times the measured deflections, were accurately calibrated with an interferometer. The tensometers placed on the stiffeners were held in place by means of rubber suction cups moistened with glycerine, as seen in figure 4, while those on the main spar were held by a special clamp shown in figure 5.

FIG. 4

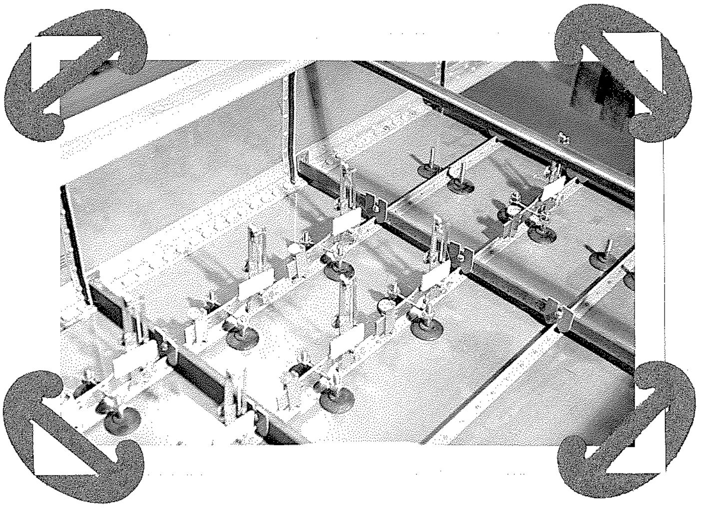
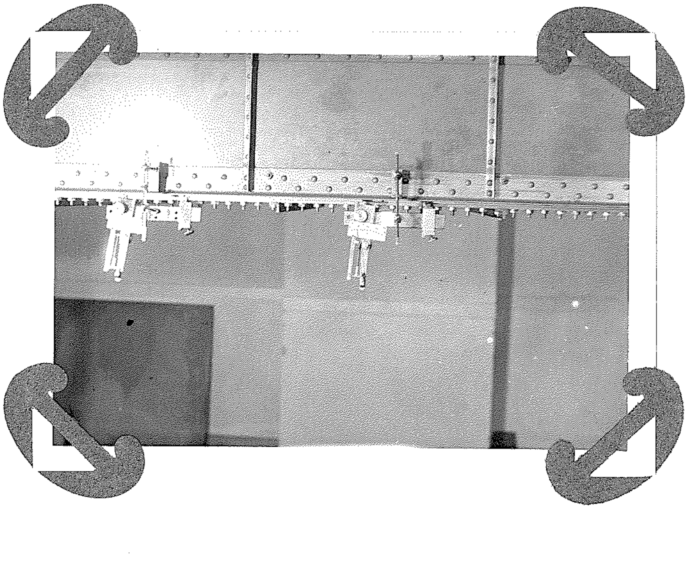
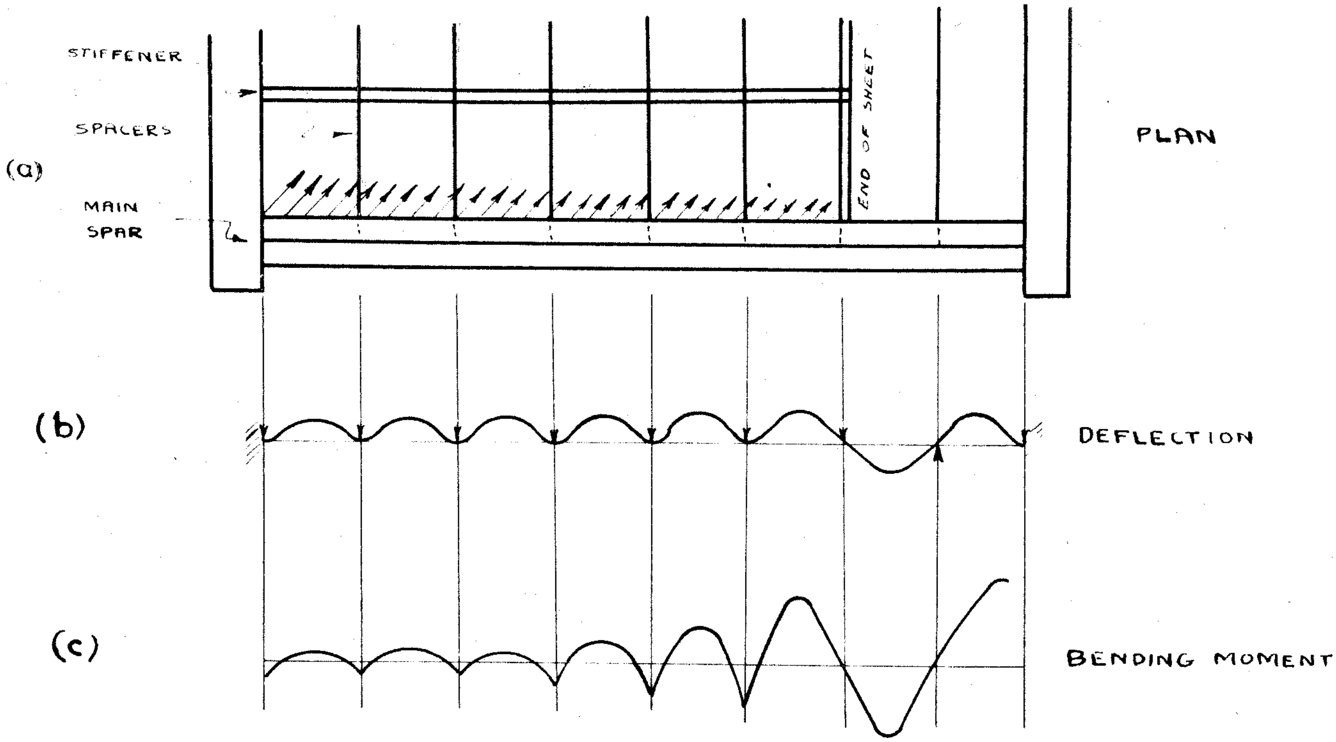


FIG. 5

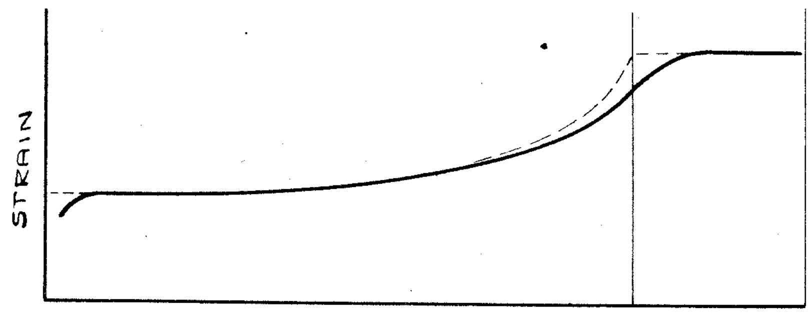


From the general nature of the set up and from the previous experiments one would expect that strain readings taken along the bottom flange would produce a graph of the general shape of the solid curve of figure 6. But with the tensometers placed at position "A" along the flange the resulting curve was the dotted line of figure 6. However, by taking two sets of readings at each station, one at "B" and another at "C" and extrapolating to the vertical neutral axis at the center of the web, "D", the resulting points produced the smooth curve shown by the solid line. This indicated the presence of and eliminated the effects of chordwise bendings. A similar effect was noted on the intermediate stiffeners.

The following diagram shows how the chordwise bending stresses arise.



The tension field in the sheet loads the main spar laterally, or chordwise, while the chordwise spacers act as supports of a continuous beam. The deflection curve thus produced is of the form shown at (b) and the bending moment of the general shape shown at (c). The stresses caused by this bending are superimposed upon the stresses from the applied moments, the combination producing the dotted curve of Fig. 6.



At the point on the main spar where the sheet ends a sudden change in the moment of inertia and neutral axis takes place. In an elastic body at such discontinuities as this the stress instead of making a sharp change takes up the load more evenly and reaches its final value about a spar depth further on. A similar discontinuity exists at the fixed end of the sheet where a securing angle changes the section properties of the beam.

In converting strain into stress the value of Young's Modulus for dural was taken as 10.4×10^6 lbs/sq. in.

Figures (12) to (27) show the stress distribution for various bending loads and thicknesses of sheet. It is of interest to note that the stresses at any station vary directly with the bending moment for both the thin and thick sheet, and while the thick sheet extrapolates to zero, the thin sheet does not. This is thought to be due to the fact that some initial stresses existed in the thin sheet set up in the unloaded condition. (See Fig. 12 to 14 and 20 to 22).

The authors have no explanation for the peculiar shape of the stress curves of stiffener "C" of the thick sheet near the free end.

V. THEORETICAL CALCULATIONS:

In order that the results obtained here may be of some use to the designer who is looking for a method of predicting the stresses in the stiffeners, an attempt is made to find an effective shear modulus, G', or better, the ratio $\frac{G'}{E}$.

Figure (7) is a plan view of the beam, divided into a number of transverse strips arbitrarily chosen in 5" widths. As the test beam is symmetrical about its longitudional axis only one half is shown. Stress distribution curves are also indicated.

A_A, A_B, and A_C are areas of stiffeners. A, B, and C respectively.

Let us consider a strip across the beam of width (δ).

The basic relationship between shear stress (τ) and strain (γ) is

$$\tau = G\gamma$$

Where G = shear modulus.

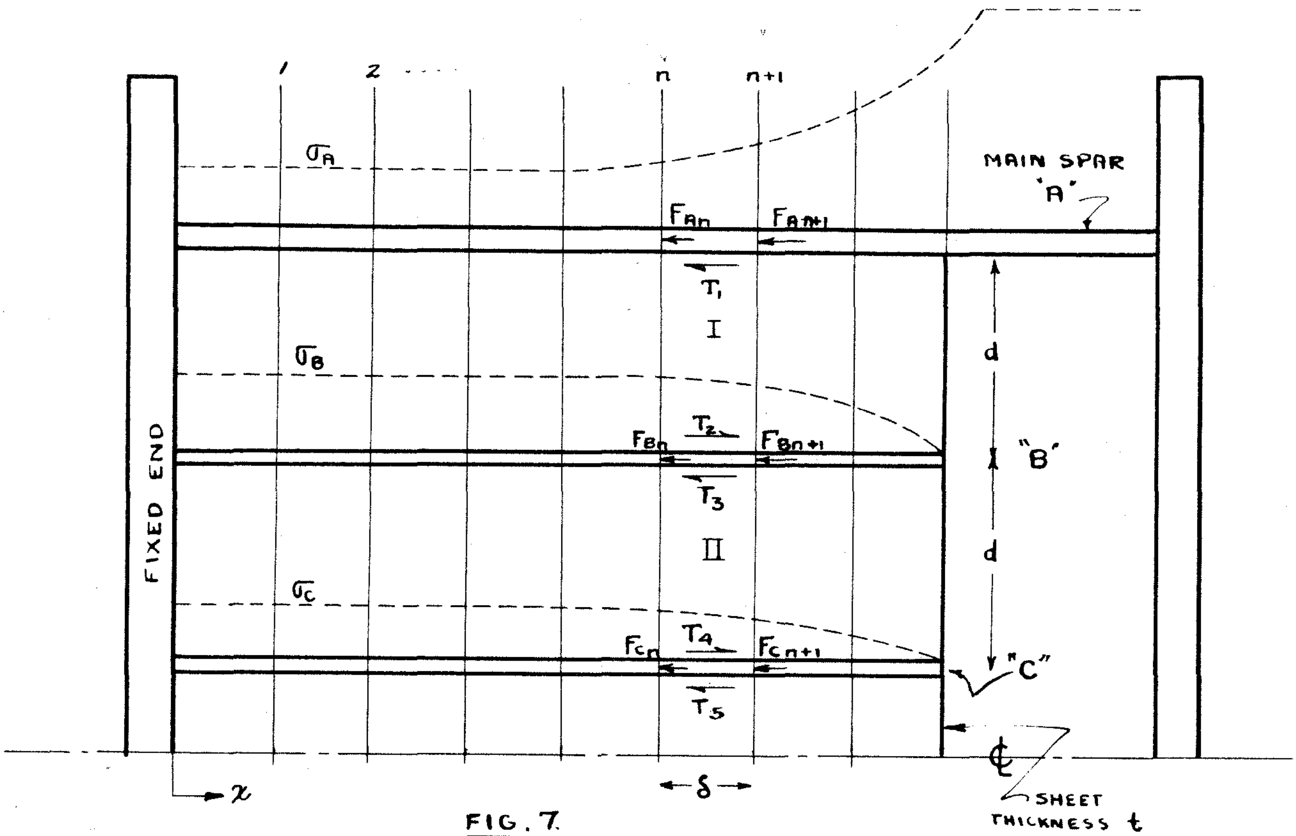


FIG. 7.

AT STATION "n" AT STATION "n+1"

FORCE IN "A" $= F_{A_n} = \sigma_{A_n} A_A$ $\qquad F_{A_{n+1}} = \sigma_{A_{n+1}} A_A$

SHEARING FORCE IN "A", $T_1 = F_{A_{n+1}} - F_{A_n} = A_A\left(\sigma_{A_{n+1}} - \sigma_{A_n}\right)$

SIMILARLY, IN STIFFENER "B", $F_{B_n} = \sigma_{B_n} A_B$, $\quad F_{B_{n+1}} = \sigma_{B_{n+1}} A_B$

$T_2 - T_3 = F_{B_n} - F_{B_{n+1}} = A_B\left(\sigma_{B_n} - \sigma_{B_{n+1}}\right)$

AND IN "C", $\quad F_{C_n} = \sigma_{C_n} A_C$ $\qquad F_{C_{n+1}} = \sigma_{C_{n+1}} A_C$

$T_4 - T_5 = F_{C_n} - F_{C_{n+1}} = A_C\left(\sigma_{C_n} - \sigma_{C_{n+1}}\right)$

BUT BECAUSE OF SYMMETRY ABOUT LONGITUDINAL ℄, $T_5 = 0$

WE CAN WRITE ① $\dfrac{T_1 + T_2}{2} \cdot \dfrac{1}{\delta t} = \tau_1 = G_1 \gamma_1$ FOR PANEL I

② $\dfrac{T_3 + T_4}{2} \cdot \dfrac{1}{\delta t} = \tau_2 = G_2 \gamma_2$ " " II

SUBTRACTING, ① - ②, AND ASSUMING THAT PANELS I + II ARE IN THE SAME STATE, IN WHICH $G_1 = G_2 = G'$ WE GET

$$③ \quad T_1 + (T_2 - T_3) - T_4 = 2\,\delta\, t\, G'(\gamma_1 - \gamma_2)$$

OR

$$A_A\left(\sigma_{A_{n+1}} - \sigma_{A_n}\right) + A_B\left(\sigma_{B_n} - \sigma_{B_{n+1}}\right) - A_C\left(\sigma_{C_n} - \sigma_{C_{n+1}}\right) = 2\,\delta\, t\, G'(\gamma_1 - \gamma_2)$$

(A_A) is the "effective" cross-section area of the main spar and it was obtained as follows: Consider a section at x inches from the fixed end of the sheet. Assuming that the stress across the depth of the beam has a linear variation the stress at the bottom fibers is composed of three parts:

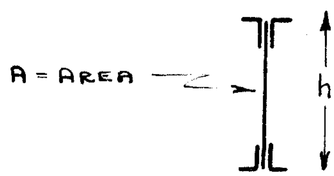
1- Compression due to the uniform bending moment M_o

2- Tension due to the bending moment produced by the shearing force T_1

3- Tension due to the shearing force T_1 acting as an end load

Then the compressive stress (σ_A) is

$$\sigma_A = \frac{M_o c}{I} - \frac{h}{2} T_1 \frac{c}{I} - \frac{T_1}{A}$$



The change in σ_A in a small length dx is

$$\frac{d\sigma_A}{dx} = -\left[\frac{ch}{2I} + \frac{1}{A}\right]\frac{dT_1}{dx} = \frac{d}{dx}\left[\frac{T_1}{\text{EFFECTIVE AREA}}\right] \quad \text{OR}$$

$$\frac{d}{dx}\left[\sigma_A A_A\right] = \frac{dT_1}{dx}$$

$$A_A = \frac{2AI}{2I + Ach} = \frac{A}{1 + \frac{chA}{2I}} = \frac{A}{1 + \frac{ch}{2\rho^2}} \qquad \rho = \sqrt{\frac{I}{A}}$$

The effective area computed in this way is 0.568 sq. in. and the area of the stiffener cross-section is 0.044 sq. in. All items on the left side of equation (3) are known. We must now find $(\delta_1 - \delta_2)$. We assume that the angle (δ) and its tangent are equal for small deformations.

$$\delta_1 = \frac{l_1}{d} \qquad \text{and} \qquad \delta_2 = \frac{l_2}{d}$$

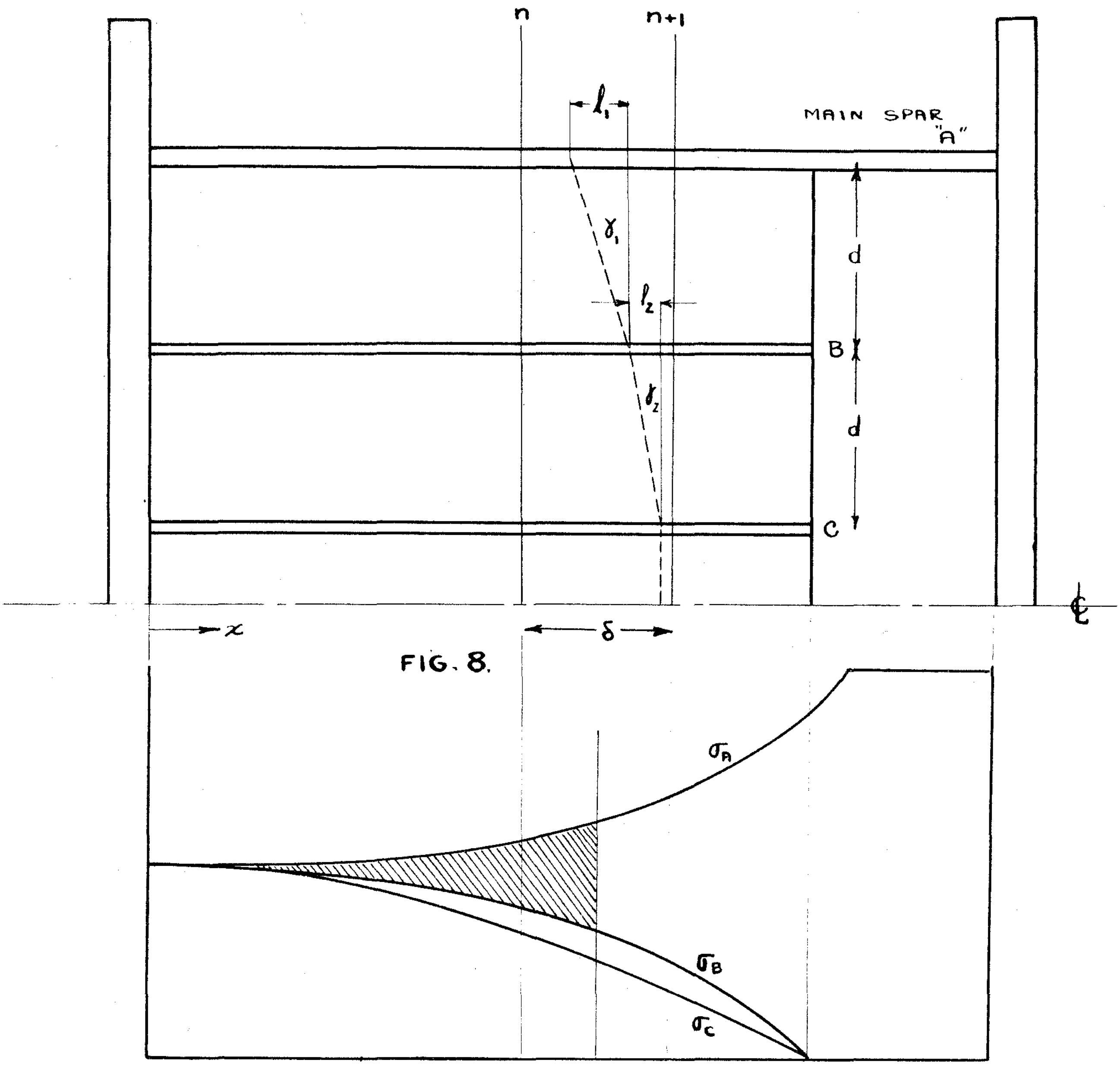


FIG. 8.

$$l_1 = \left[\frac{\sigma_{A_1}+\sigma_{A_2}}{2}\cdot\frac{\delta}{E} + \frac{\sigma_{A_2}+\sigma_{A_3}}{2}\cdot\frac{\delta}{E} + \cdots\cdots + \frac{\sigma_{A_{n-1}}+\sigma_{A_n}}{2}\cdot\frac{\delta}{E} + \frac{\sigma_{A_n}+\sigma_{A_{n+1}}}{2}\cdot\frac{\delta}{E}\right] - \left[\frac{\sigma_{B_1}+\sigma_{B_2}}{2}\cdot\frac{\delta}{E} + \cdots\cdots + \frac{\sigma_{B_n}+\sigma_{B_{n+1}}}{2}\cdot\frac{\delta}{E}\right]$$

$$= \frac{\delta}{E}\left[\frac{\sigma_{A_1}}{2} + \sigma_{A_2} + \cdots\cdots + \sigma_{A_n} + \frac{\sigma_{A_{n+1}}}{2}\right] - \left[\frac{\sigma_{B_1}}{2} + \sigma_{B_2} + \cdots\cdots + \sigma_{B_n} + \frac{\sigma_{B_{n+1}}}{2}\right]$$

$$= \frac{1}{E}\left[\text{AREA UNDER } \sigma_A \text{ CURVE TO } (n+1)\right] - \left[\text{AREA UNDER } \sigma_B \text{ CURVE TO } (n+1)\right]$$

But since an average value of γ_1 should be taken over the interval between (n) and (n+1) the area shown in Fig. 8 should be taken.

$$(4) \quad \gamma_1 = \frac{l_1}{d} = \frac{1}{dE}\Big[\text{area under } \sigma_A \text{ curve to } (n+\tfrac{1}{2})\Big] - \Big[\text{area under } \sigma_B \text{ curve to } (n+\tfrac{1}{2})\Big]$$

Similarly, for γ_2

$$(5) \quad \gamma_2 = \frac{l_2}{d} = \frac{1}{dE}\Big[\text{area under } \sigma_B \text{ curve to } (n+\tfrac{1}{2})\Big] - \Big[\text{area under } \sigma_C \text{ curve to } (n+\tfrac{1}{2})\Big]$$

In our case we have assumed $\delta = 5$ inches

and our stiffener spacing is $d = 5$ inches

We now have $(\gamma_1 - \gamma_2)$ in terms of E. Substituting in equation (3) we get the equation for $\frac{G'}{E}$

$$(6) \quad \frac{G'}{E} = \frac{A_A(\sigma_{A_{n+1}} - \sigma_{A_n}) + A_B(\sigma_{B_n} - \sigma_{B_{n+1}}) - A_C(\sigma_{C_n} - \sigma_{C_{n+1}})}{\frac{2\delta t}{d}\left[X - Y\right]}$$

where

X = area between σ_A and σ_B curves to $(n+\frac{1}{2})$

Y = area between σ_B and σ_C curves to $(n+\frac{1}{2})$

The areas were obtained from the stress distribution curves with a planimeter. Results of the computations by this formula are plotted in figures 9 to 11.

SAMPLE CALCULATIONS

For a section at 85% of the span from the fixed end of the 0.025 sheet subjected to a bending moment of 120,000 in.lbs. n = 60 inches and n+1 = 65 inches and the numerator of equation (6) will be:

$$A\,(\sigma_{A_{n+1}} - \sigma_{A_n}) = 0.568\,(12000 - 12750) = 426 \text{ lbs.}$$

$$A\,(\sigma_{B_n} - \sigma_{B_{n+1}}) = 0.044\,(5100 - 3450) = 72 \text{ lbs.}$$

$$A\,(\sigma_{C_n} - \sigma_{C_{n+1}}) = 0.044\,(3500 - 2000) = -66 \text{ lbs.}$$

432 lbs.

For the denominator:

X = 5.80 sq.in.

Y = 1.12 sq.in.

X-Y = 4.68 sq.in. and since one square inch of chart area represents 2,000 lbs/sq.in. times 10 inches, or 20,000 lbs/in.

X-Y = 4.68 x 20,000 = 93,600 lbs/in.

$$\frac{2\,\delta\, t}{d}(X-Y) = \frac{2 \times 5 \times 0.025}{5} \times 93{,}600 = 4680 \text{ lbs.}$$

Then,

$$\frac{G'}{E} = \frac{432}{4680} = 0.092$$

VI. DISCUSSION:

It is seen that $\frac{G'}{E}$ decreases with increasing bending moment and also decreases with the distances from the fixed end of the sheet. It is of interest to note that the curve when extrapolated to zero moment (Fig. 9) reaches the elastic value of $\frac{G'}{E}$ where, taking $\mu = 0.30$

$$\frac{G'}{E} = \frac{1}{2(1+\mu)} = 0.385$$

The thick sheet gives higher values of $\frac{G'}{E}$ than the thin sheet, (Fig. 11) but they were not nearly as consistant as those for the thin sheet. This is due to the fact that the stresses in the thick sheet and stiffeners were not as high, and small errors in stress difference and areas have much greater effect. Much better accuracy would have undoubtedly been attained had the thick sheet been subjected to a higher bending load, but, as can be seen from figure 6, the stresses in the main spar caps near the end were 20,000 lbs/sq. in., beyond which there was danger of some permanent set, which we wished to avoid.

More experimenting will be necessary with other stiffener number, size and spacings, lengths of panel and unequal end moments to verify these results. The application of torsional loads and the testing of cambered sheet in a similar manner offer further extensions of this problem.

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VII. REFERENCES:

1. White, R.J. and Antz, Hans M. : The Stress Distribution in Reenforced Plates under Concentrated Edge Loads. M. S. Thesis C.I.T. 1935 and Journal of Aeronautical Sciences vol. 3 no. 6 page 209 April 1936.

2. Donnell, L.H. : Stability of Thin-walled Tubes under Torsion. N.A.C.A. Technical Report No. 479.

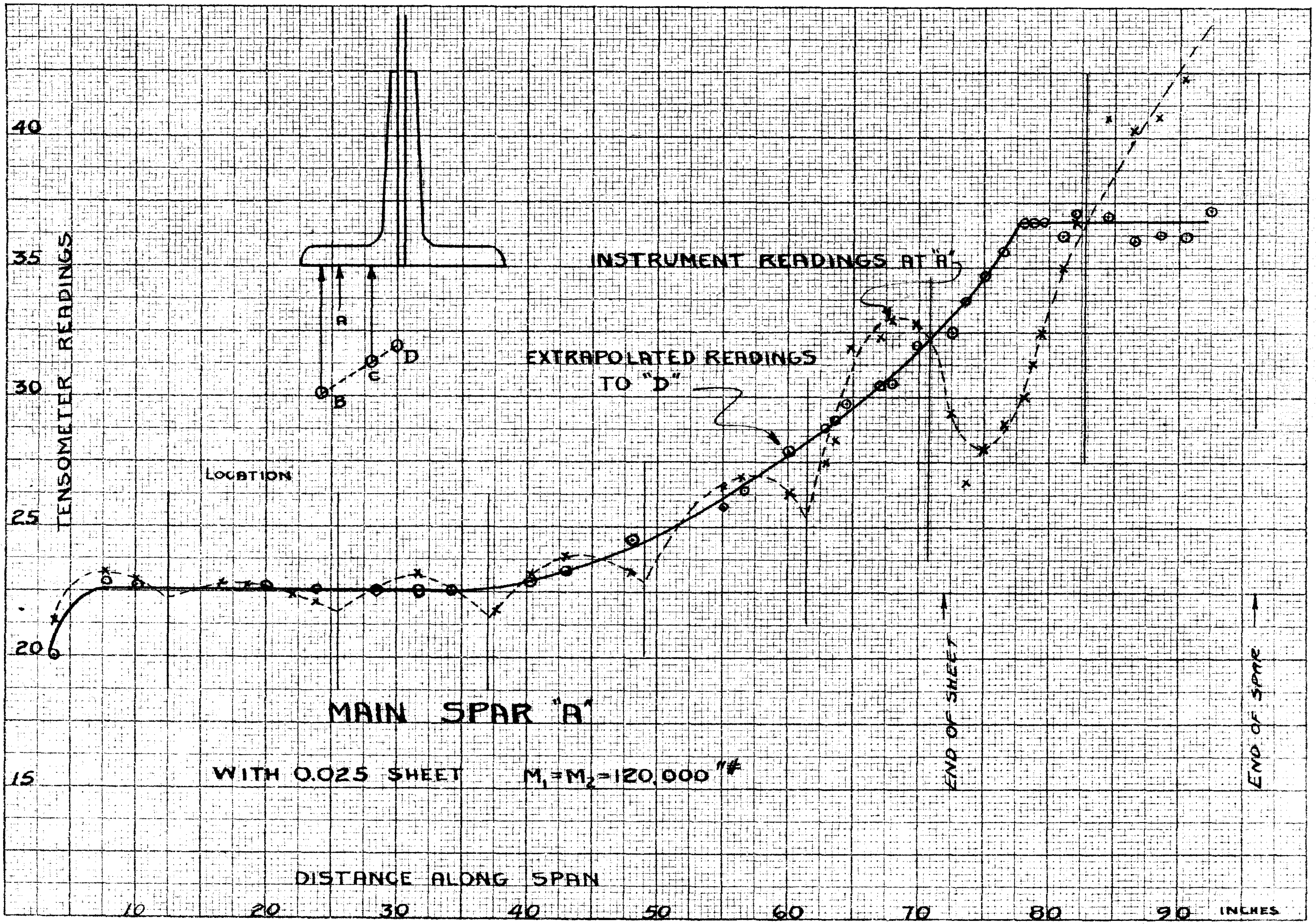

TENSOMETER READINGS
40
35
30
25
20
15
A
B
C
D
LOCATION
INSTRUMENT READINGS AT "A"
EXTRAPOLATED READINGS
TO "D"
END OF SHEET
END OF SPAR
MAIN SPAR "A"
WITH 0.025 SHEET $M_1 = M_2 = 120,000$ "#
DISTANCE ALONG SPAN
10
20
30
40
50
60
70
80
90
INCHES

FIG. 6.

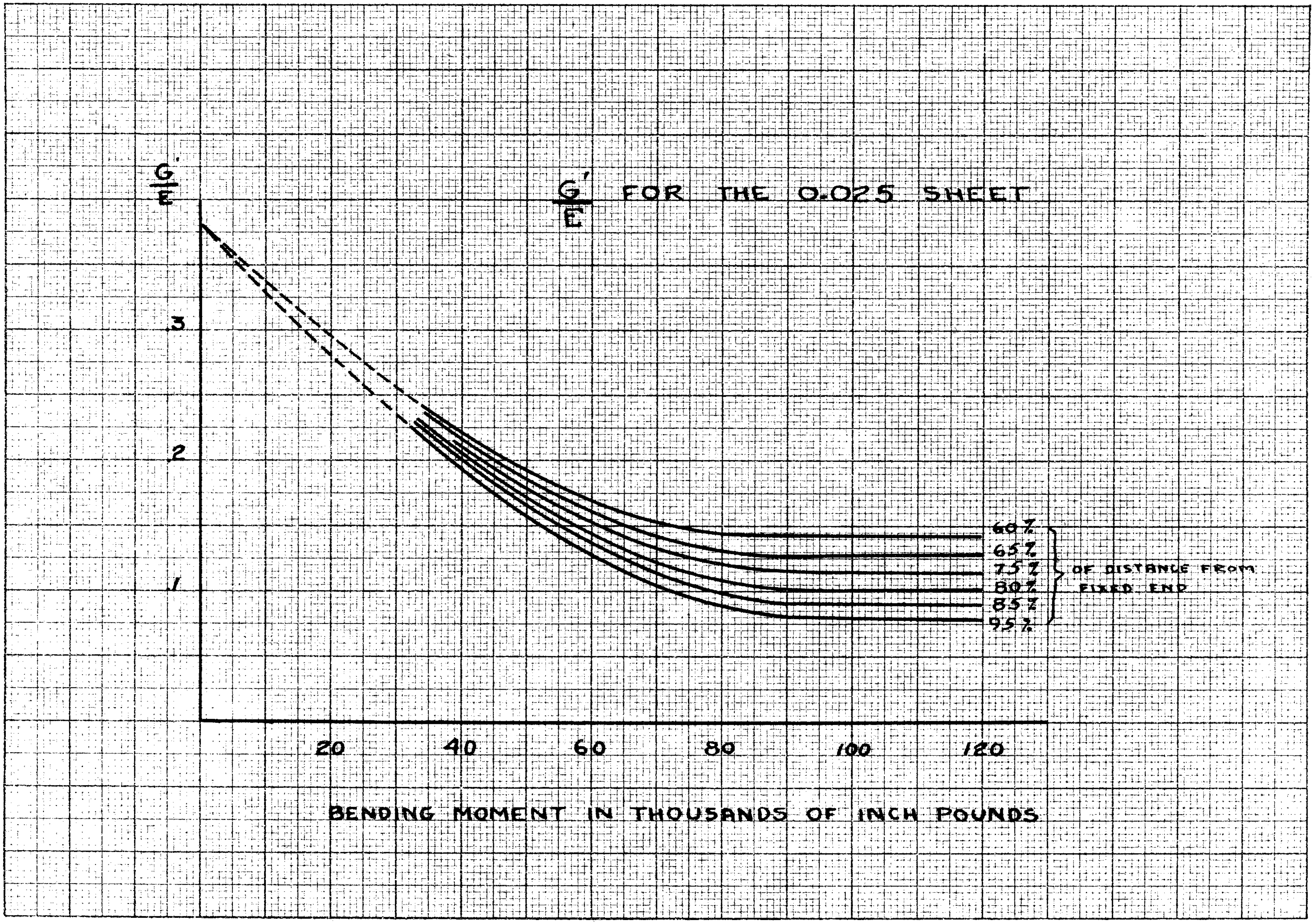

G'/E FOR THE 0.025 SHEET
G/E
3
2
1
20
40
60
80
100
120
BENDING MOMENT IN THOUSANDS OF INCH POUNDS
60%
65%
75%
80%
85%
95%
OF DISTANCE FROM FIXED END

FIG. 9.

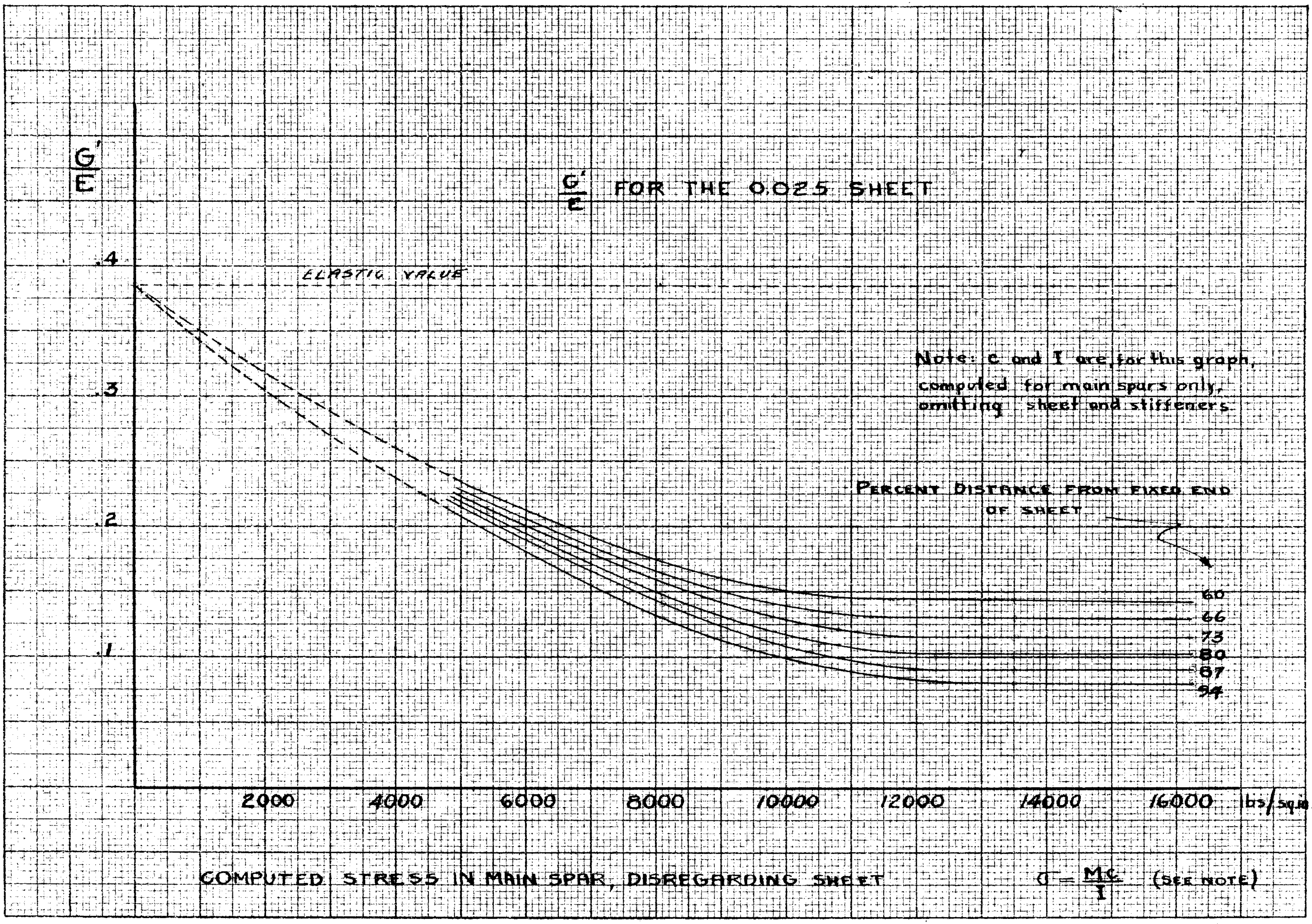

G'/E
G'/E FOR THE 0.025 SHEET
.4
.3
.2
.1
ELASTIC VALUE
Note: c and I are, for this graph, computed for main spars only, omitting sheet and stiffeners.
PERCENT DISTANCE FROM FIXED END OF SHEET
60
66
73
80
87
94
2000
4000
6000
8000
10000
12000
14000
16000
lbs/sq in.
COMPUTED STRESS IN MAIN SPAR, DISREGARDING SHEET
σ = Mc/I (SEE NOTE)

FIG. 9A.

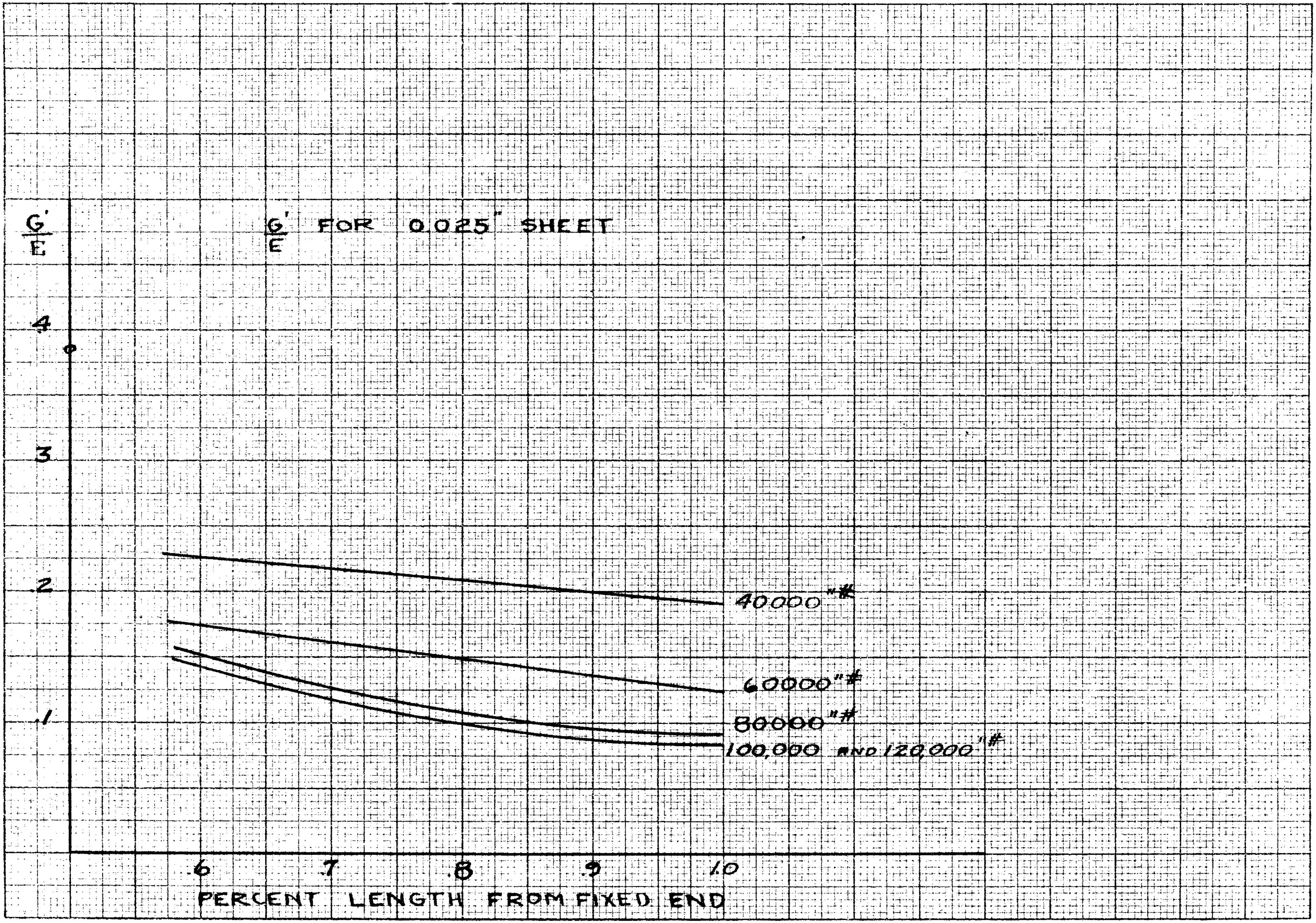
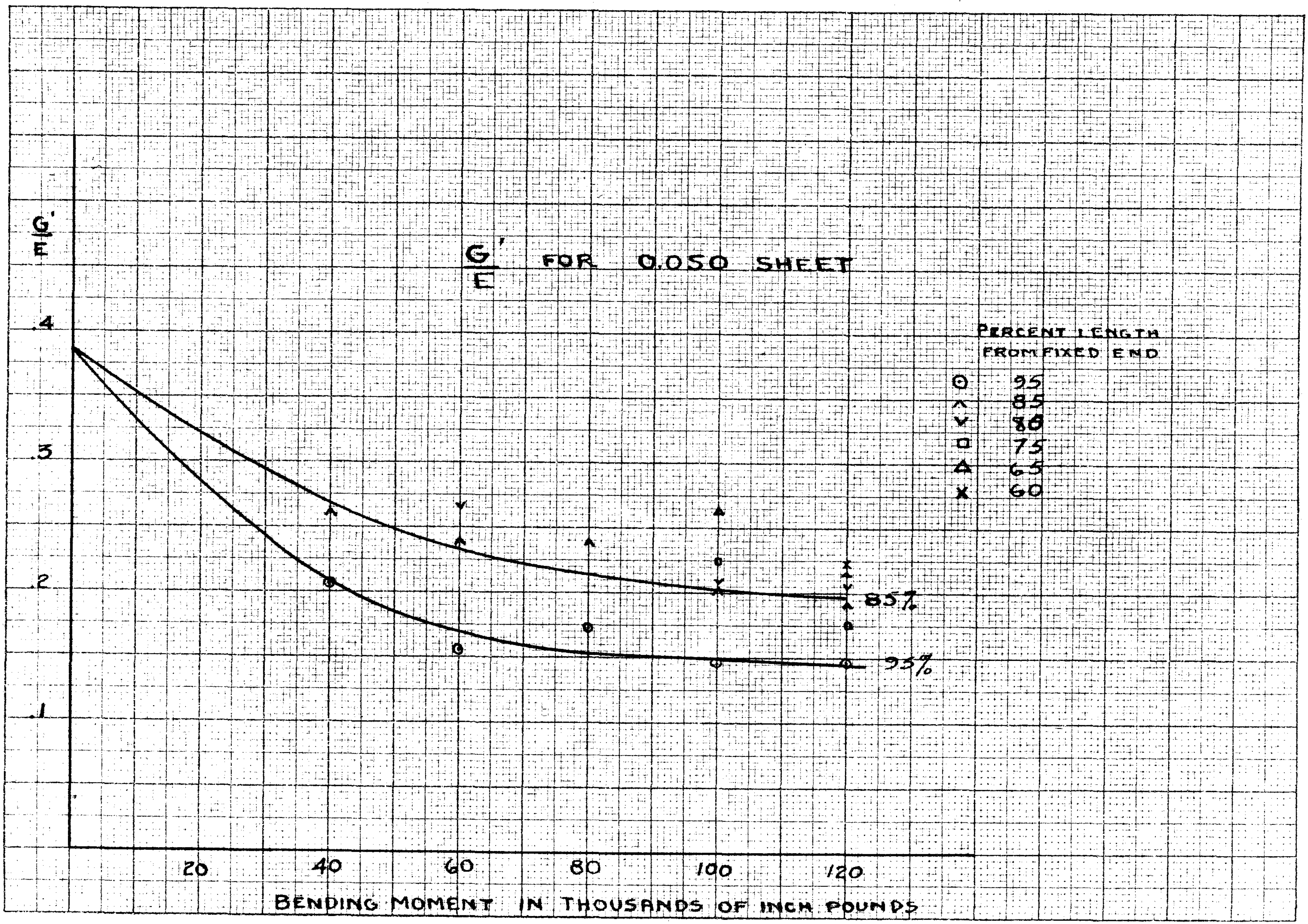

G'/E
G'/E FOR 0.025" SHEET
4
3
.2
.1
40000"#
60000"#
80000"#
100,000 AND 120,000"#
.6
.7
.8
.9
1.0
PERCENT LENGTH FROM FIXED END

FIG. 10.



G'/E FOR 0.050 SHEET
G'/E
.4
.3
.2
.1
20
40
60
80
100
120
BENDING MOMENT IN THOUSANDS OF INCH POUNDS
PERCENT LENGTH FROM FIXED END
95
85
80
75
65
60
85%
95%

FIG. 11.

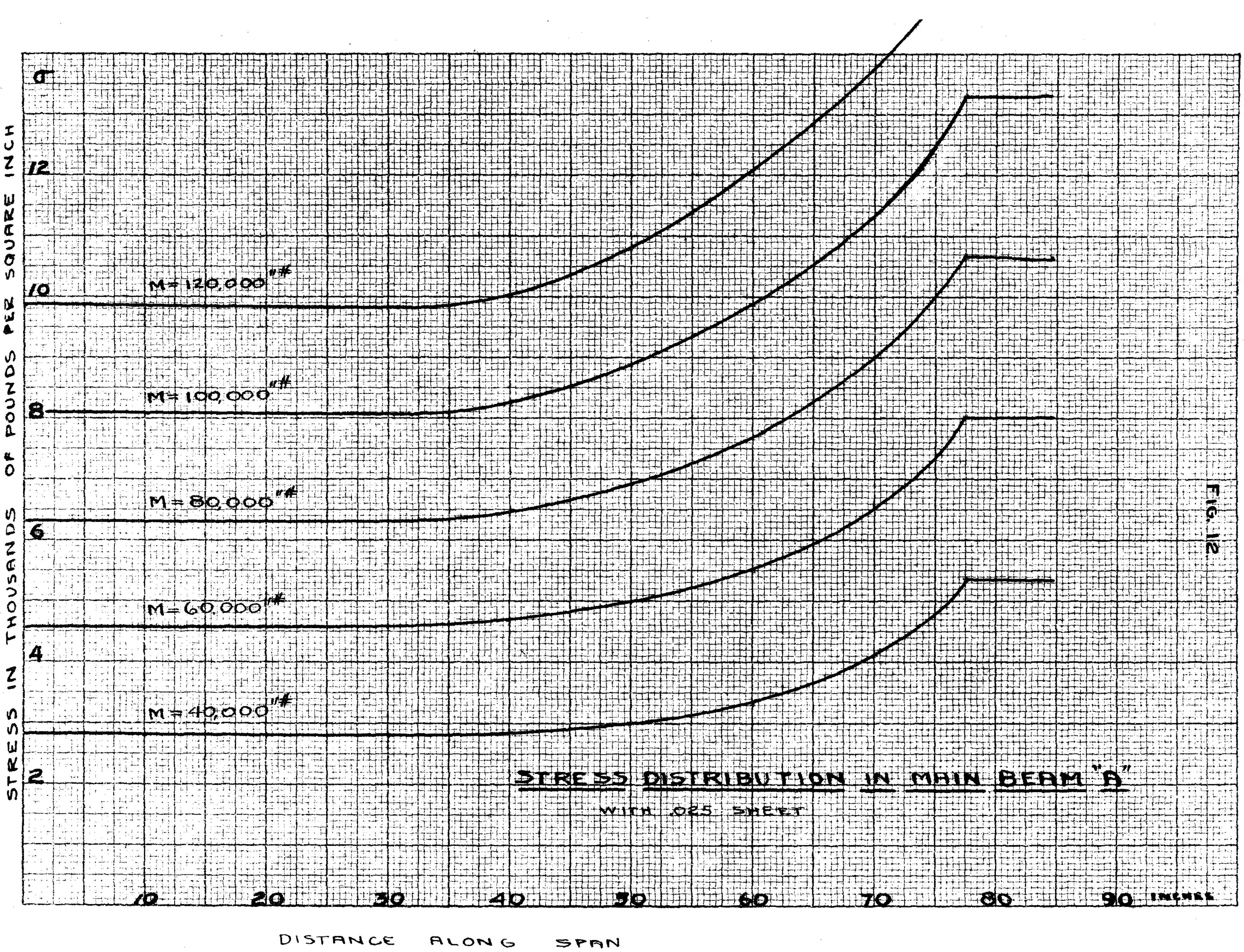


FIG. 12
STRESS DISTRIBUTION IN MAIN BEAM "A"
WITH .025 SHEET
M=120,000"#
M=100,000"#
M=80,000"#
M=60,000"#
M=40,000"#
σ
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90 INCHES
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
DISTANCE ALONG SPAN

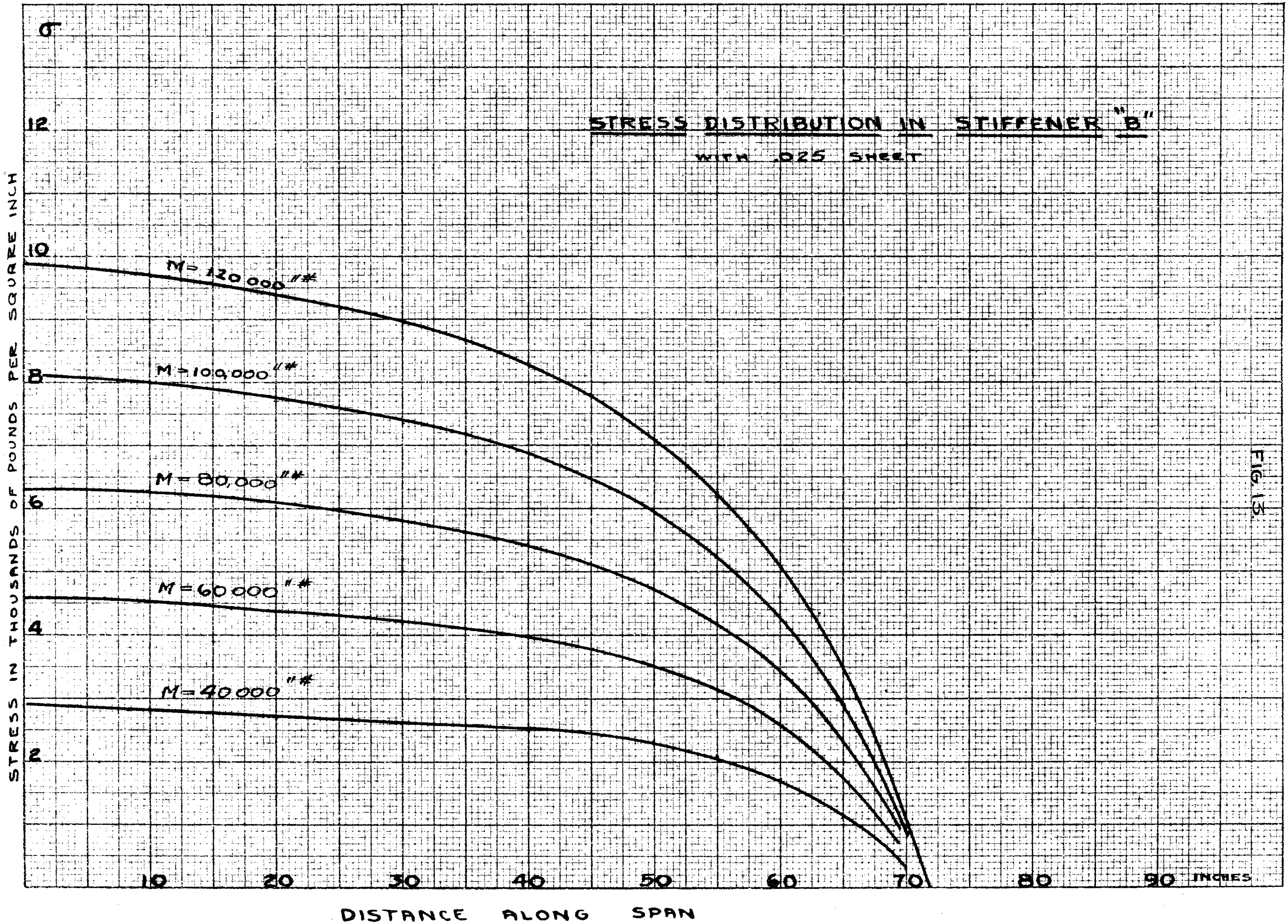
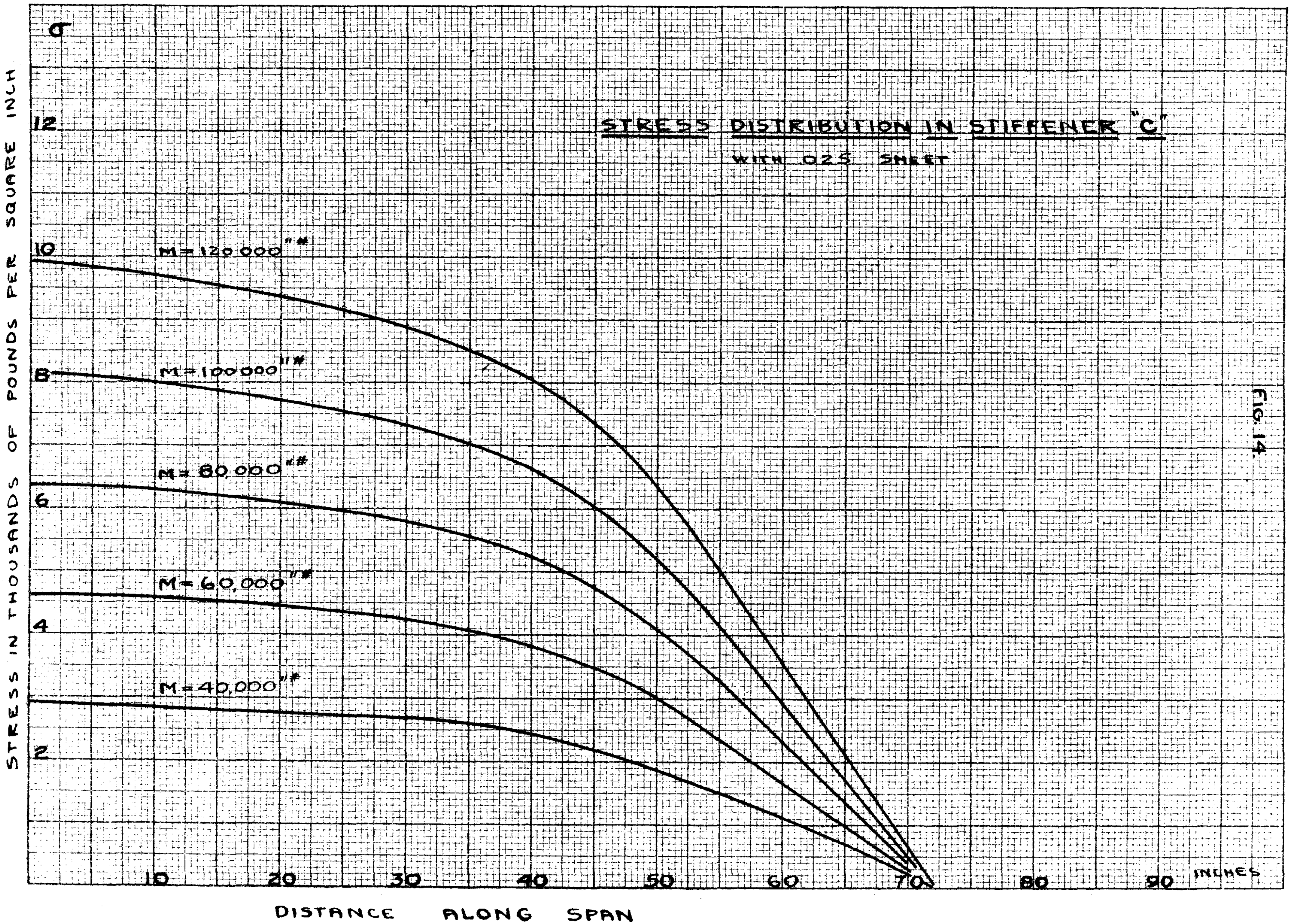
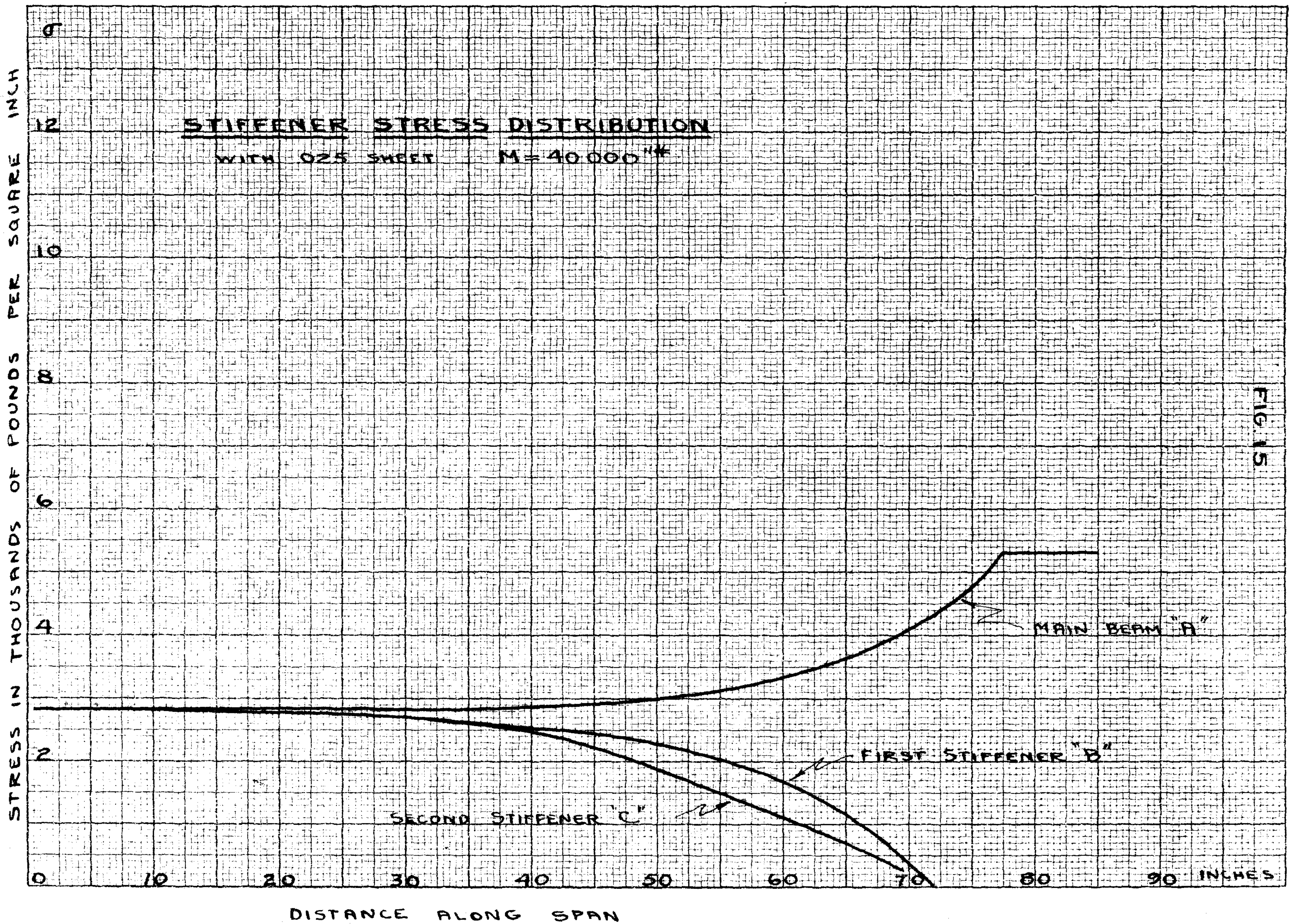
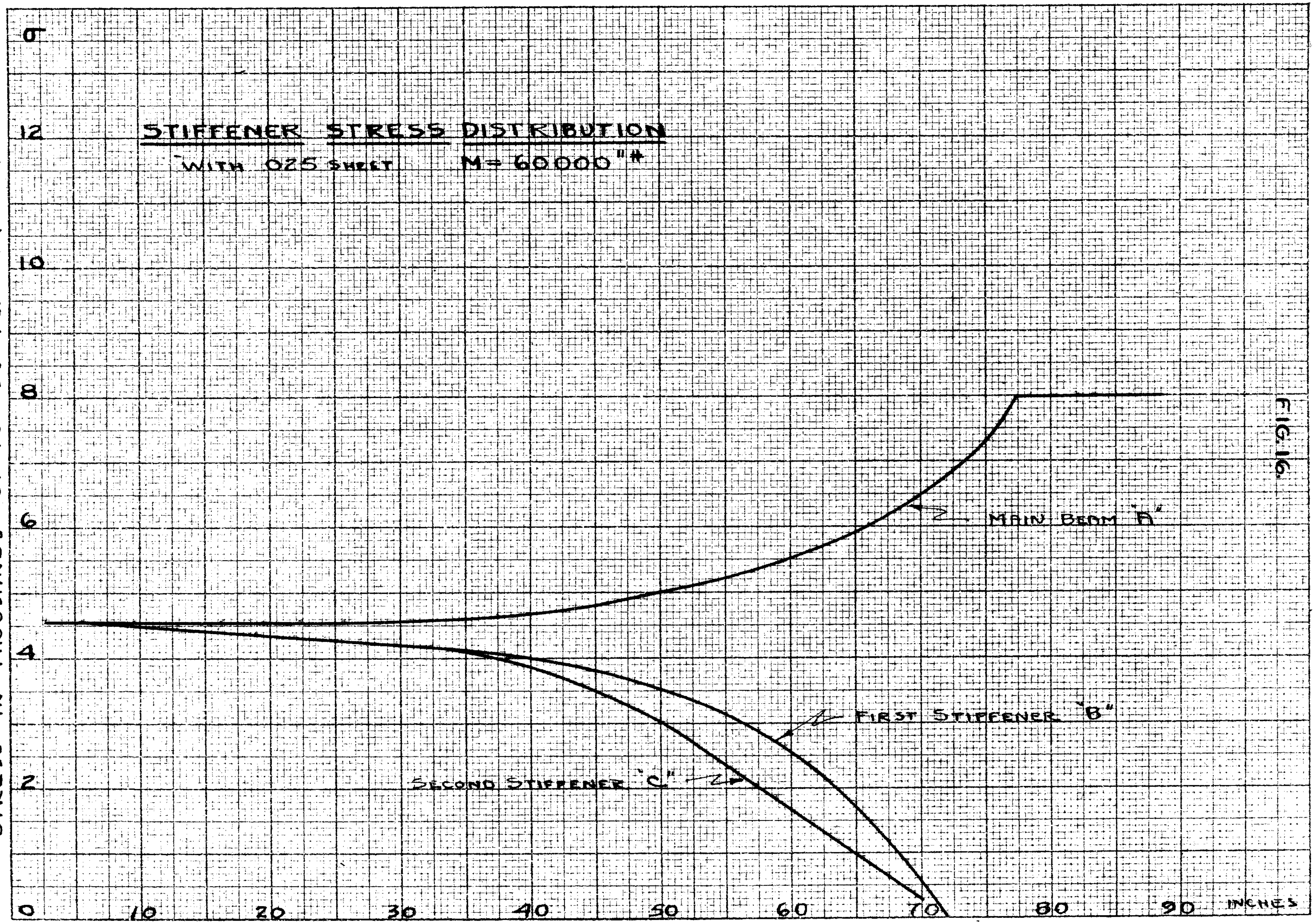

STRESS DISTRIBUTION IN STIFFENER "B"
WITH .025 SHEET
σ
12
10
8
6
4
2
M = 120,000"#
M = 100,000"#
M = 80,000"#
M = 60,000"#
M = 40,000"#
10
20
30
40
50
60
70
80
90 INCHES
DISTANCE ALONG SPAN
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH

FIG. 13.


STRESS DISTRIBUTION IN STIFFENER "C"
WITH .025 SHEET
σ
12
10
8
6
4
2
M=120,000"#
M=100000"#
M=80,000"#
M=60,000"#
M=40,000"#
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN
FIG. 14.



STIFFENER STRESS DISTRIBUTION
WITH .025 SHEET M = 40 000"#
σ
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
INCHES
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
FIG. 15
DISTANCE ALONG SPAN
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH


σ
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
INCHES
STIFFENER STRESS DISTRIBUTION
WITH .025 SHEET
M = 60000"#
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
DISTANCE ALONG SPAN
FIG. 16.

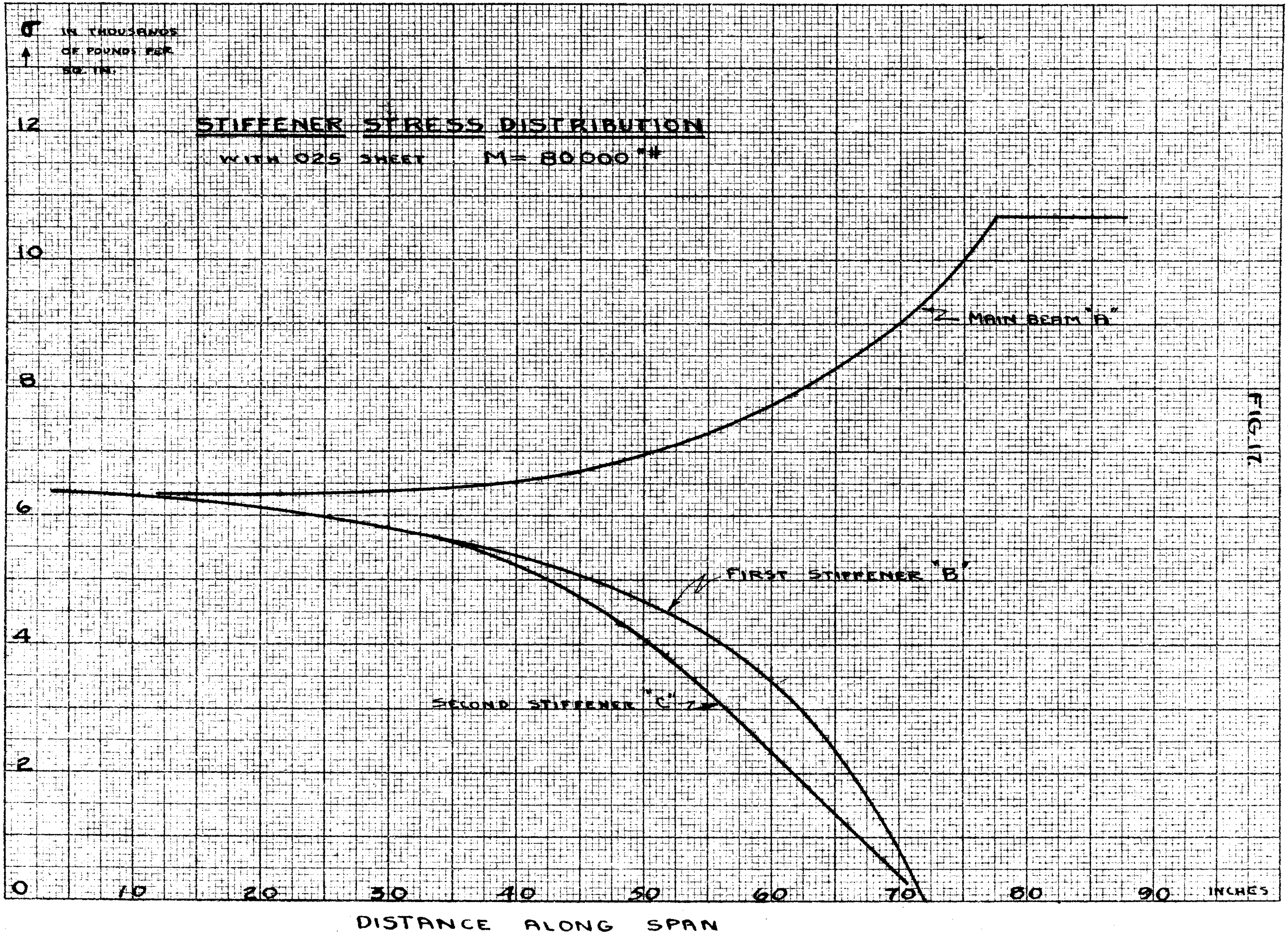

σ IN THOUSANDS OF POUNDS PER SQ. IN.
STIFFENER STRESS DISTRIBUTION
WITH .025 SHEET M = 80000 "#
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN

FIG. 17.

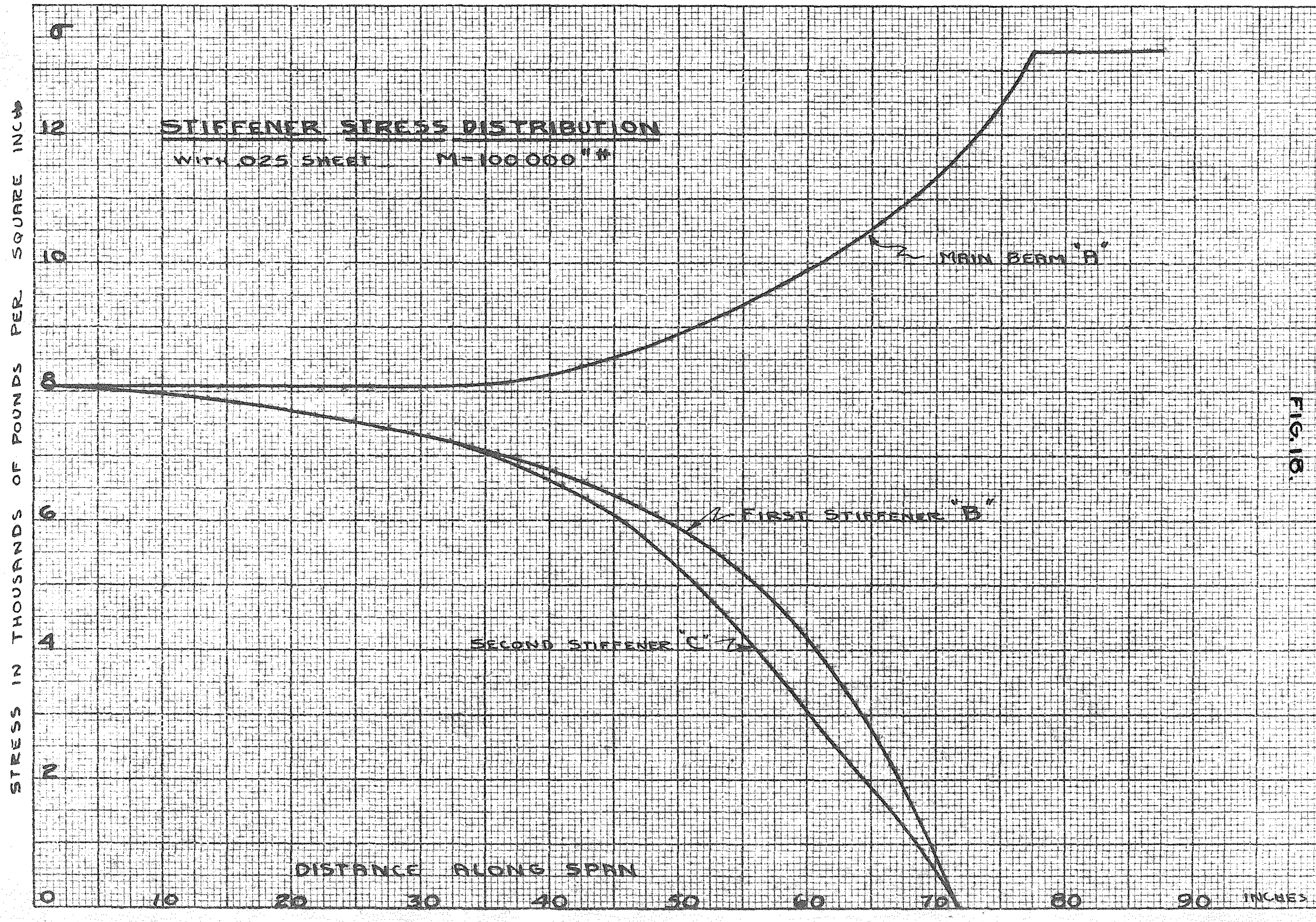
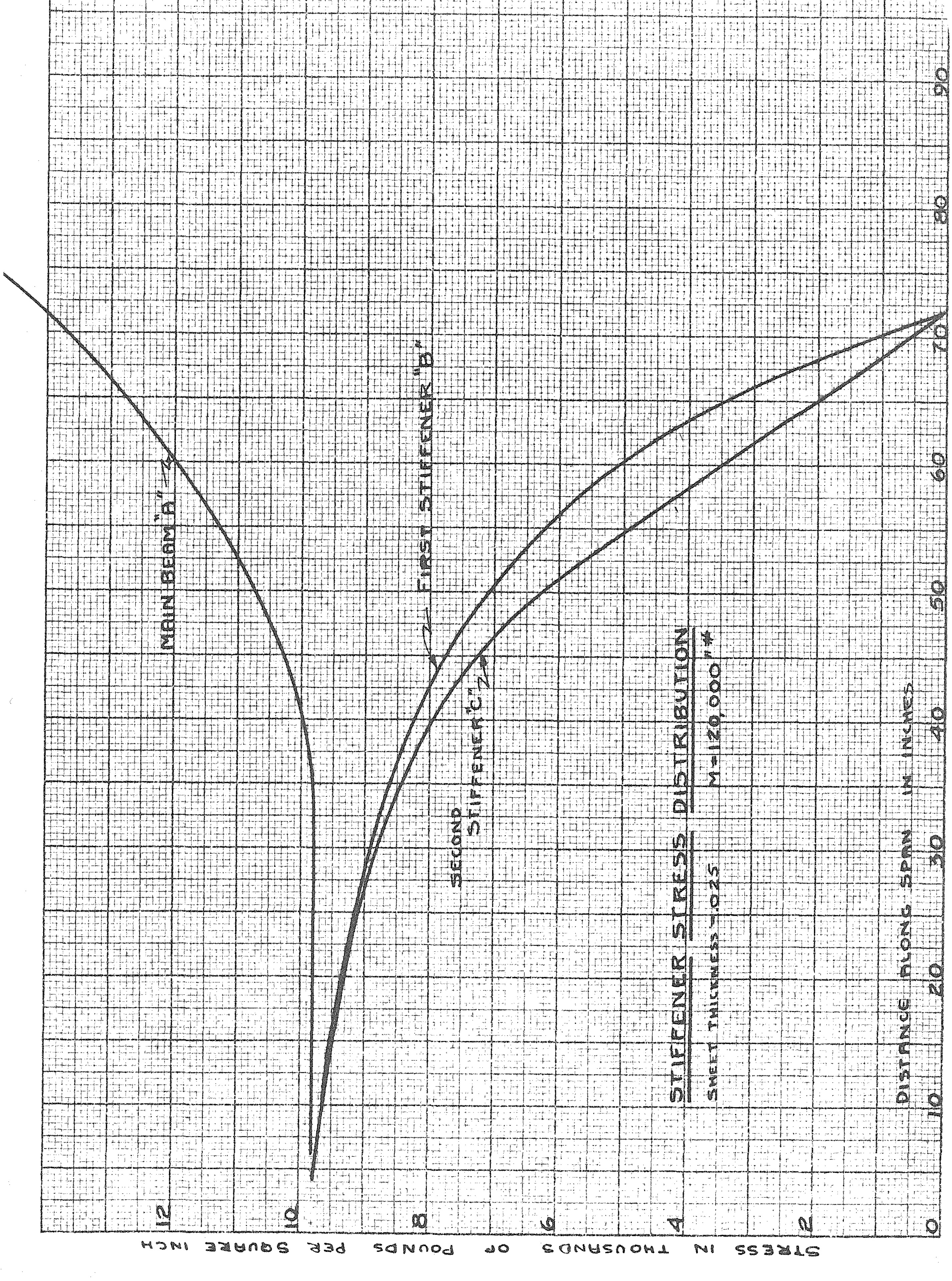

STIFFENER STRESS DISTRIBUTION
WITH .025 SHEET M-100,000"#
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
σ
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN

FIG. 18.

FIG. 19.



STIFFENER STRESS DISTRIBUTION
SHEET THICKNESS=.025 M=120,000"#
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
DISTANCE ALONG SPAN IN INCHES
0
10
20
30
40
50
60
70
80
90
2
4
6
8
10
12
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH

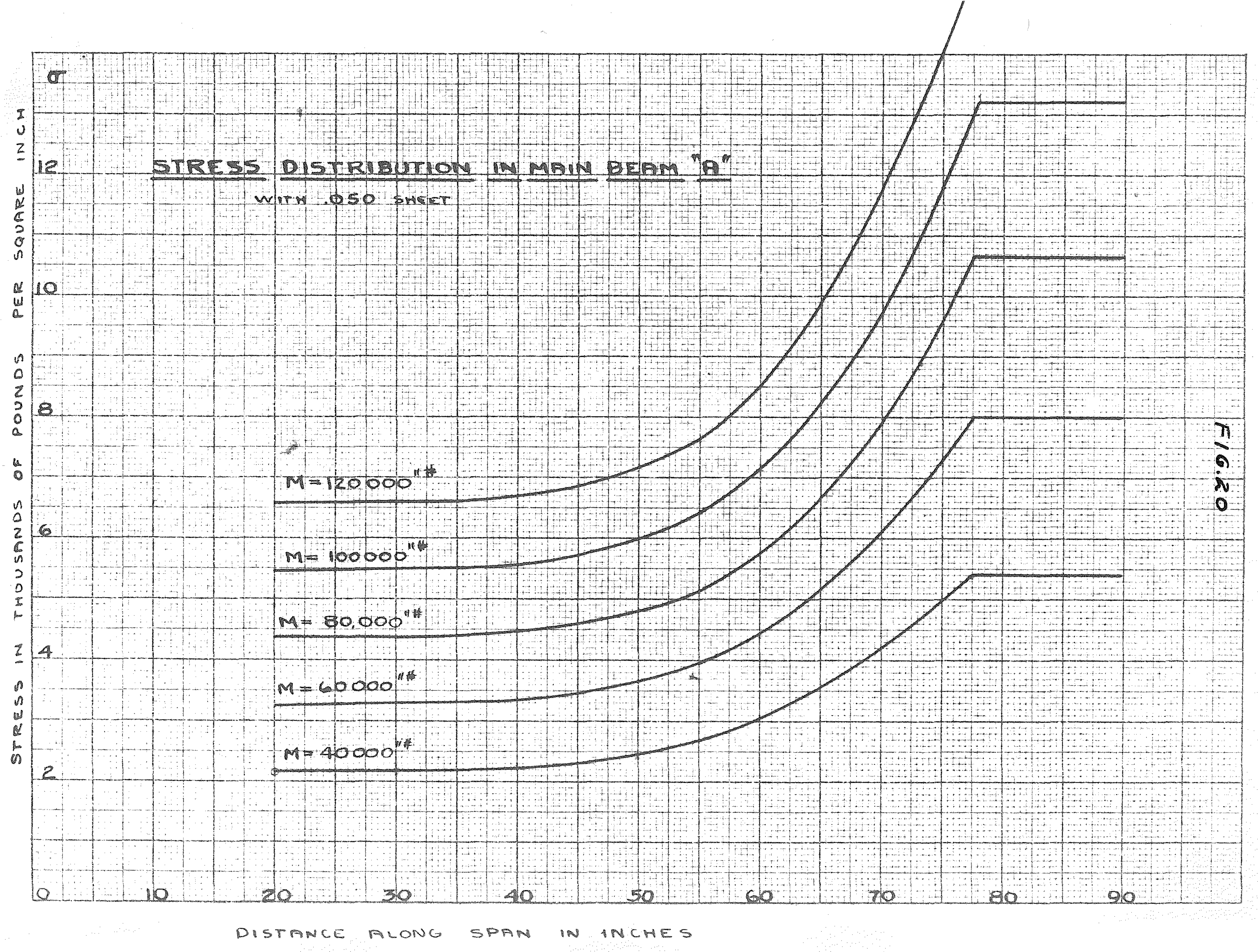

STRESS DISTRIBUTION IN MAIN BEAM "A"
WITH .050 SHEET
σ
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
M = 120000"#
M = 100000"#
M = 80,000"#
M = 60000"#
M = 40000"#
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
DISTANCE ALONG SPAN IN INCHES

FIG. 20

STRESS DISTRIBUTION IN STIFFENER "B"

WITH .050 SHEET

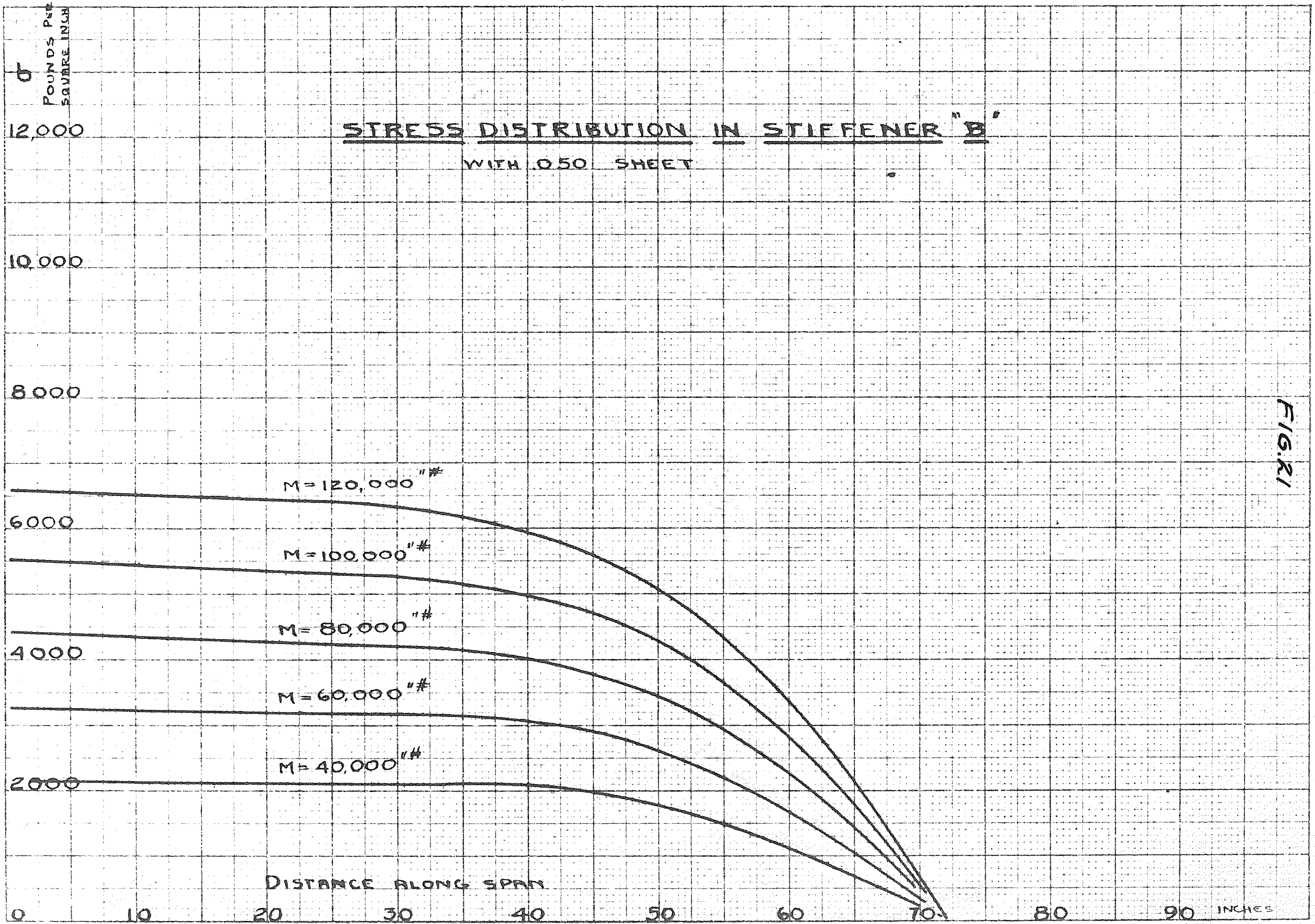
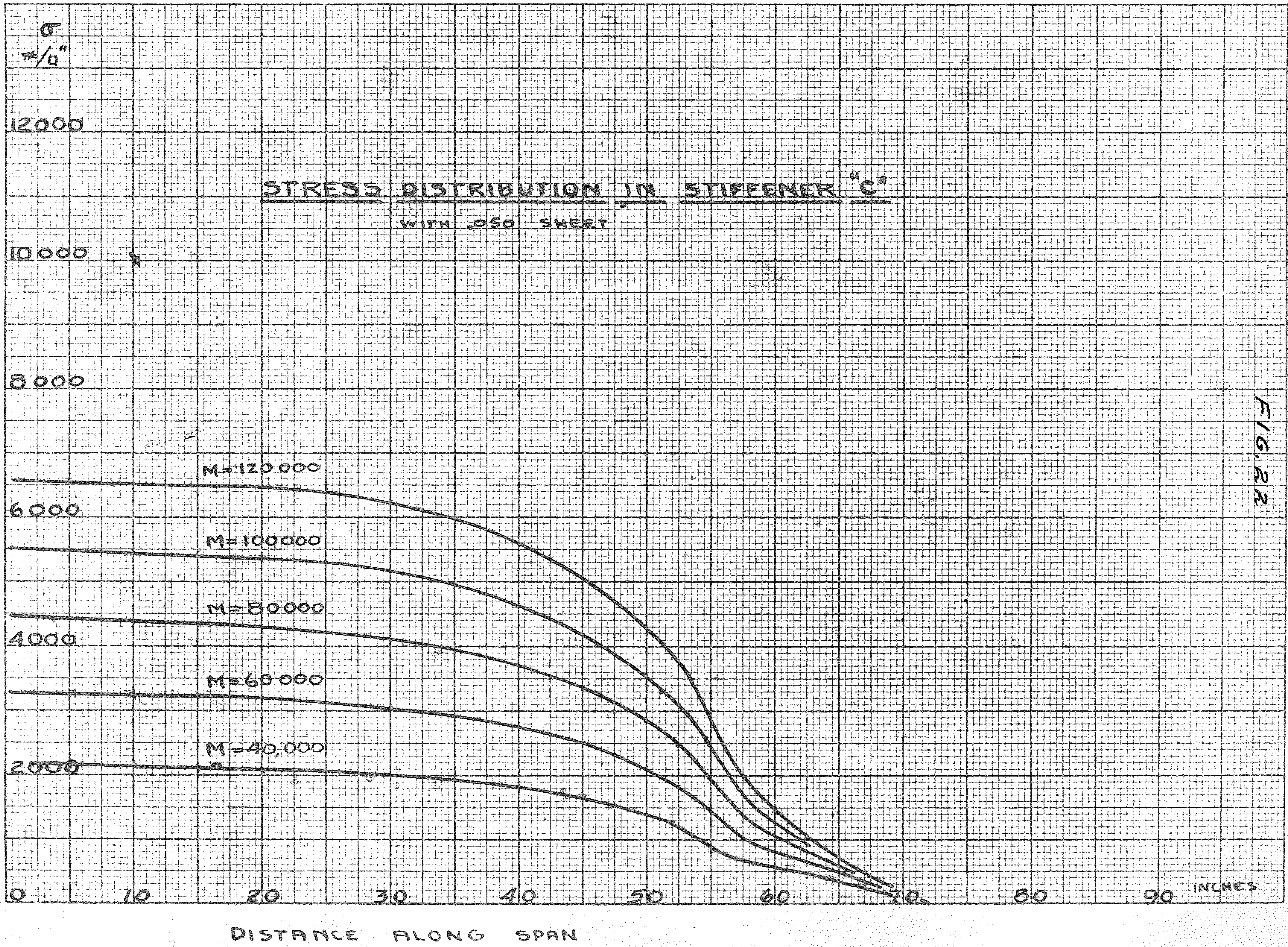
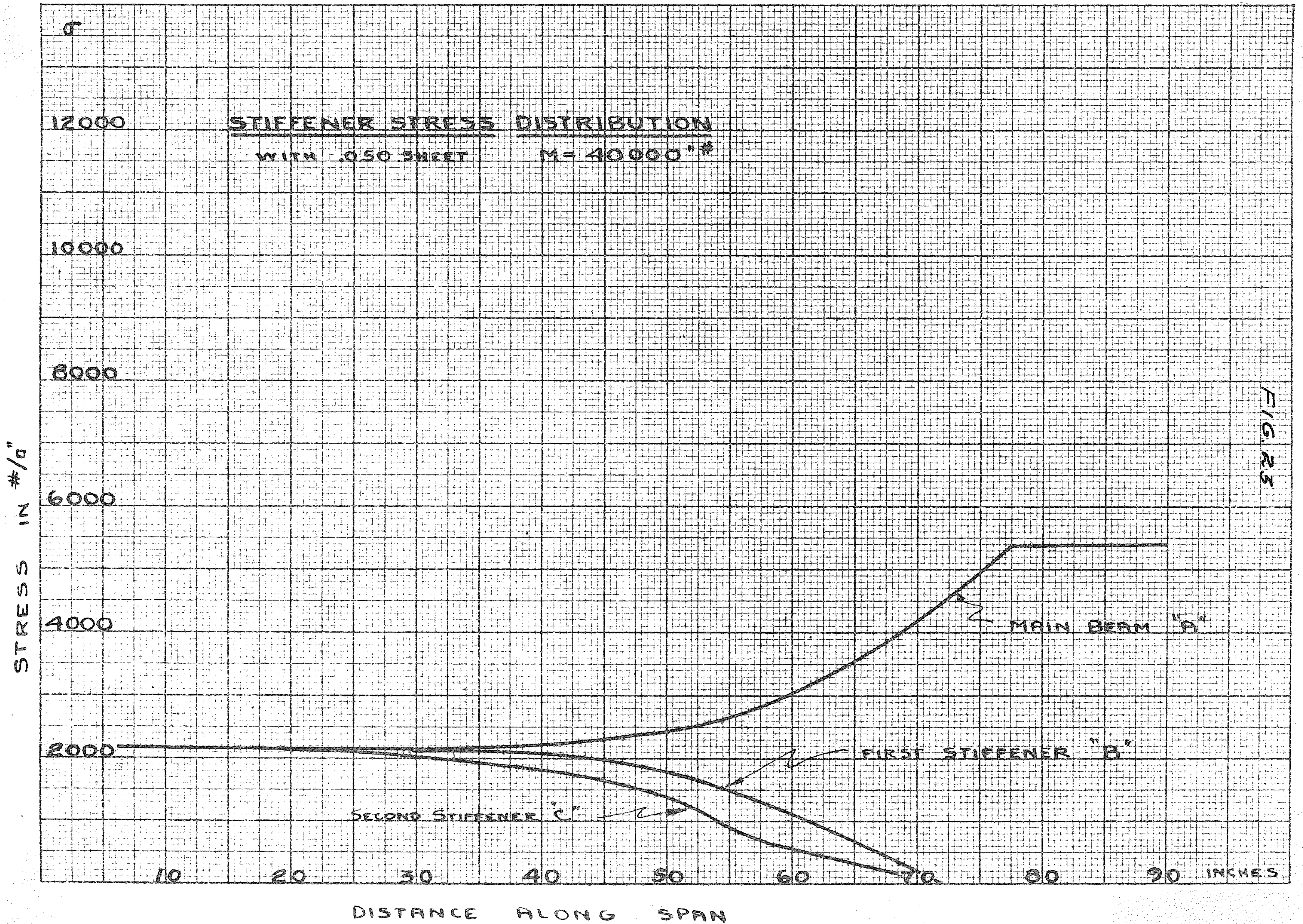


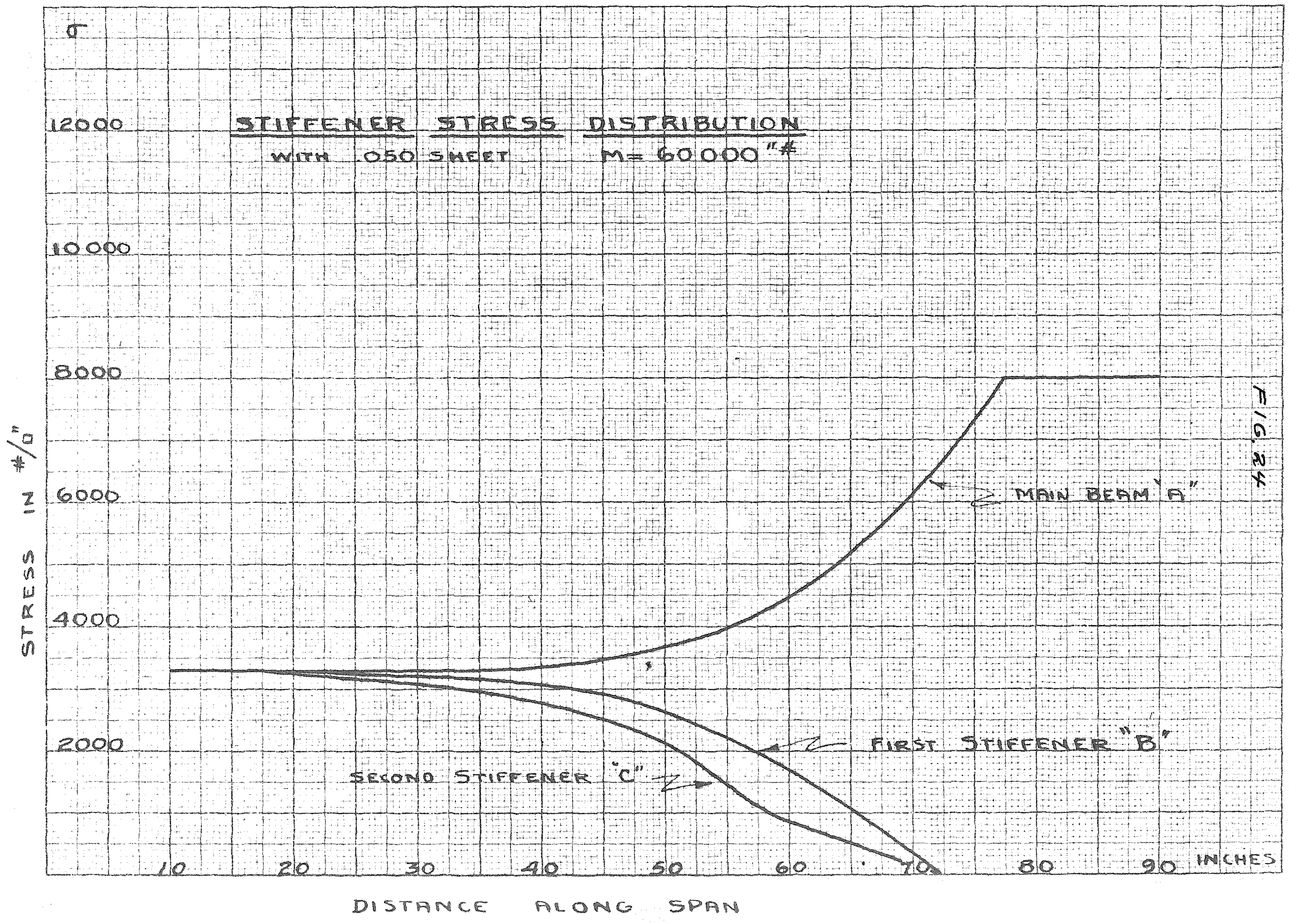
FIG. 21

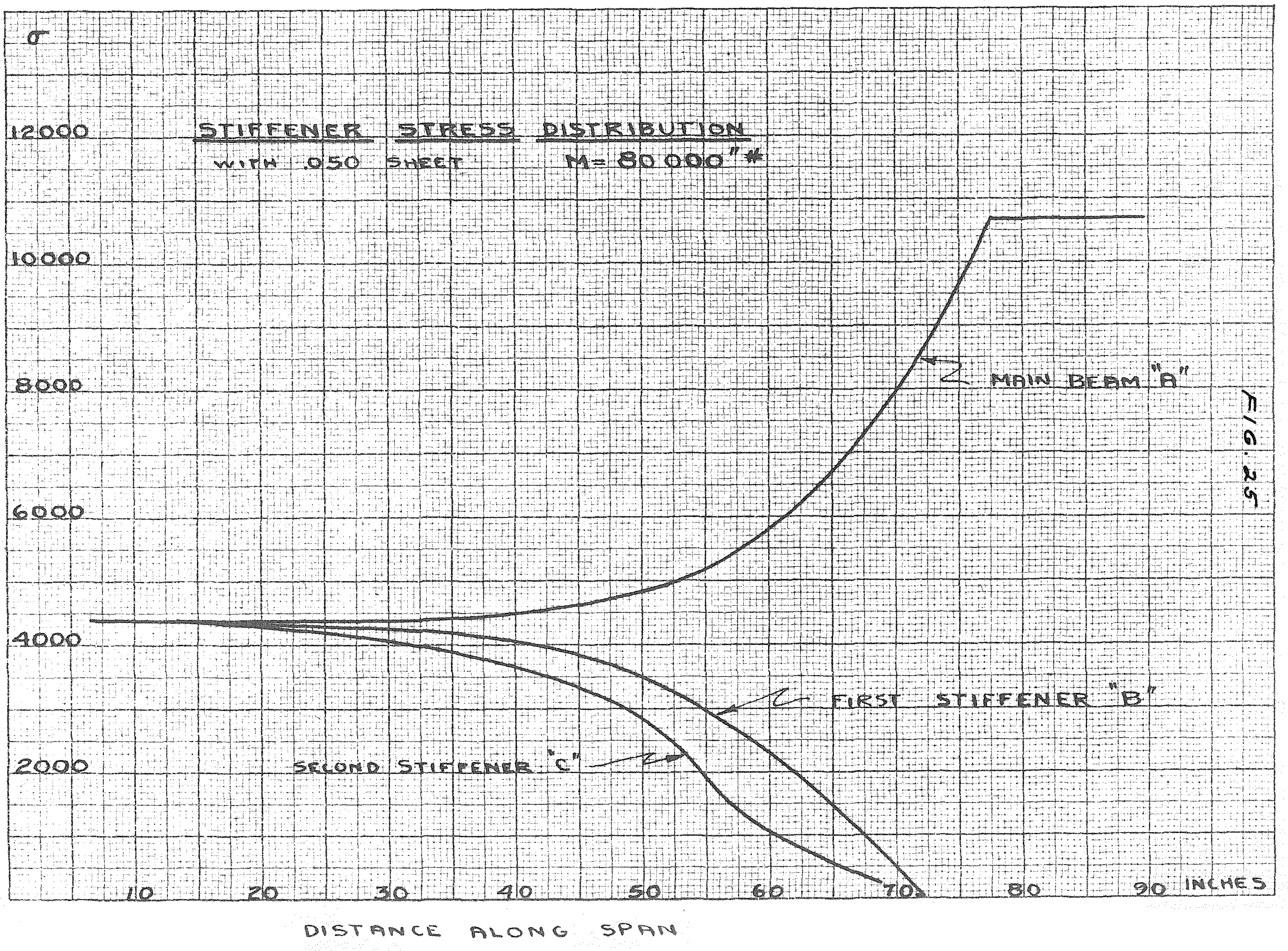


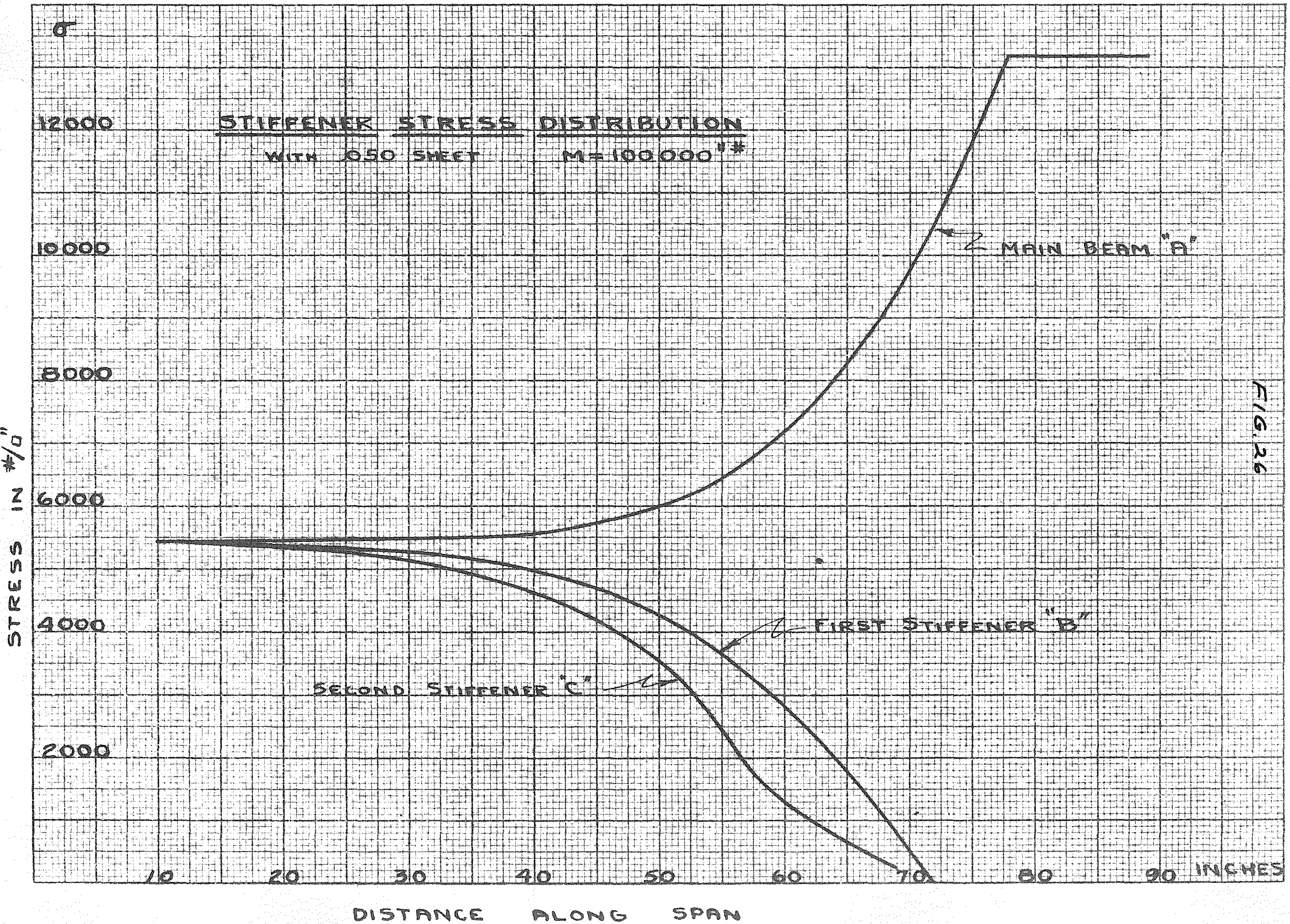
σ
#/□"
12000
10000
8000
6000
4000
2000
STRESS DISTRIBUTION IN STIFFENER "C"
WITH .050 SHEET
M=120000
M=100000
M=80000
M=60000
M=40,000
0
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN

FIG. 22


STIFFENER STRESS DISTRIBUTION
WITH .050 SHEET M= 40000"#
σ
12000
10000
8000
6000
4000
2000
STRESS IN #/□"
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
FIG. 23

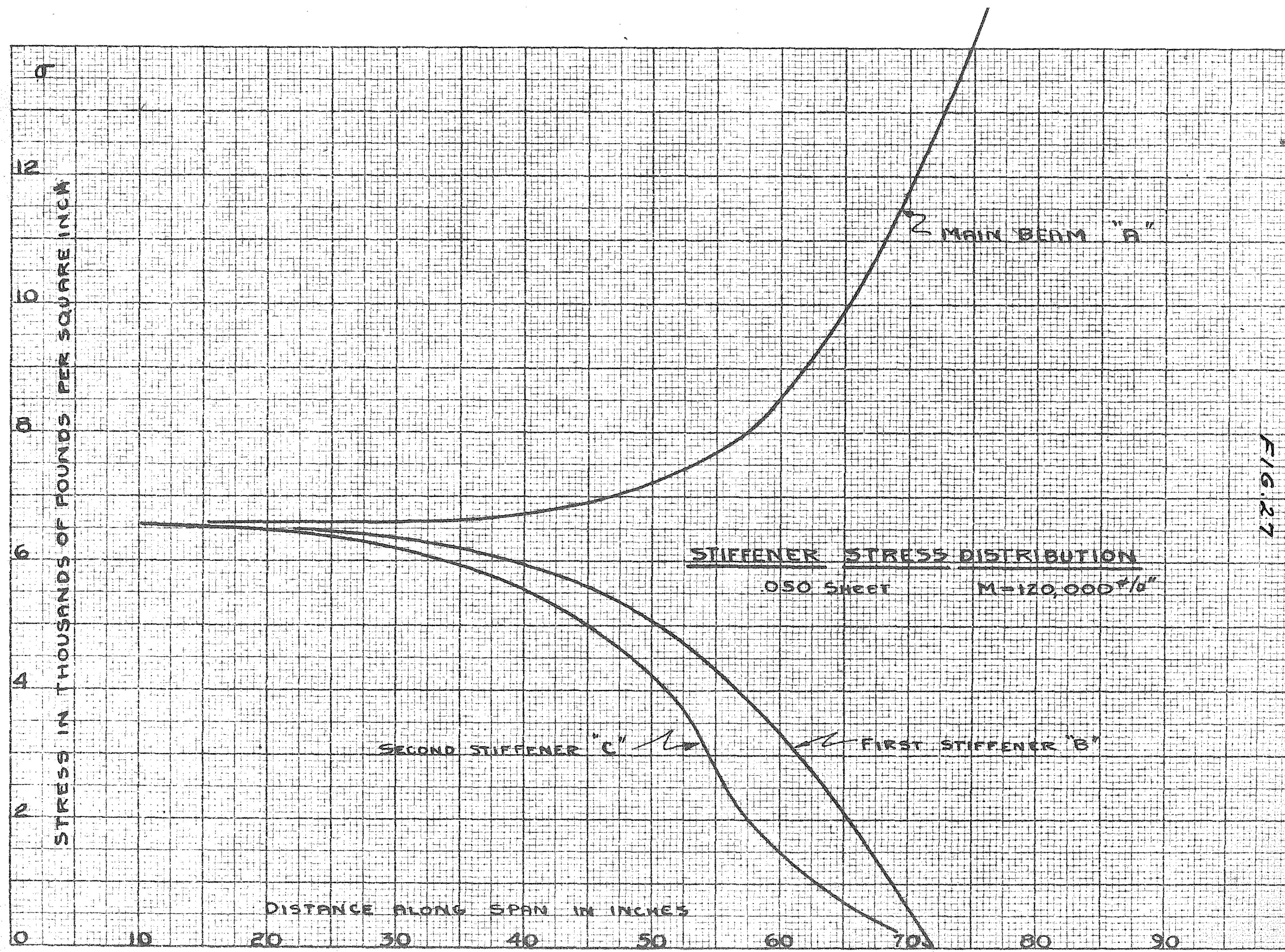

σ
STIFFENER STRESS DISTRIBUTION
WITH .050 SHEET
M= 60000"#
12000
10000
8000
6000
4000
2000
STRESS IN #/□"
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN
FIG. 24


STIFFENER STRESS DISTRIBUTION
WITH .050 SHEET
M= 80 000"#
σ
12000
10000
8000
6000
4000
2000
STRESS IN #/□"
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
FIG. 25



STIFFENER STRESS DISTRIBUTION
WITH .050 SHEET M=100,000"#
σ
12000
10000
8000
6000
4000
2000
STRESS IN #/□"
10
20
30
40
50
60
70
80
90
INCHES
DISTANCE ALONG SPAN
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"

FIG. 26



STIFFENER STRESS DISTRIBUTION
.050 SHEET M=120,000 #/0"
MAIN BEAM "A"
FIRST STIFFENER "B"
SECOND STIFFENER "C"
STRESS IN THOUSANDS OF POUNDS PER SQUARE INCH
DISTANCE ALONG SPAN IN INCHES
σ
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80
90

FIG. 27