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THE EFFECT OF INTERNAL DIAPHRAGMS ON FATIGUE BEHAVIOR OF CURVED BOX GIRDERS

by

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December 17, 1976

Dr. D. A. VanHorn
Chairman, Department of
Civil Engineering

ACKNOWLEDGMENTS

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ABSTRACT

This paper examines the effects of spacing of rigid interior diaphragms on the stresses and deflections of curved box girders. Available computer programs were employed and existing results were utilized with little emphasis on the procedure of computation. The objective was to assess the qualitative relationship between stresses and the coupling influence of diaphragm spacing and curvature, so as to gain insight to the fatigue behavior of box girders.

Results of the analyses showed that decreasing of diaphragm spacing effectively controlled the torsional stresses. The ratio of diaphragm spacing to radius of curved box girders was introduced as a parameter for monitoring stress ranges. It appeared that the relationship between stress ranges and the spacing-to-radius ratio was practically linear for a given geometry of curved box girders. More study is recommended to explore further this ratio as a parameter for controlling the magnitude of stress ranges.

1. INTRODUCTION

Horizontally curved steel box girders with a composite concrete deck (Fig. 1) often are used as bridge members on highways, particularly at the entrances and exists of modern expressways. The ability of the box shape to distribute vehicular loads in the transverse direction of the bridge is the main advantage of these box girders. Because of the curvature, loads on a curved bridge generates torsional stresses in addition to the flexural stresses in the bridge. The box-shaped cross section enables distribution of the torsional stresses among its component parts better than the distribution among parallel plate girders of deck-and-girder type bridges.

Torsional stresses include the St. Venant shearing stresses in the plane of a cross section, the warping normal and warping shearing stresses resulting from warping of the plane cross section (but retaining its shape), and the distortional normal and shearing stresses due to deformation of the cross section. There are a number of methods for evaluating these stresses, such as the theory of thin-walled elastic beams(1,2,3), the theory of folded plates(4), the method of beam-on-elastic-foundation (BEF) analogy(5,6), and various numerical procedures including the method of finite element(7,8). Numerous summaries have been made on the application of these methods to the analysis and design of steel or composite box girders(9,10,11).

The results of these studies have clearly indicated the necessity of transverse diaphragms. Sufficiently rigid diaphragms at supports and in the interior of box girders (as shown in Fig. 1) are essential for maintaining the cross-sectional shapes of box girders against distortion and for reducing the distortional stresses(6,12,13). The spacing of interior diaphragms has been found to be one of the most important factor in this regard.

The objective of this study was to examine the effects of the spacing of rigid interior diaphragms on the stresses and deflections of curved box girders, so as to evaluate the fatigue behavior of these box girders. Existing methods of analysis were employed, and available results were used with little emphasis on computations.

2. DIAPHRAGM SPACING

Besides the spacing of interior diaphragms, the factors influencing the stresses and deflections of horizontally curved box girders include the cross-sectional geometry and dimensions, the length and radius of the girder centroidal axis, the supporting conditions, and the location and magnitude of the loading. A random survey of six curved bridge box girders with rectangular cross sections gave the ranges of nondimensional geometrical parameters as shown in Table 1. The dimensions are defined in Fig. 2.

Also listed in Table 1 are the parametric values of a box girder specimen which is to be tested in Fritz Engineering Laboratory. Except for the length-to-depth ratio, all parametric values fall within the listed ranges. The dimensions of this specimen are shown in Fig. 3. This specimen was arbitrarily chosen for examination.

The finite element method was selected for analysis. The SAP IV computer program(14) was used. Figure 4 shows the discretization of the box girder for the program. The material properties were assumed to be the the following: a yield point of 248 N/mm^2 (36 ksi), the modulus of elasticity being 0.21 MN/mm^2 (30,000 ksi), and a Poisson's ratio of 0.3. Two concentrated loads of 445 kN (100 kips) each were placed directly over the inner web of the box at the quarter points of the simple span. The loads caused bending, rotation, and distortion of the box girder cross section as shown schematically in Fig. 5. The results from the finite element procedure were the total stresses and deflections without separation into flexural, torsional, and distortional components.

The number of interior diaphragms (ND) was varied from 0 to 5 as shown in Fig. 6. The cases of 0 and 5 interior diaphragms had loads between diaphragms whereas for ND = 3 the loads were placed directly over diaphragms.

The results are given in Figs. 7 to 14. Figures 7 and 8 show the total longitudinal normal stresses at the inner and the outer web, respectively. Near the load, the normal stresses were reduced in the inner (loading) web as the number of interior diaphragms increased. Meanwhile, the corresponding stresses in the outer web were increased. For both webs the increase in number of diaphragms equalized the normal stresses along the center half of the span resulting at the bending stresses. This implied that the stress gradient across the bottom flange would reduce to zero as the number of diaphragms increased. That this was true is depicted by Fig. 9. With five interior diaphragms, the stress gradient was practically zero except near the load point. In other words, with sufficient number of interior diaphragms, the torsional stresses were present only locally near the load.

The effects of the interior diaphragms on vertical deflections and distortions are shown in Figs. 10 and 11. Figure 10 shows the reduction in deflection as the number of diaphragms were increased. The cross-sectional distortion (the angle γ in Fig. 2) is plotted along the span length in Fig. 11, and is seen to reduce quite rapidly with ND.

The transverse bending stresses due to cross-sectional distortion can also be expected to be reduced corresponding to the distortion. These stresses are plotted in Figs. 12 and 13. The decrease of stresses were quite significant as ND changed from 1 through 3 to 5. For the case of three interior diaphragms, the loads were at the quarter point diaphragms and the transverse flexural stresses in the webs near these diaphragms were directly effected by the loads.

Figure 14 illustrates the effects of diaphragm spacing on the total shearing stresses. It appears that only small changes of shearing stresses took place when diaphragm spacing was increased.

For comparison, the stresses and deflections were computed for a straight box girder having the same loading condition and geometry of the curved specimen, except for the radius. The length-to-radius ratio for the straight box was zero. The total longitudinal normal stresses had the same pattern of variation along the length as for the curved box girders. This can be seen when comparing the stress profile plots (Figs. 15 and 16) with Figs. 7 and 8 for the curved box. Because the bending normal stresses were identical for the straight and the curved box girder, a direct comparison of the torsional normal stresses could be made. Figures 17 and 18 show that, regardless of diaphragm spacing, the torsional stresses were lower for the straight box girder. The increase in number of interior diaphragms from 1 to 3, however, had stronger effects on the torsional stresses.

Results of deflections and distortions from the straight and curved box girder specimen are compared in Tables 2 and 3. The influence of curvature (L/R) and of diaphragm spacing both were not priminent on the total deflections, as is indicated by the very small changes in values in Table 2. On distortion, the effects of both curvature and diaphragm spacing were important. At the load point, the distortion was reduced to approximately one-half by adding interior diaphragms at the quarter points in either box girder. The curvature caused a change of maximum distortion of the same order of magnitude at the load point. Thus, in order to reduce distortional stresses in box girders, the required number of interior diaphragms must be determined with consideration of the box girder curvature or the length-to-radius ratio.

3. DIAPHRAGM SPACING TO RADIUS RATIO

To explore further the influence of diaphragm spacing and curvature on the stresses of box girders, analysis was made of an arbitrary box girder with a prismatic cross section, but variable span length and radius. The dimensions of the model are given in Fig. 10. Rigid interior diaphragms of 9.5 mm (3/8 in.) thick were placed at a spacing of L/2 to L/12. The span length-to-radius ratio varied from 1/24 to 0.6. The computer program CURDI was used for the analysis. This program(7) employs the finite strip method and provides rapid solutions to the element forces and displacements of box girders. The discretization of the box girder for analysis is shown in Fig. 20.

The outcome of the analysis were stresses and deflections which could be plotted in figures similar to Figs. 7 to 18. The trend was the same; increase of the number of diaphragms decreased the torsional and distortional stresses. To incorporate the curvature, the maximum normal stress ranges corresponding to the applied load are plotted in Fig. 21 as a function of a/R, the ratio of diaphragm spacing to box girder radius. It appears from this plot that the stress range versus a/R relationship was linear for any ratio of L/R, a condition which could lend great help in determining the necessary spacing of diaphragms. Additional information is needed to examine this relationship some more.

There are only limited results of analysis with regard to stresses and diaphragm spacing in curved box girders. Heins(12,15) used the partial differential equation of distortion by Dabrowski(2). A parametric study was conducted from which an empirical formula was established for estimating distortional stresses of curved box girders. The results from the parametric study were used here in the examination of diaphragm spacing and curvature.

The two box girder cross sections of Ref. 12 are shown in Fig. 22. The girders had the same width but different depth. The number of diaphragms varied from one to nineteen. Three different lengths of span were examined. The computed maximum distortional stresses are plotted in Figs. 23 and 24 against the number of diaphragms. Regardless of the L/R ratio, the distortional stress decreased with increasing number of diaphragms. Box girders with higher L/R values, that is, with longer spans or sharper curves, had higher distortional stresses.

The relationship between stress ranges and spacing-to-radius ratios are depicted in Figs. 25 to 30 for the two box girders with different span lengths. The relationship is practically linear for low values of L/R. For sharp curved box girders with high L/R values, the stress range decreases with decreasing of diaphragm spacing at a rate slightly different from a linear one. For comparison, straight box girder stress ranges are also included in the figures. The lines for these cases are straight and the abscessa is a/L.

Since the non-linear lines in Figs. 25 to 30 are concaved upward and all lines converge to a point, straight line approximations connecting the terminal points of the curves are on the conservative side. This, as stated earlier, could lend great help in deciding the spacing of interior diaphragms of curved (and straight) box girders.

4. FATIGUE CONSIDERATIONS

The generation of torsional and distortional stresses in curved box girders under live load results in higher ranges of longitudinal stresses. Stress range controls the fatigue life of bridge components(16). Thus, torsional and distortional stresses might reduce the fatigue life of curved box girders if such stresses are not controlled.

While studies are in progress to investigate the effects of stress gradient or the fatigue behavior of curved plate girders and box girders(17), the initial stage of fatigue crack propagation has been well described(18). Design stress range curves have been specified by AASHTO(19) and are reproduced in Fig. 31. It is of paramount importance that the live load stresses do not exceed the specified values at a desired life span of the structure.

For a given geometry, loading, and supporting conditions of a curved box girder, the bending stresses are determined. Only the torsional and distortional stresses can be reduced through the adding of interior diaphragms. The stress range versus diaphragm spacing plots similar to Figs. 25 to 30 could be used in conjunction with the AAASHTO design stress range curves to determine the diaphragm spacing. For an expected life of a structural detail, the allowable stress range of Fig. 31 is applied to the stress range versus spacing plot of the box girder and an appropriate spacing can be chosen.

The distortional component of torsion also causes transverse bending of the web plates (as shown in Figs. 12 and 13). Such stresses may induce fatigue cracking of the junction of box girder components. Fortunately the addition of transverse interior diaphragms reduces the transverse bending stresses effectively. At the diaphragm where a load is applied, local stresses maybe significant (see Fig. 13) and must be analyzed.

5. SUMMARY AND CONCLUSIONS

In summary the following conclusions could be made:

1. Curved box girders were subjected to higher stresses as compared to straight box girders because of the curvature.
2. Increasing the number of diaphragms or reducing the diaphragm spacing, effectively controlled the longitudinal normal stresses as well as the transverse bending stresses.
3. The overall deflection was not significantly effected by diaphragm spacing but the distortion was effected.
4. The plots of stress range versus spacing-to-radius ratio (a/R) were practically linear for low values of span length to radius ratio (L/R).
5. Straight line approximation of stress range to a/R relationship was in the conservative side.
6. These stress range a/R lines could be used with the AASHTO design stress range curves to determine the required diaphragm spacing.

More in-depth study on the parameter of a/R is recommended.

TABLE 1

RESULTS OF SURVEY OF SOME BOX GIRDER BRIDGE PARAMETERS FOR ANALYSIS

DIMENSIONLESS PARAMETER	RANGE	SELECTED VALUES
$\frac{b}{d}$	0.96 — 1.0	1.0
$\frac{e}{b}$	0.1 — 0.6	0.33
$\frac{L}{d}$	16.0 — 37.0	12.0
$\frac{d}{t_w}$	88.0 — 168.0	96.0
$\frac{b}{t_b}$	24.0 — 330.0	96.0
$\frac{t_b}{t_t}$	0.3 — 1.0	0.33
$\frac{L}{R}$	0.06 — 1.09	0.3

TABLE 2

COMPARISON OF DEFLECTIONS

		LOCATION ALONG SPAN			
L/R	ND	$1/8$ L	$1/4$ L	$3/8$ L	$1/2$ L
0	1	5.16	9.27	10.54	10.79
0.3		5.59	9.91	10.92	11.18
0	3	4.85	8.79	10.29	10.72
0.3		5.08	8.89	10.16	10.41

TABLE 3

COMPARISON OF DISTORTIONS

		LOCATION ALONG SPAN			
L/R	ND	1/8 L	1/4 L	3/8 L	1/2 L
0	1	0.000312	0.00144	0.00089	0.00053
0.3		0.00202	0.00267	0.00167	0.001
0	3	-0.00026	0.0007	0.0004	0.0002
0.3		0.00081	0.0015	0.001	0.0007

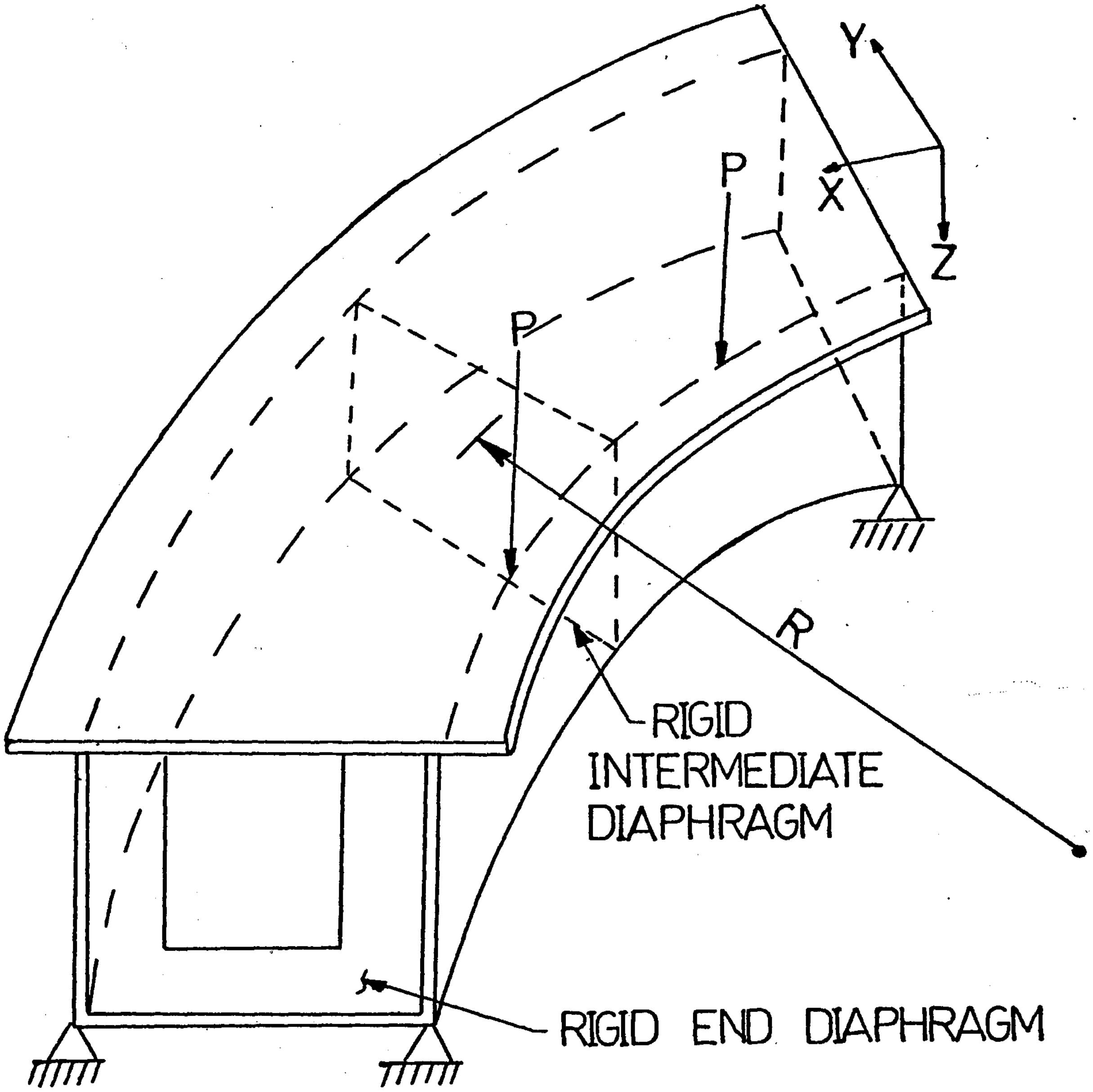


Fig. 1 Curved Box Girder

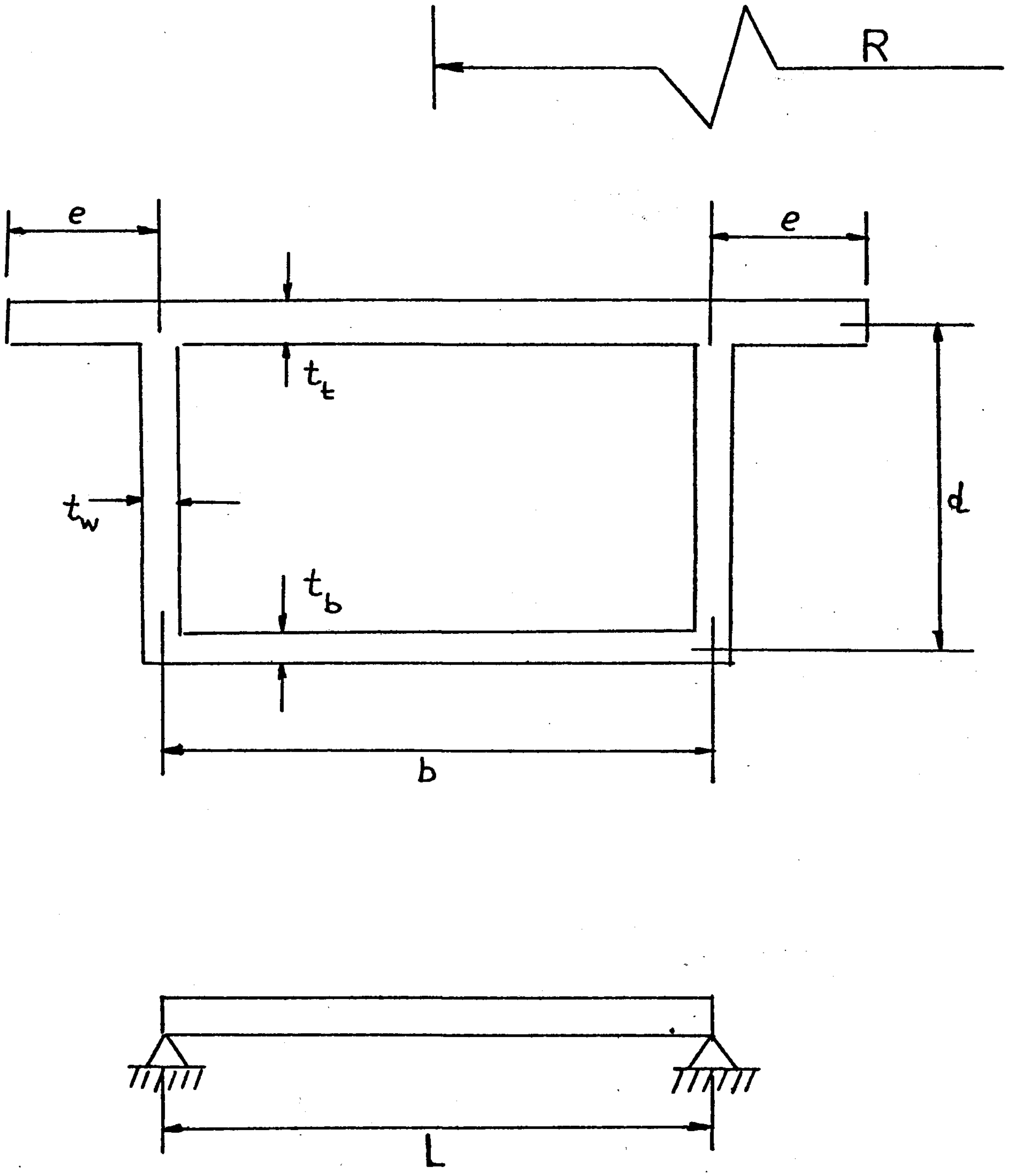


Fig. 2 Variable Parameters for Existing Bridges

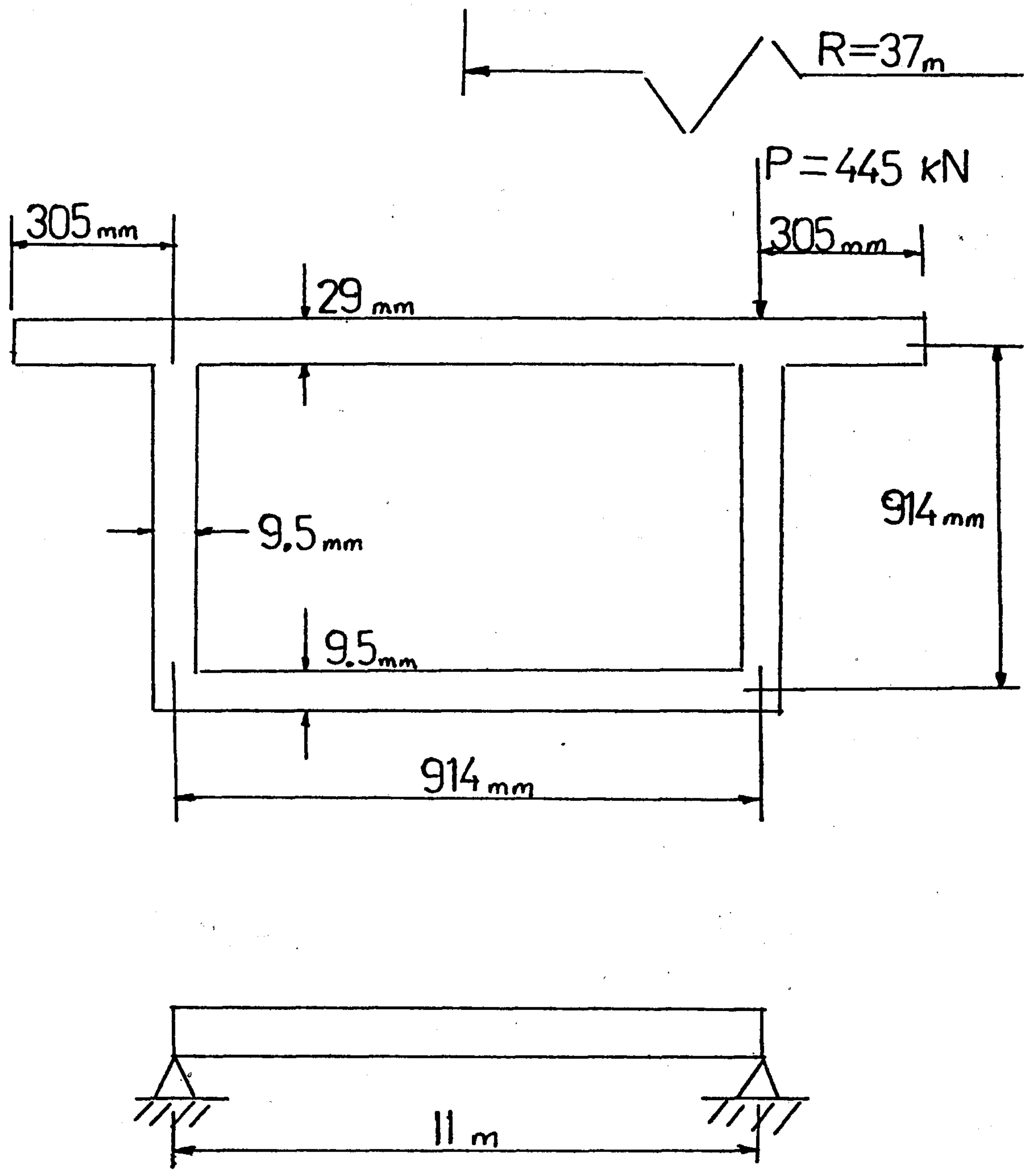
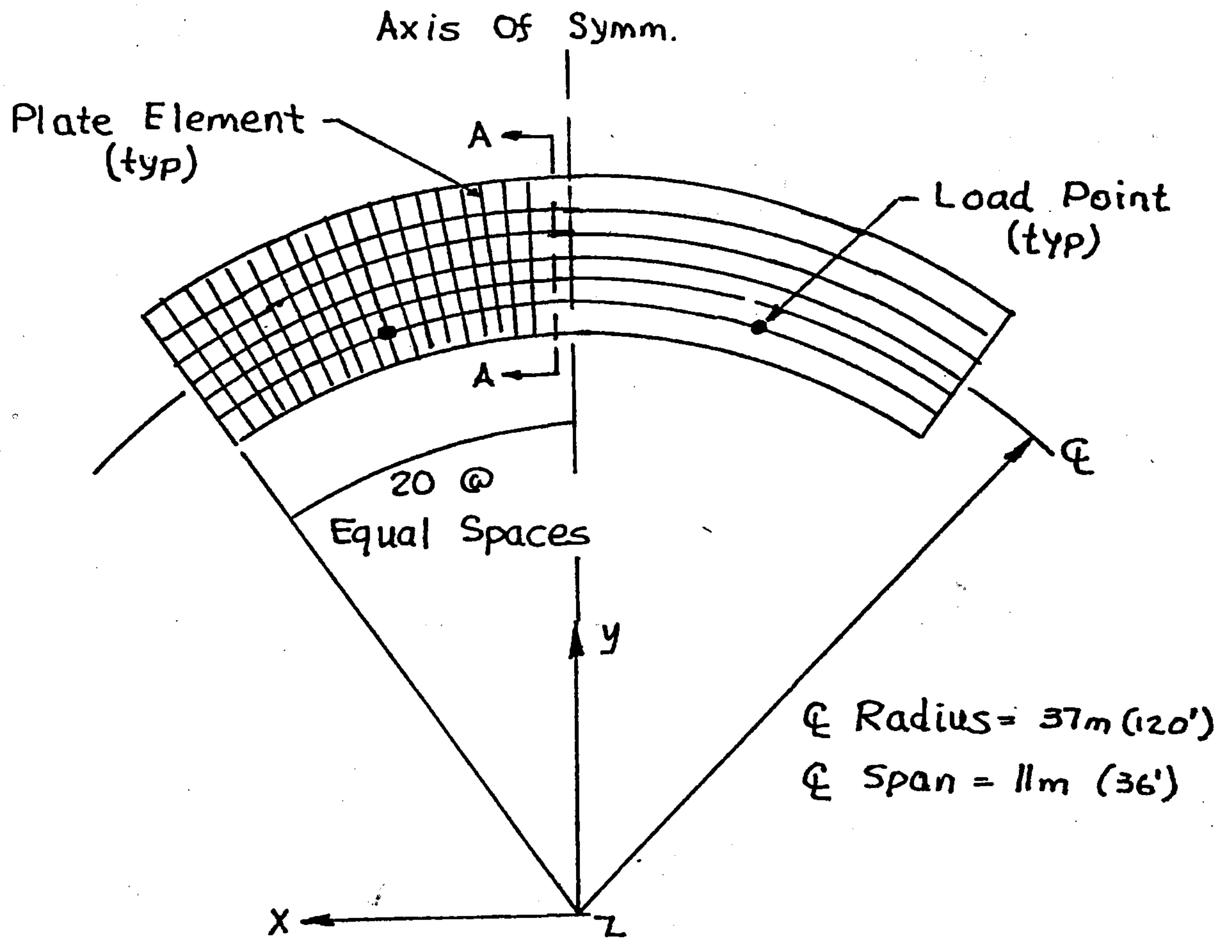


Fig. 3 Computer Input Dimensions for Model Box Girder BG3



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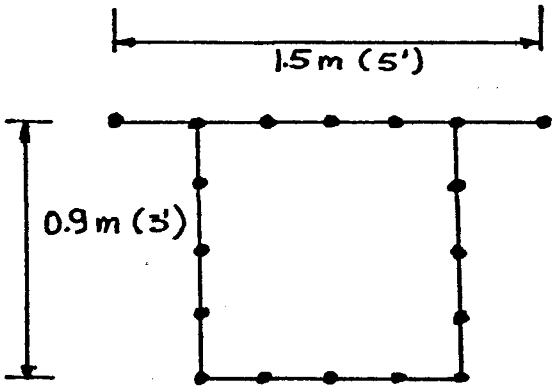


Section A-A

Fig. 4 Finite Element Discretization for Analysis of Box Girder Model by SAP IV

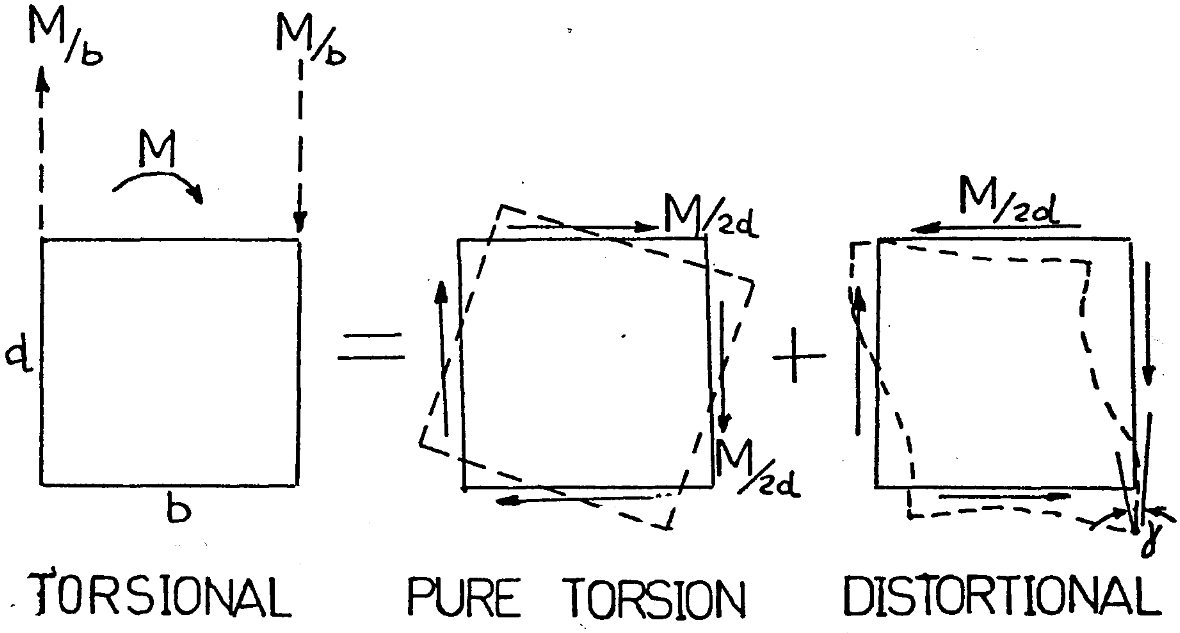


Fig. 5 Torsional Loading Components

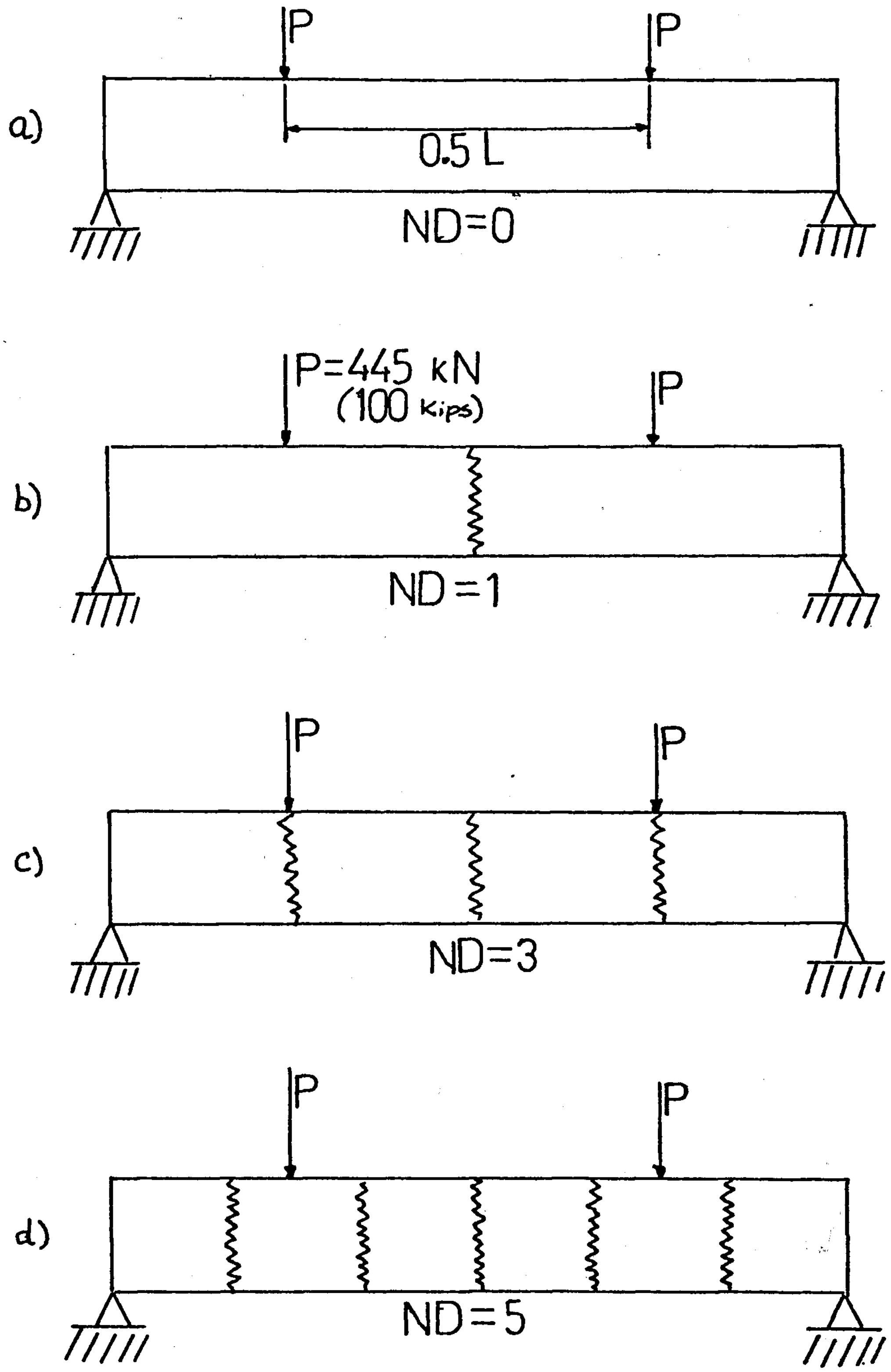


Fig. 6 Concentrated Loads and Number of Diaphragms Used

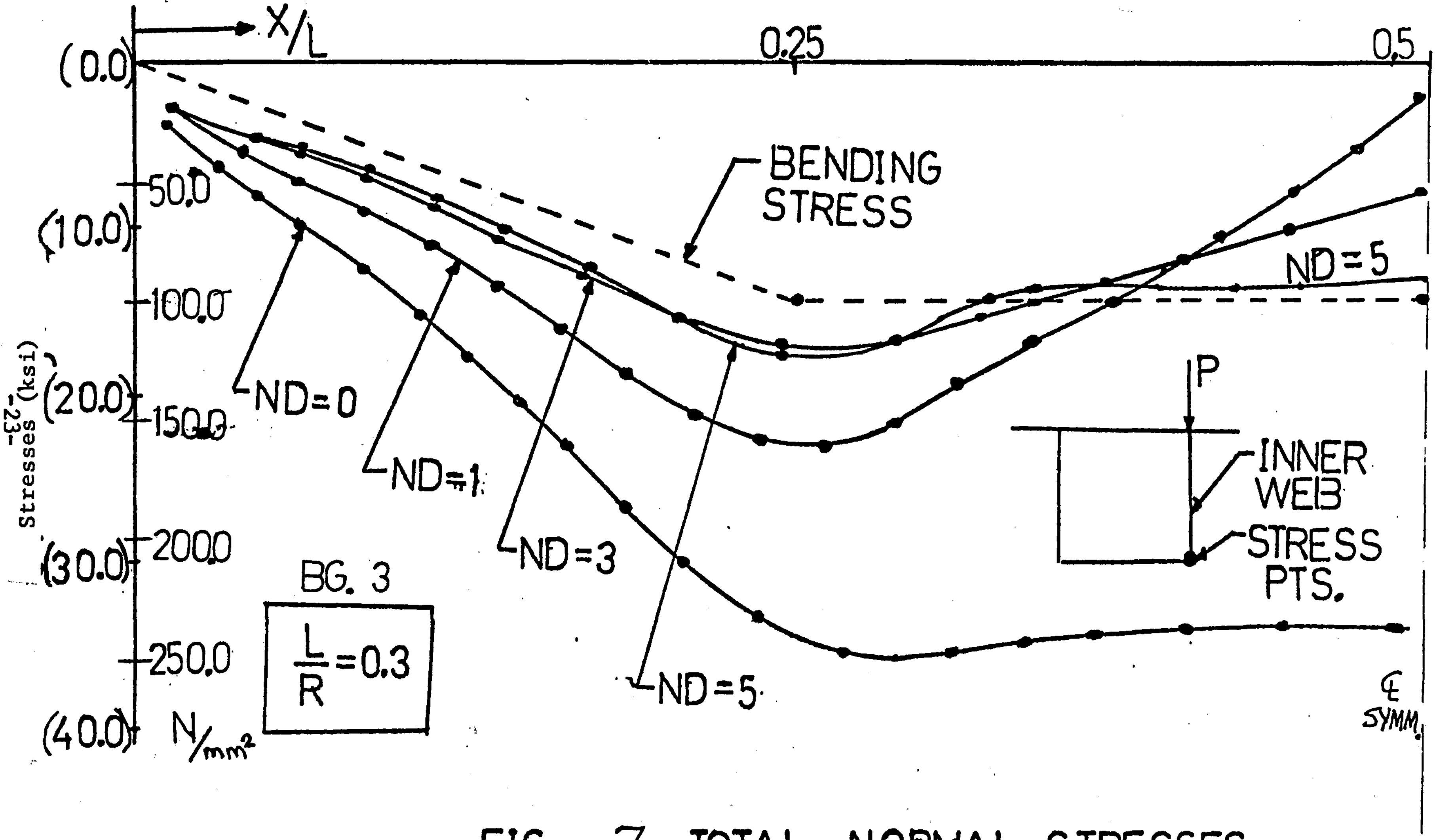


FIG. 7 TOTAL NORMAL STRESSES

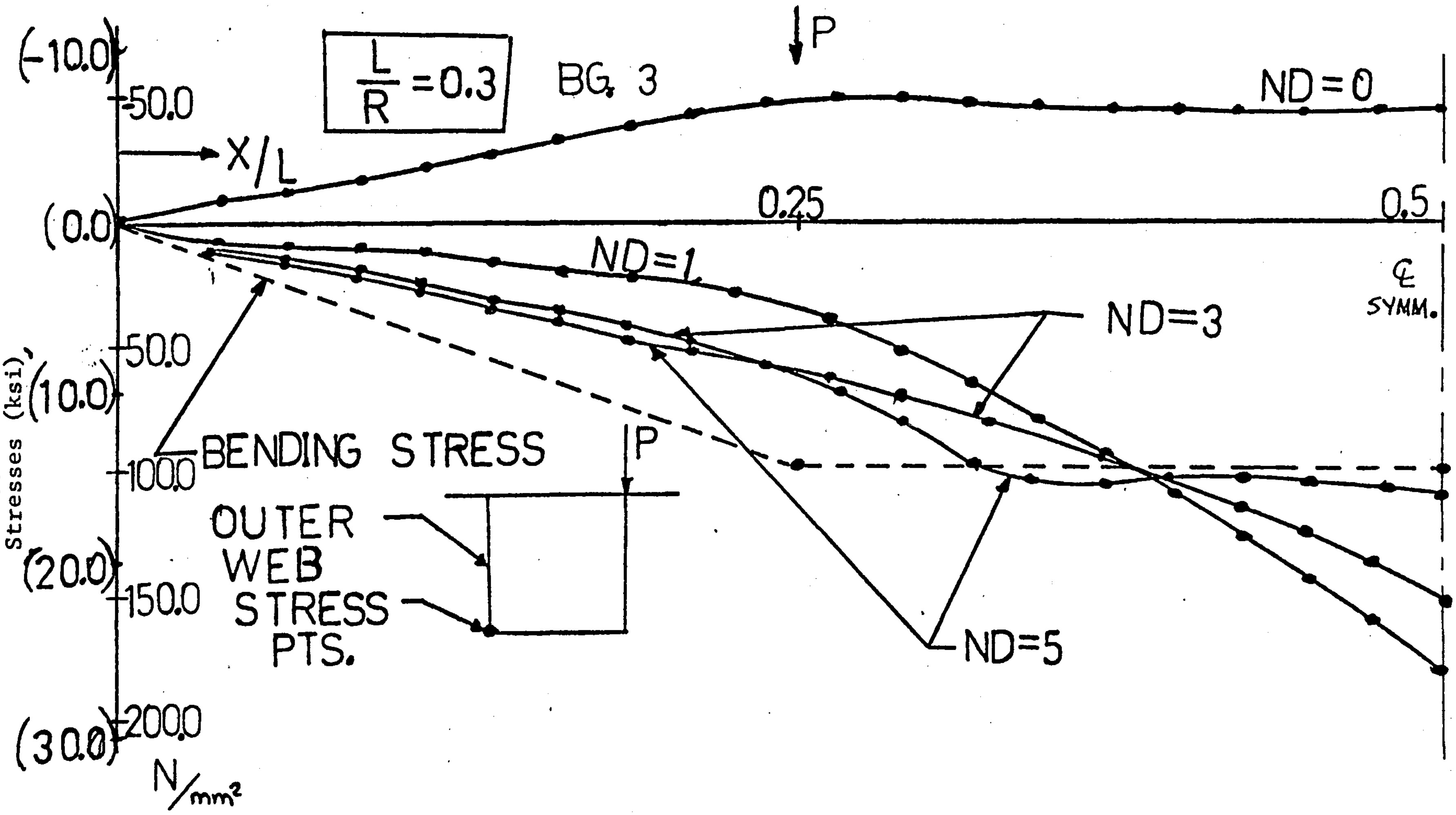


FIG. 8 TOTAL NORMAL STRESSES

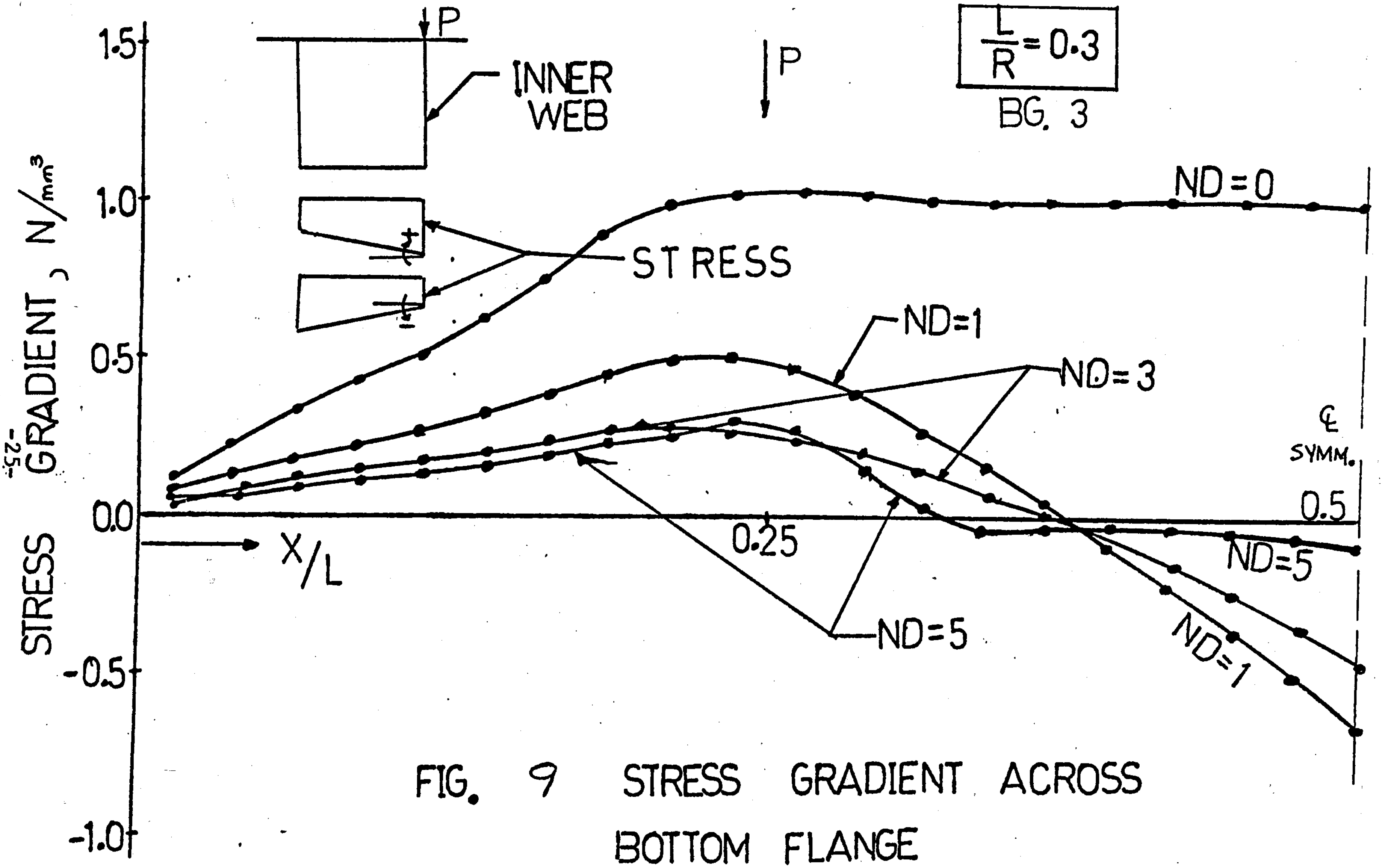


FIG. 9 STRESS GRADIENT ACROSS BOTTOM FLANGE

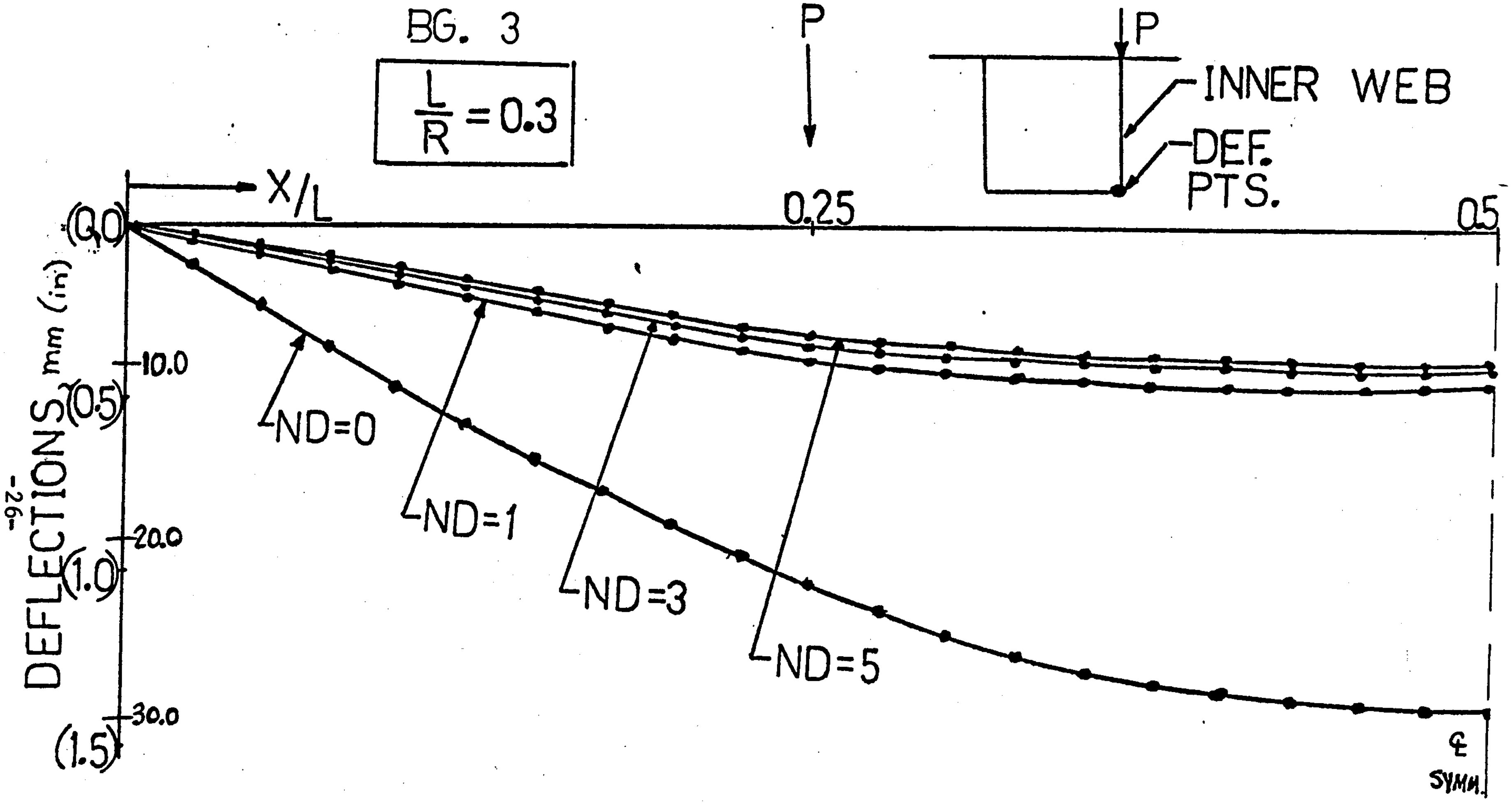


FIG. 10 VERTICAL DEFLECTIONS

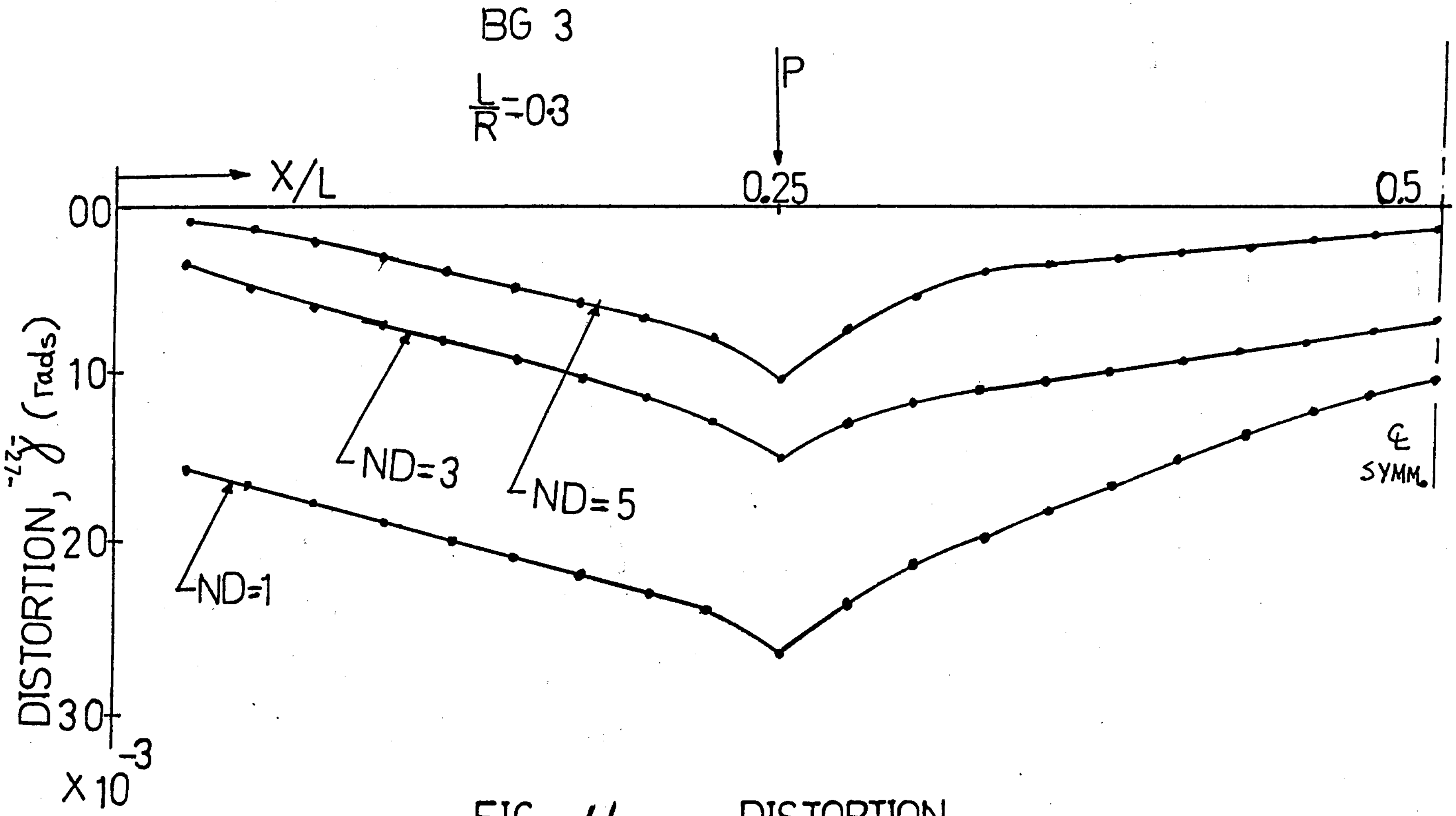


FIG. 11 DISTORTION

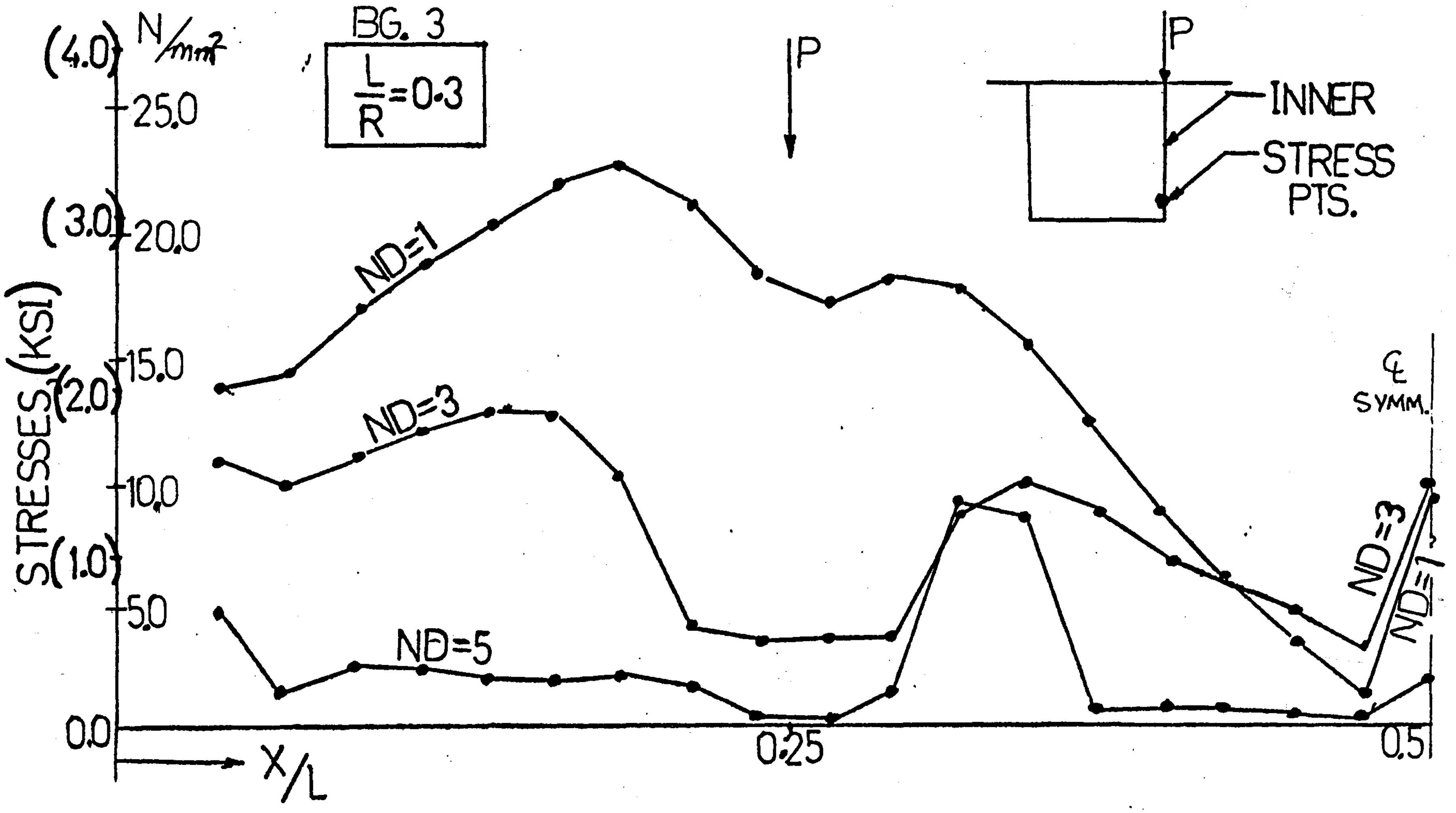


FIG. 12 TRANSVERSE FLEXURAL STRESSES

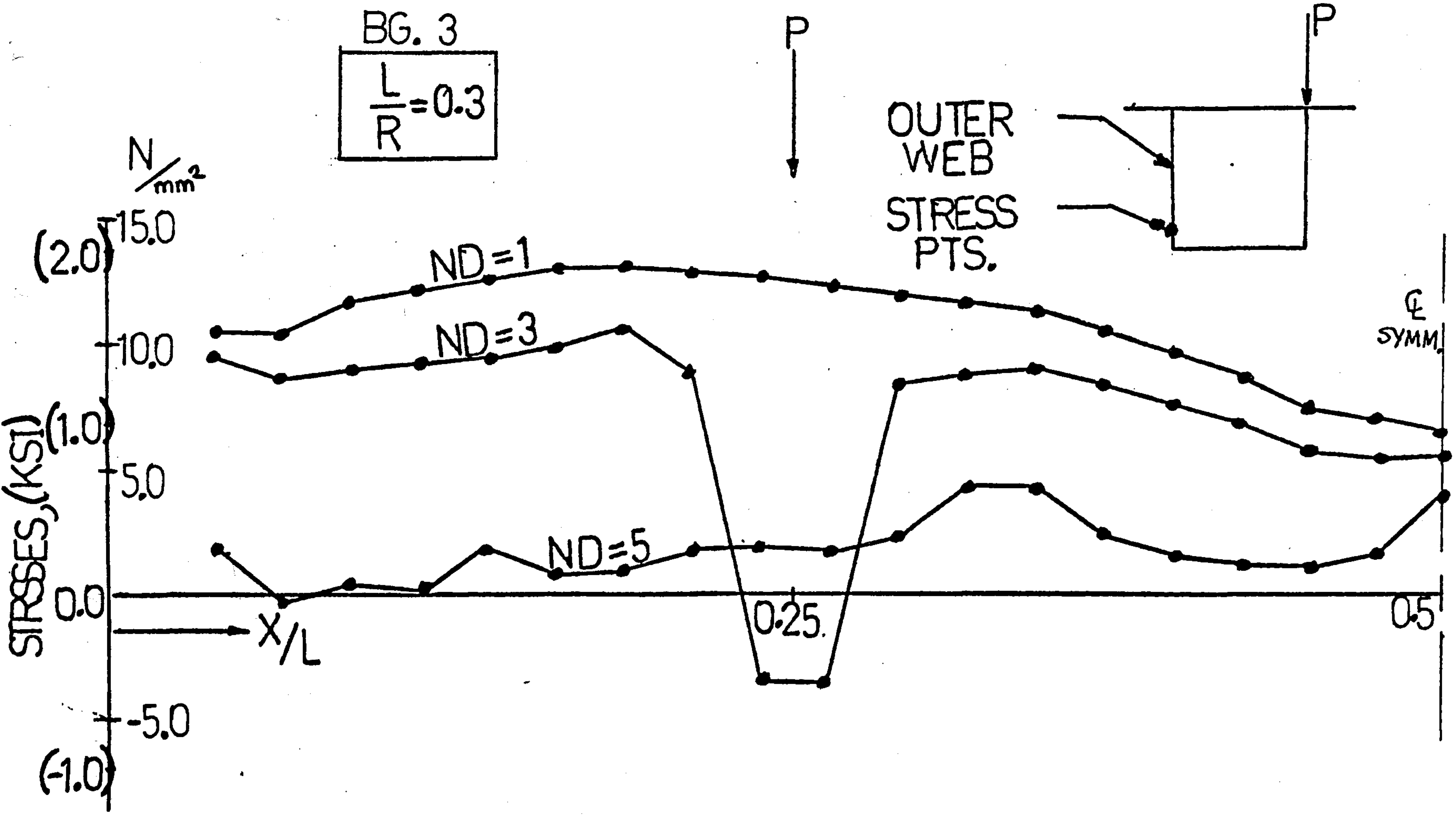


FIG. 13 TRANSVERSE FLEXURAL STRESSES

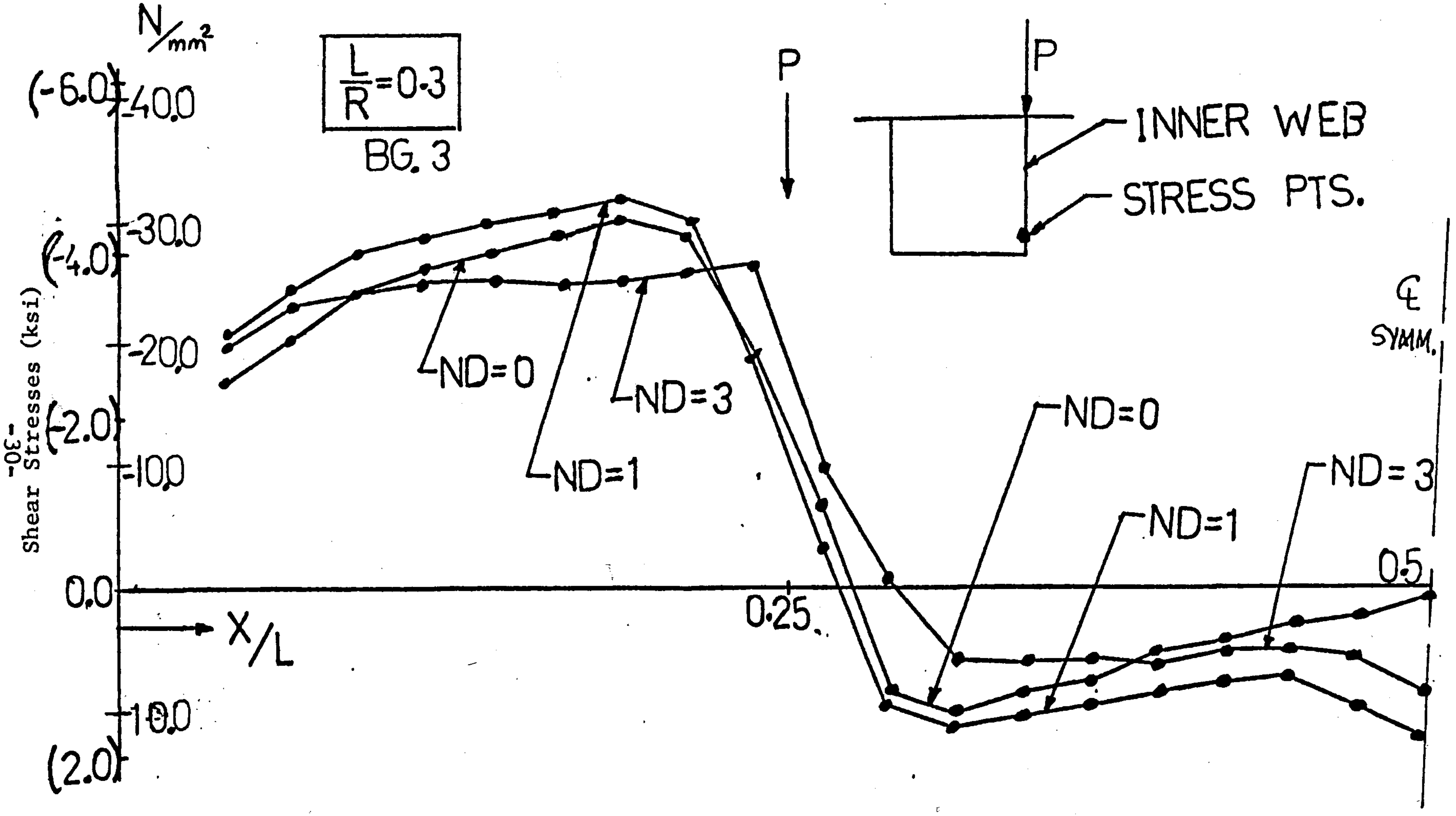


FIG. 14 SHEAR STRESSES

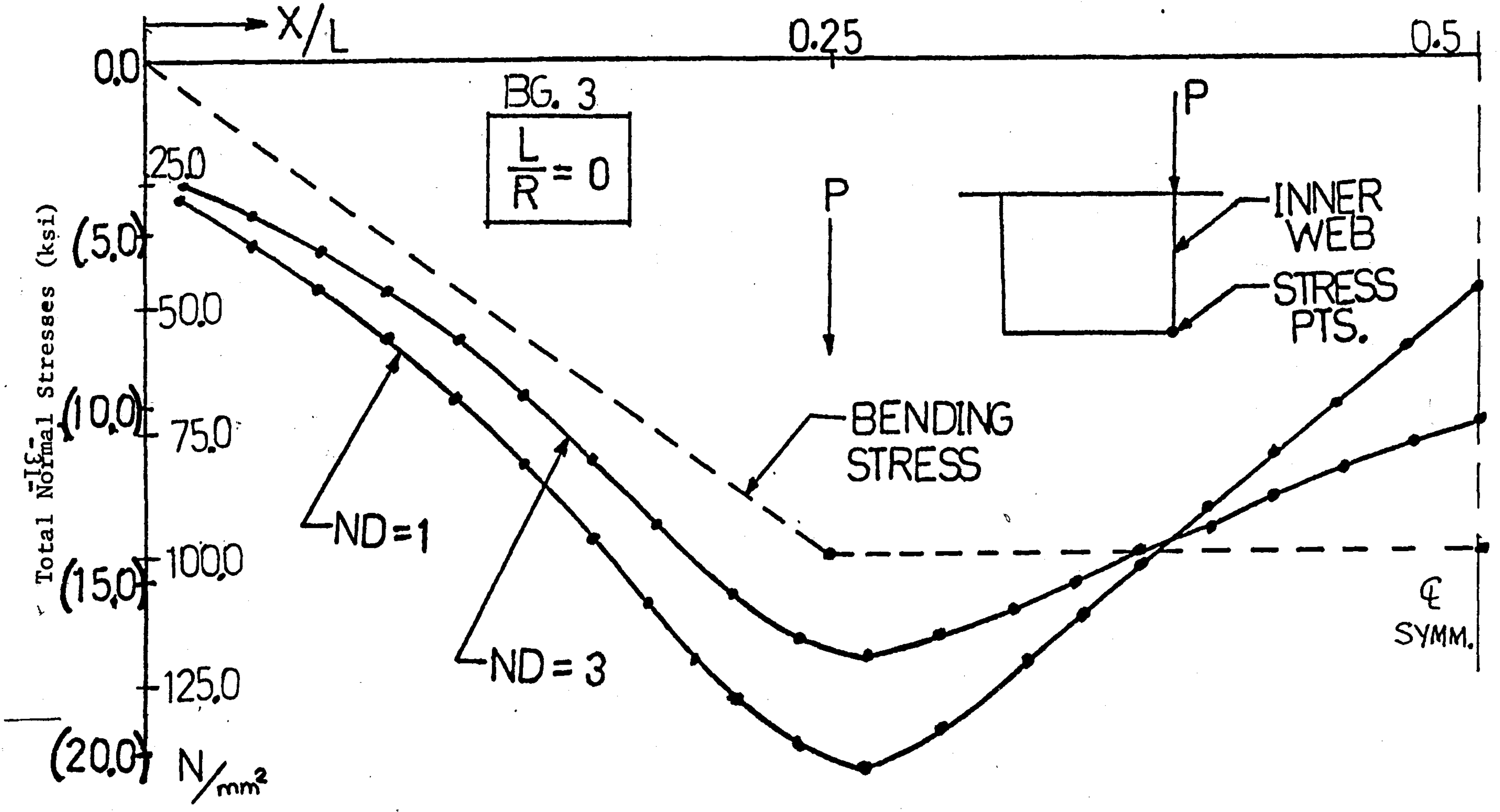


FIG. 15 TOTAL NORMAL STRESSES

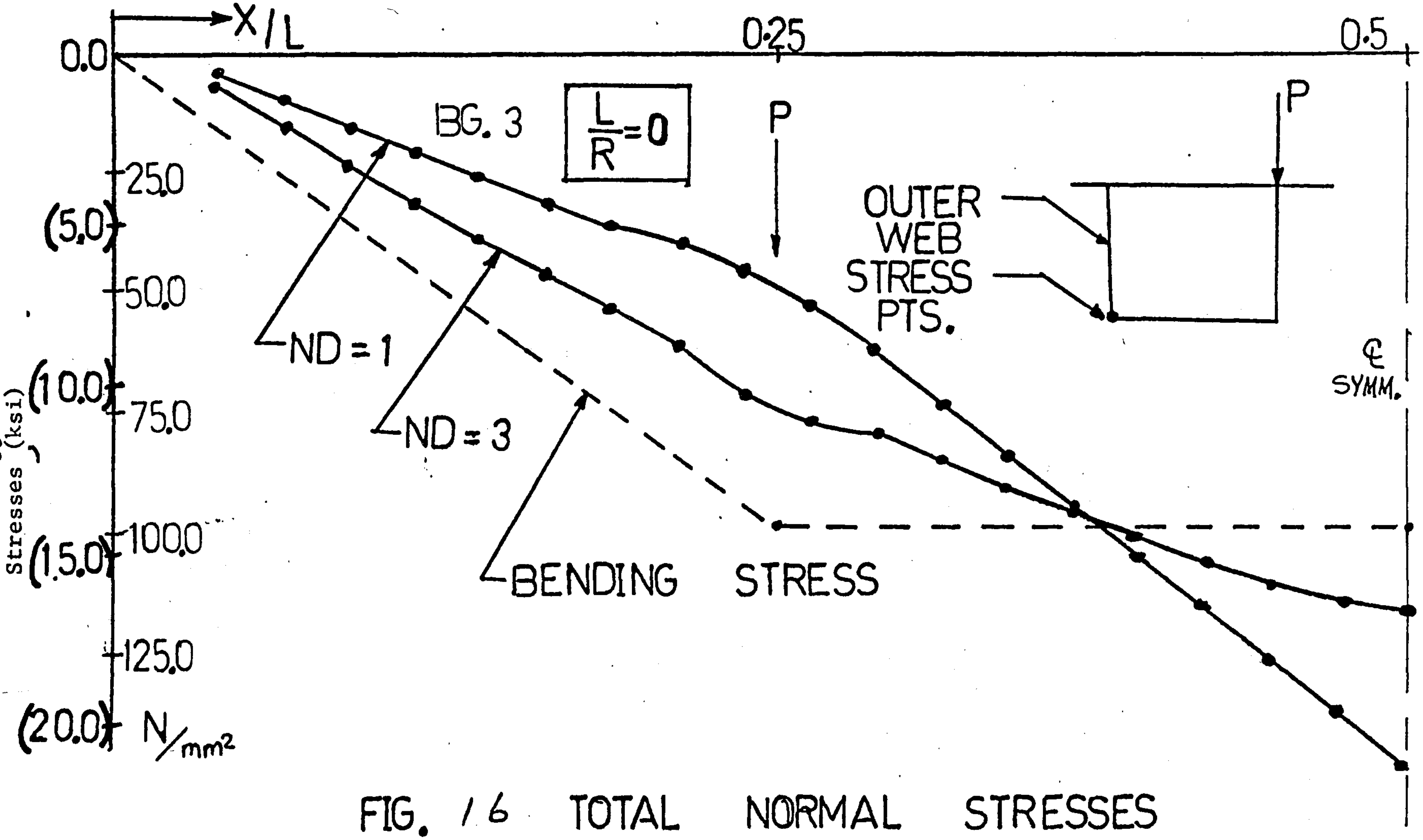


FIG. 16 TOTAL NORMAL STRESSES

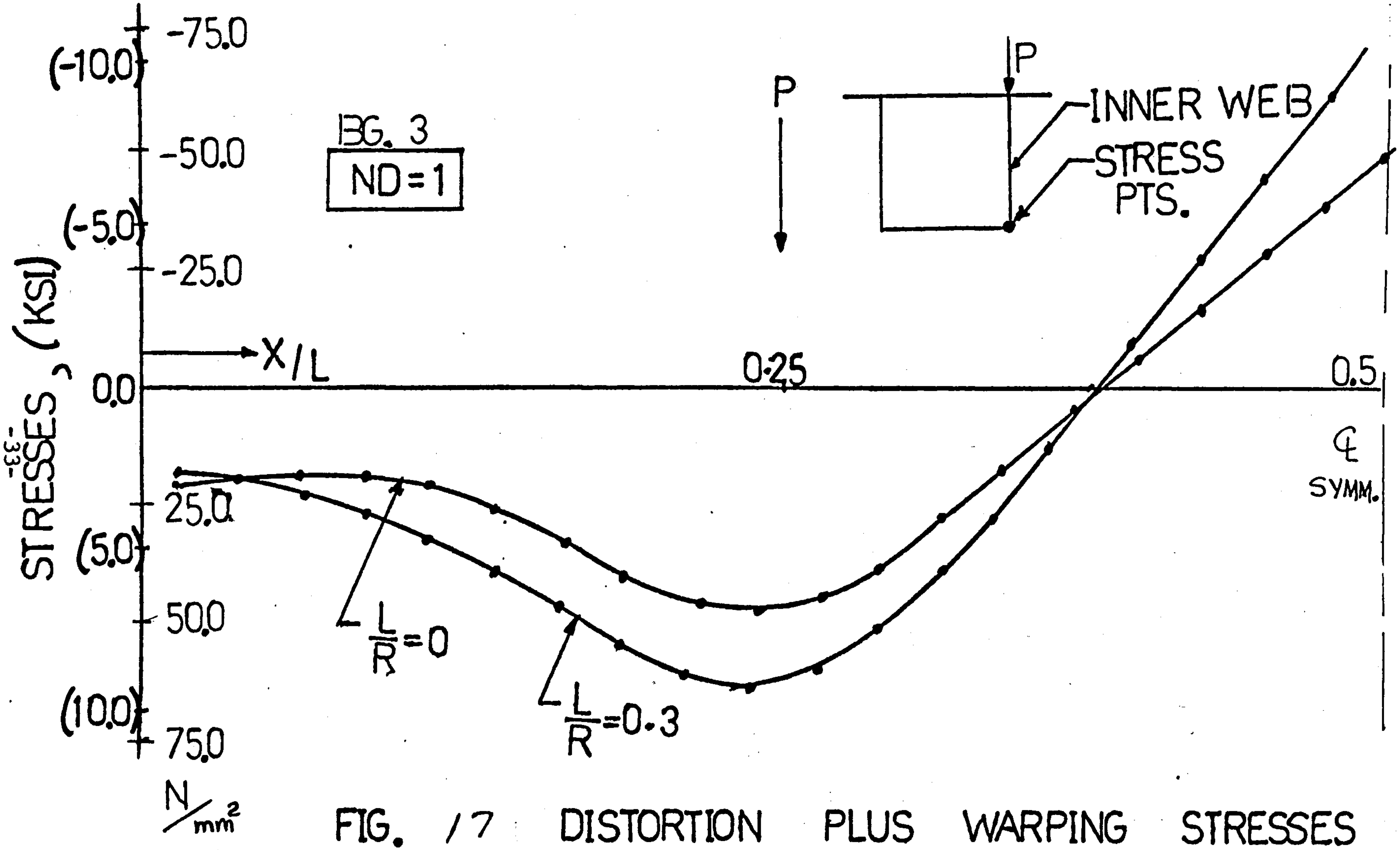


FIG. 17 DISTORTION PLUS WARPING STRESSES

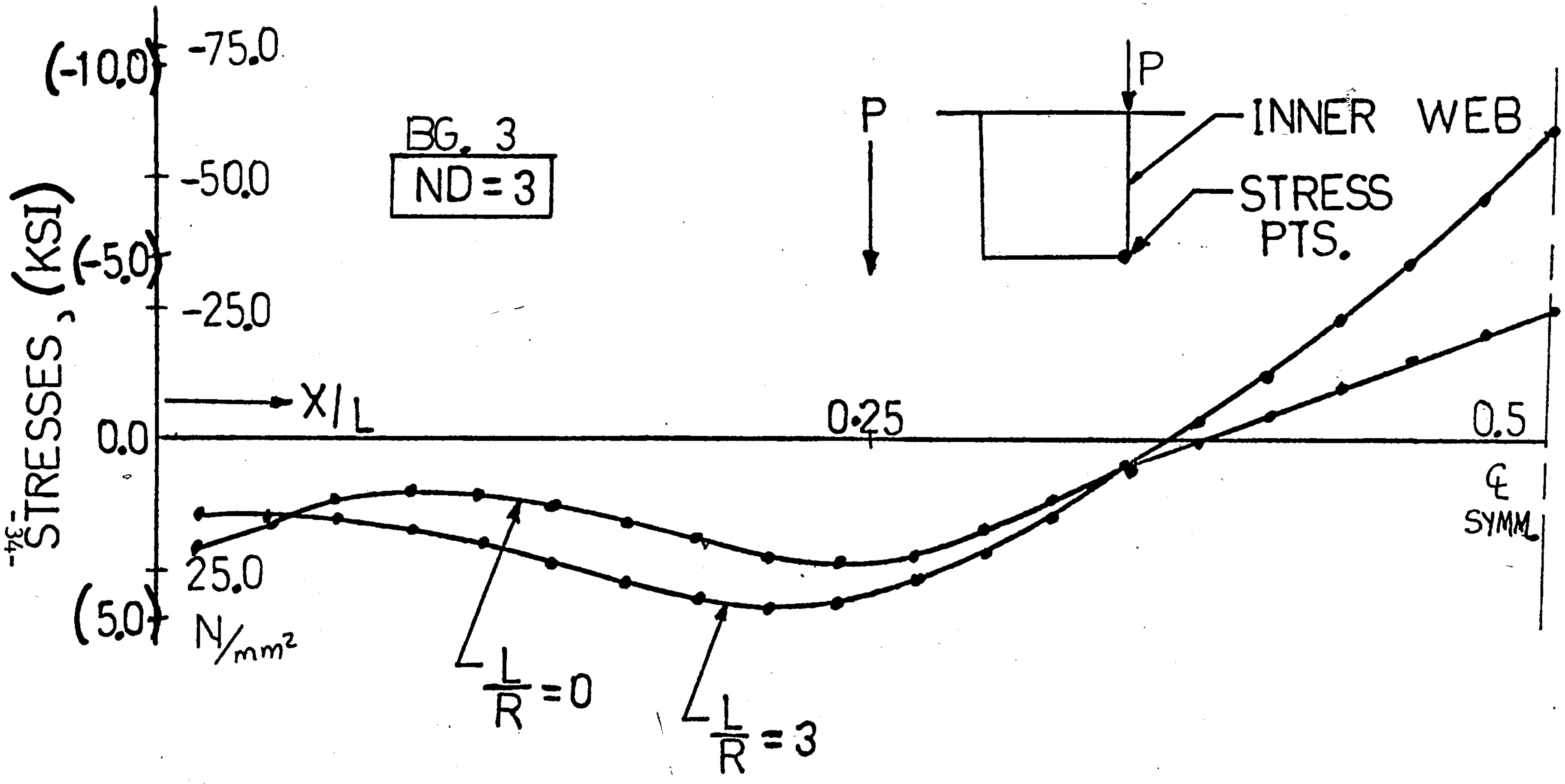


FIG. 18 DISTORTION PLUS WARPING STRESSES

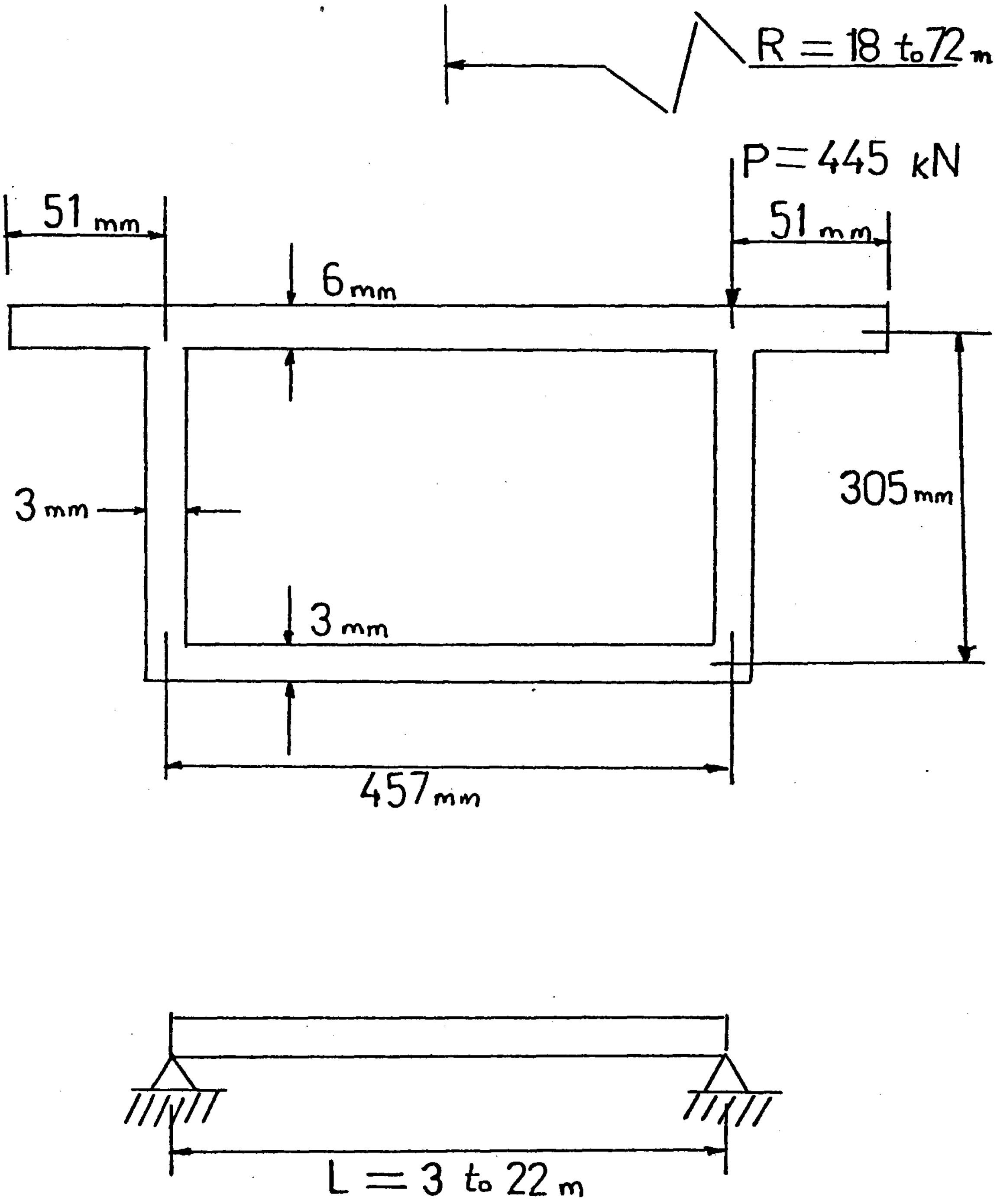
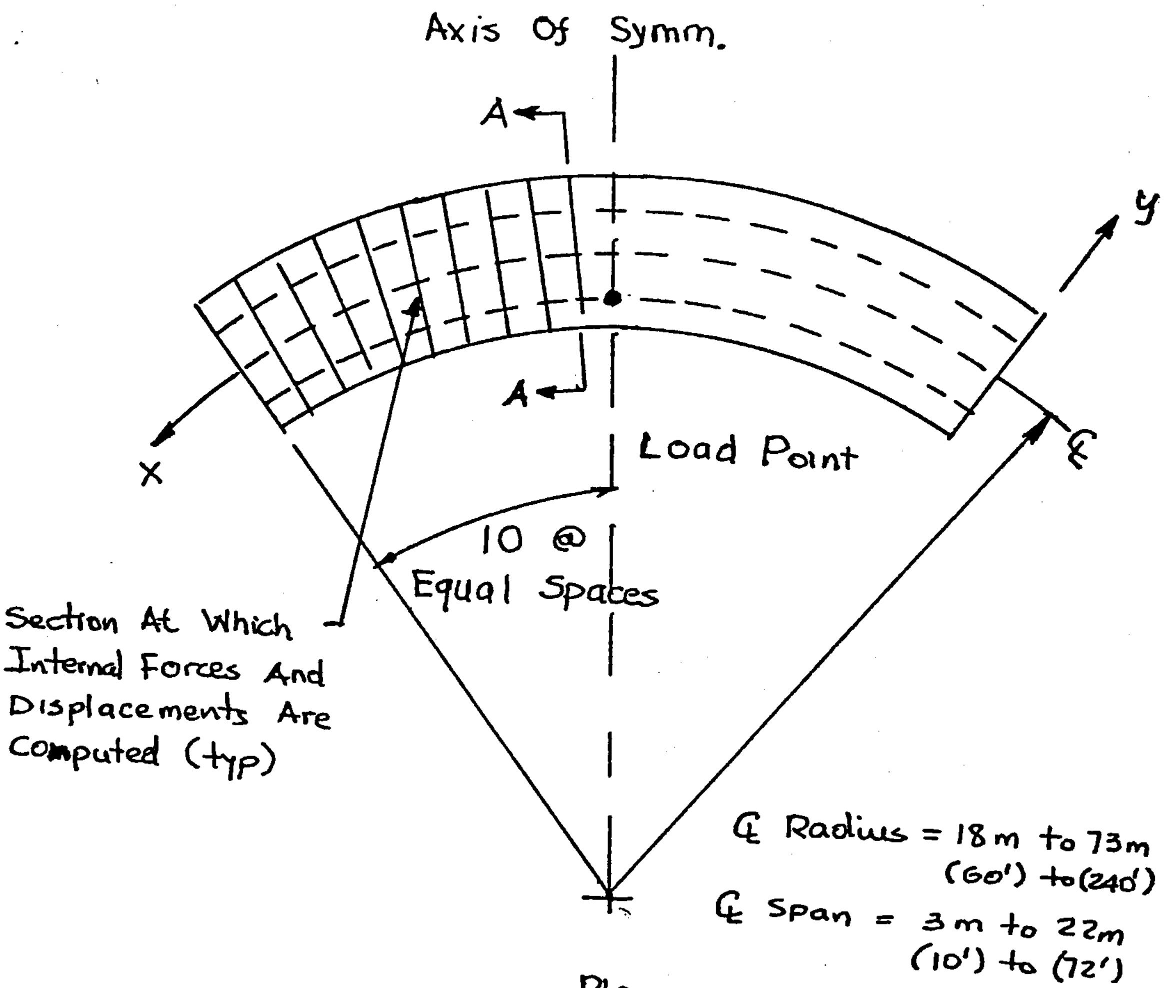


Fig. 19 Computer Input Dimensions of Model Box Girder, BG4



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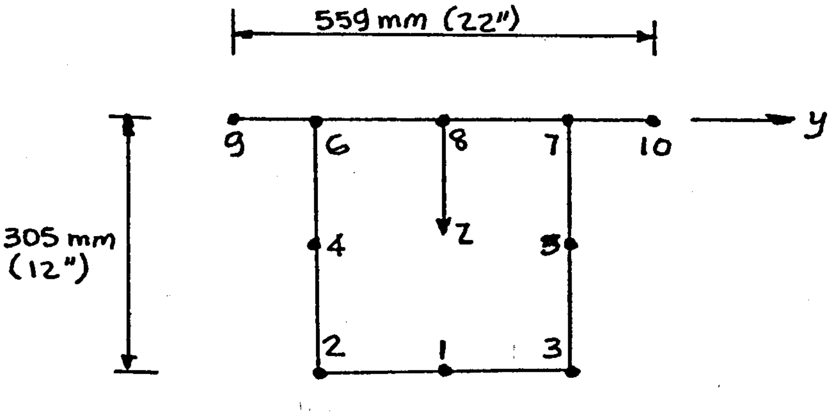


Section A-A

Fig. 20 Finite Strip Discretization for Analysis of Box Girder Model by CURDI

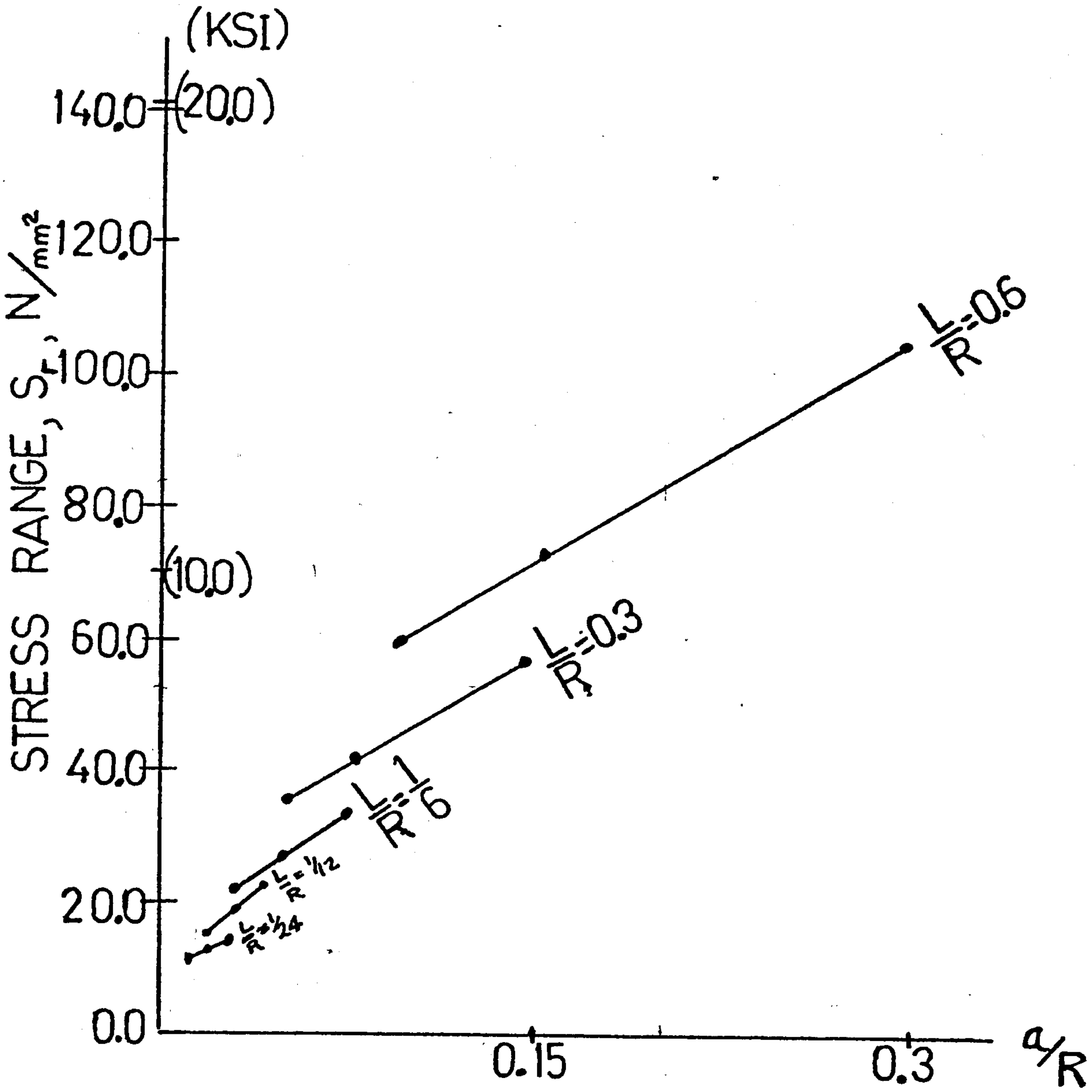
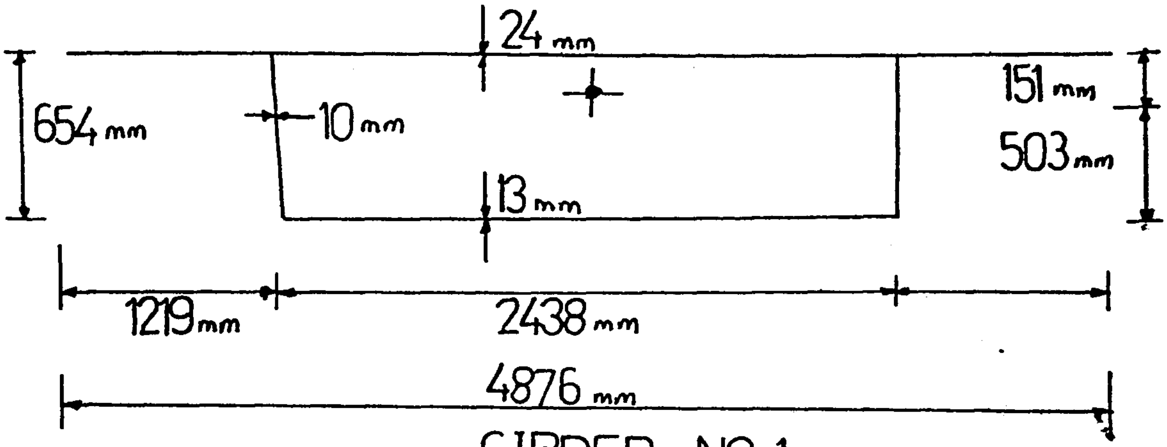
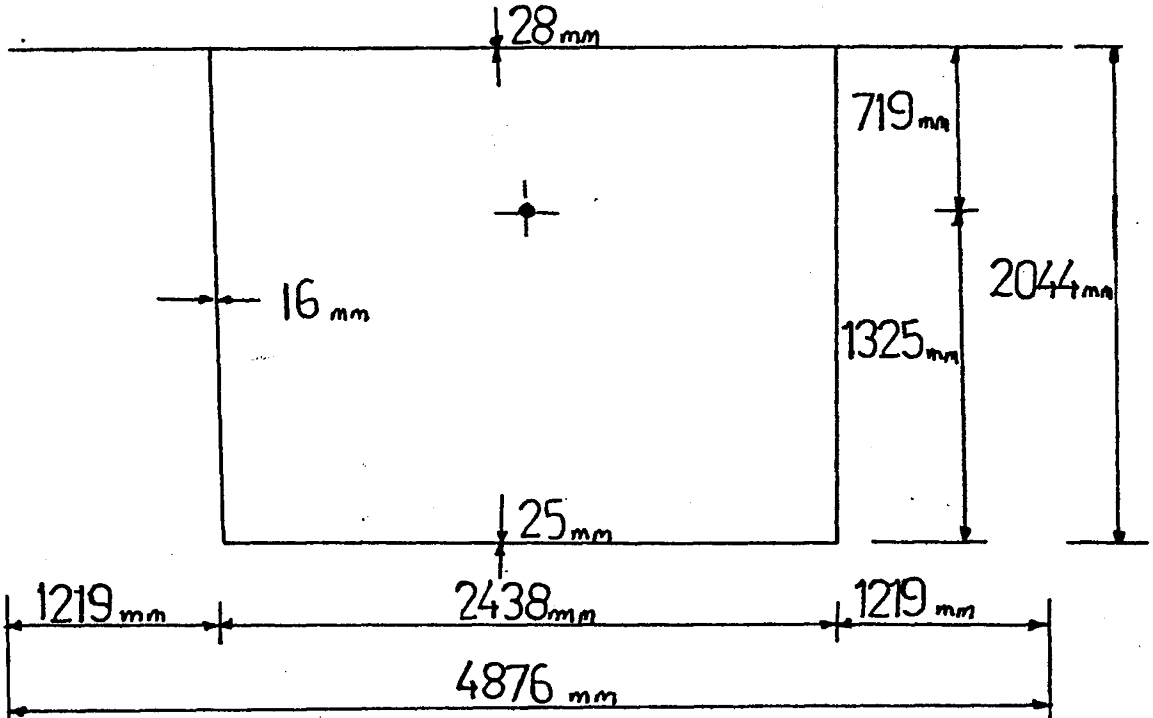


FIG. 2 / STRESS RANGE, S_r, VS DIAPHRAGM SPACING OVER RADIUS, a/R



GIRDER NO.1



GIRDER NO. 2

Fig. 22 Box Girder Geometries for Analytical Solution

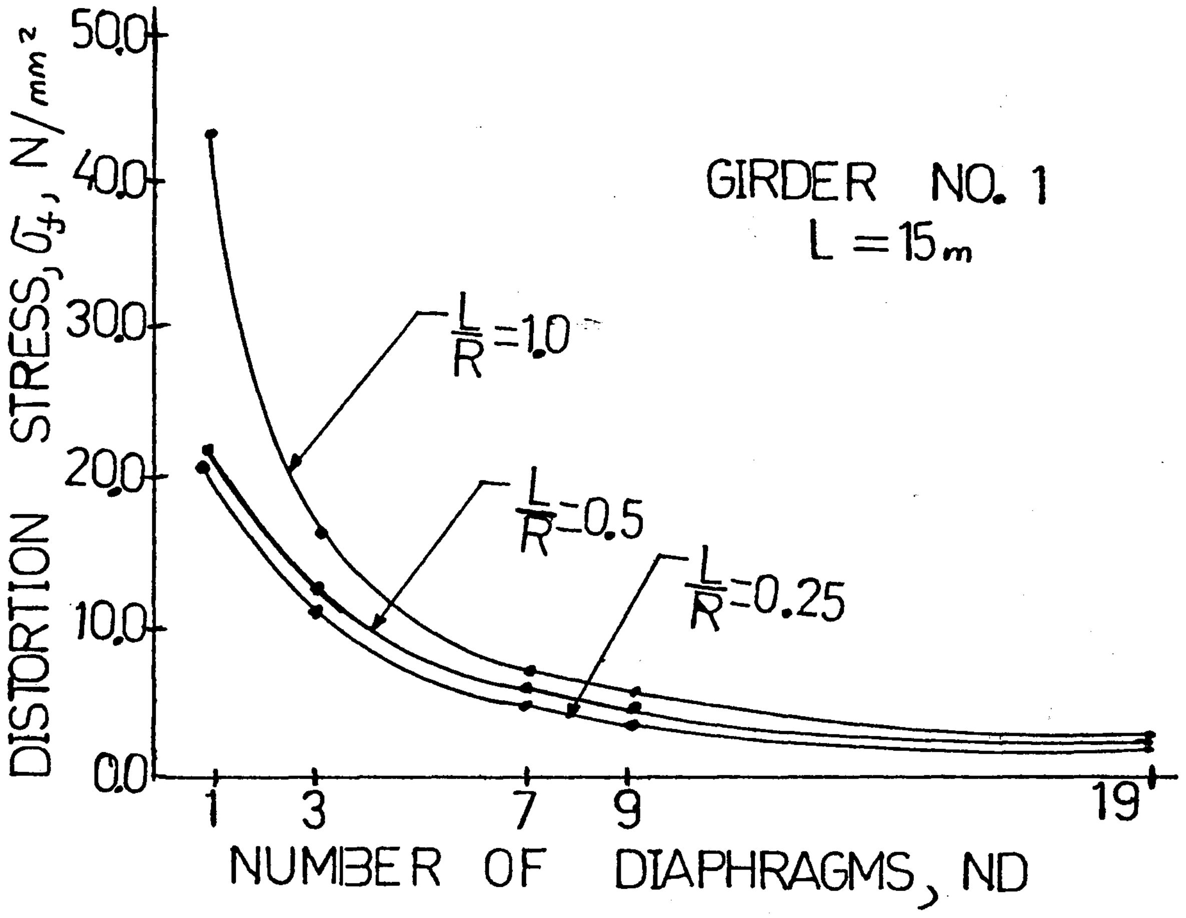


FIG. 2.3 DISTORTION STRESS, σ_f, (N/mm²) VS. ND

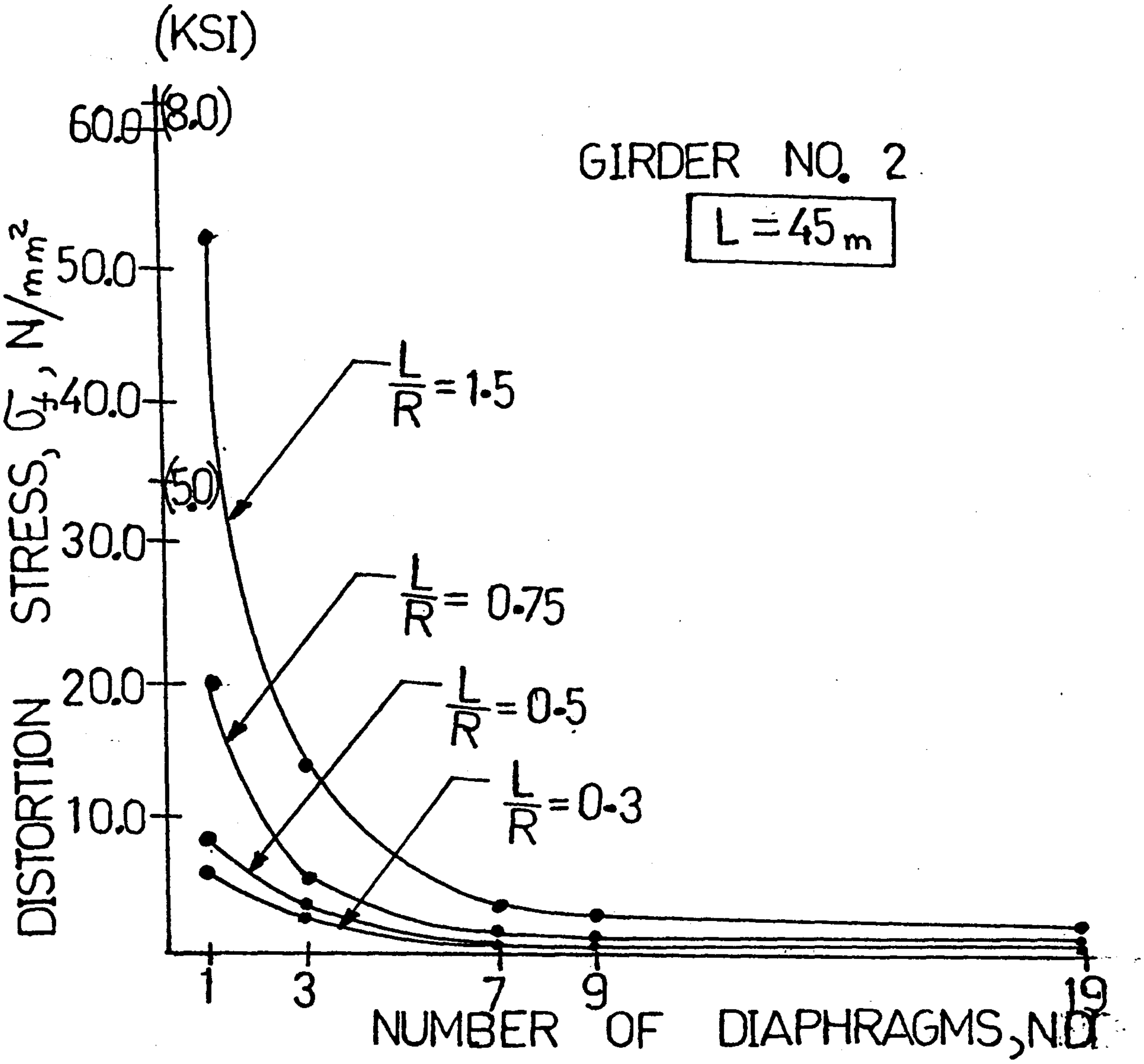


FIG. 2 4 DISTORTION STRESS, σ_t, (N/mm^2) VS. ND

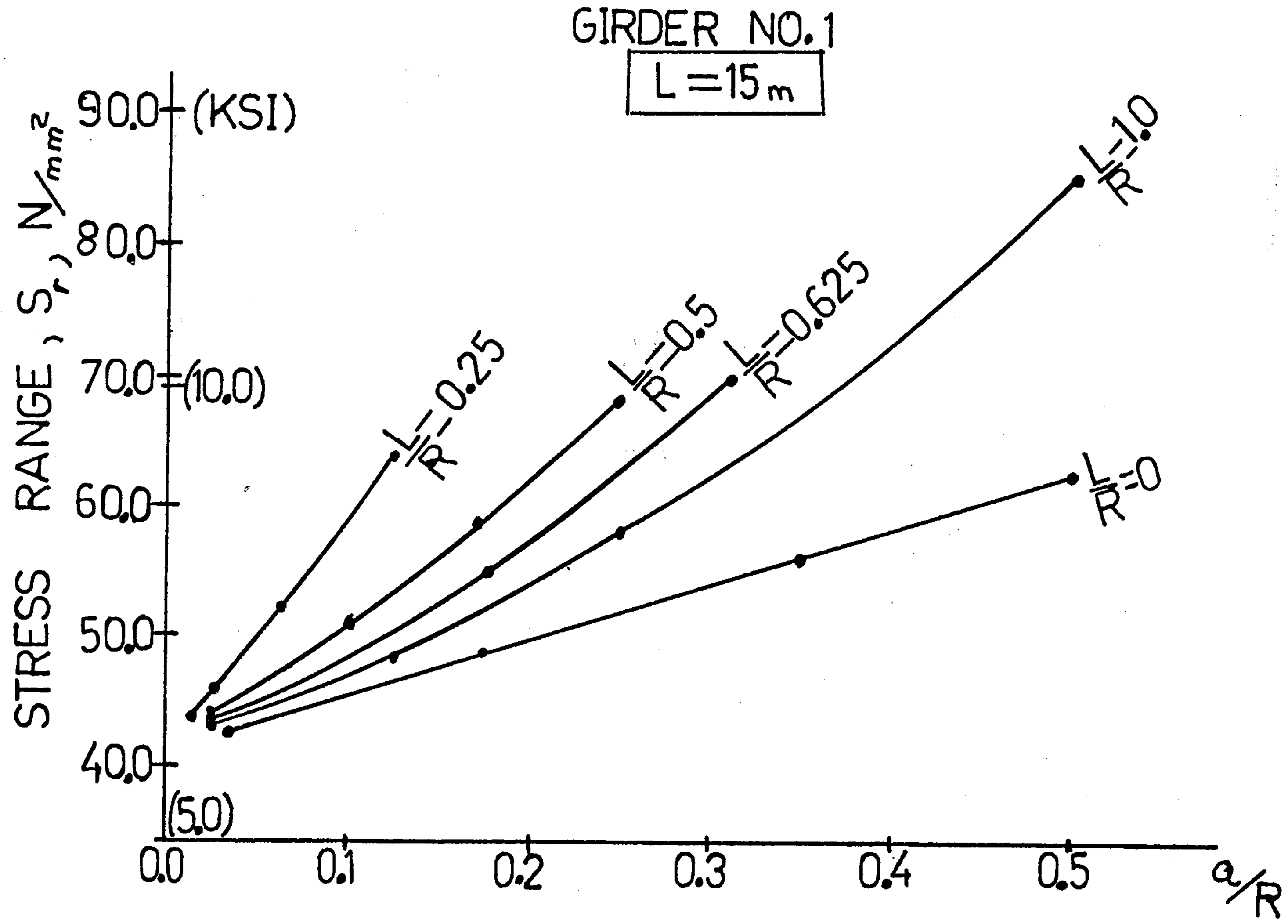


FIG. 2.5 STRESS RANGE, S_r, (N/mm^2) VS. a/R

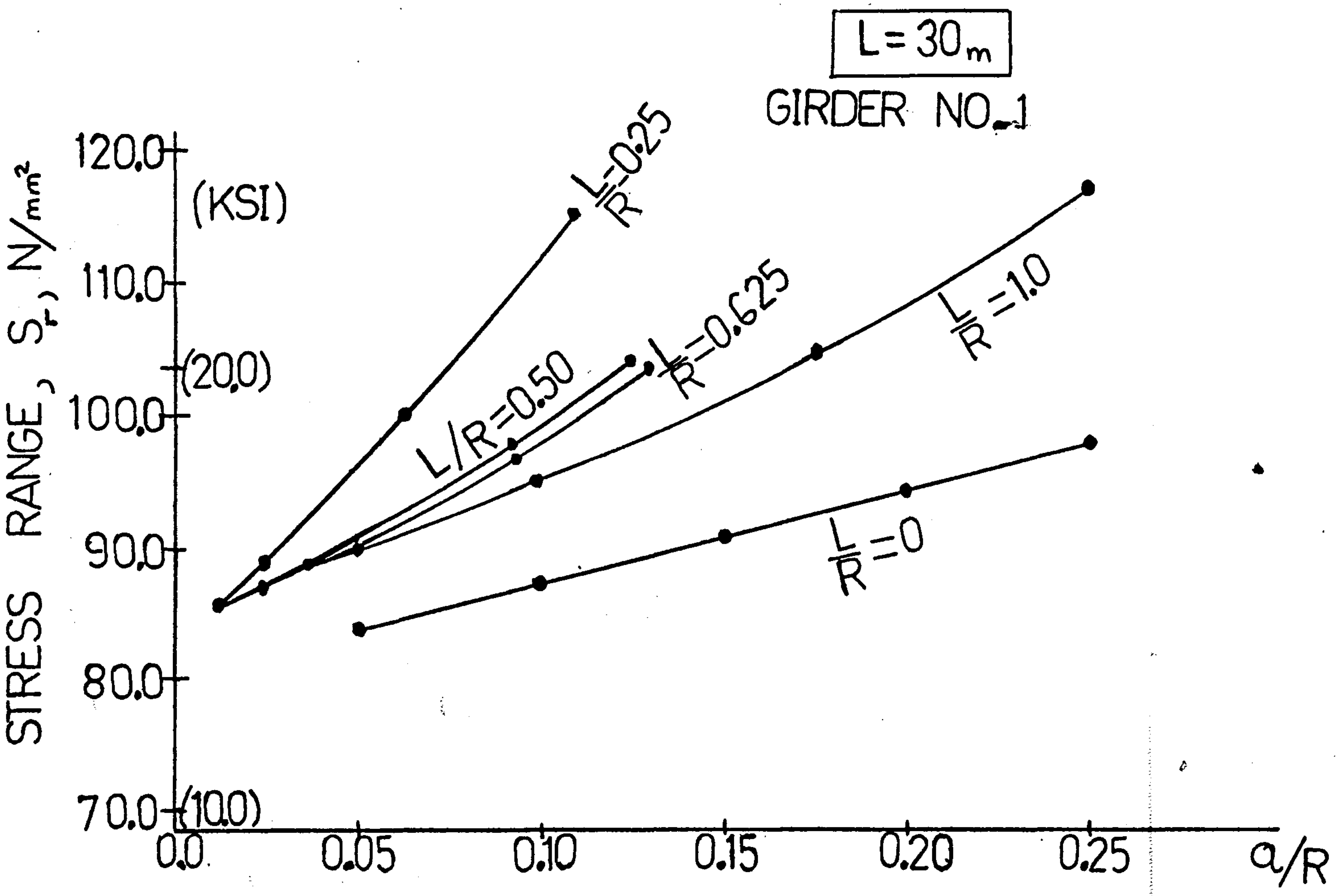


FIG. 2.6 STRESS RANGE, S_r, (N/mm^2) VS. a/R

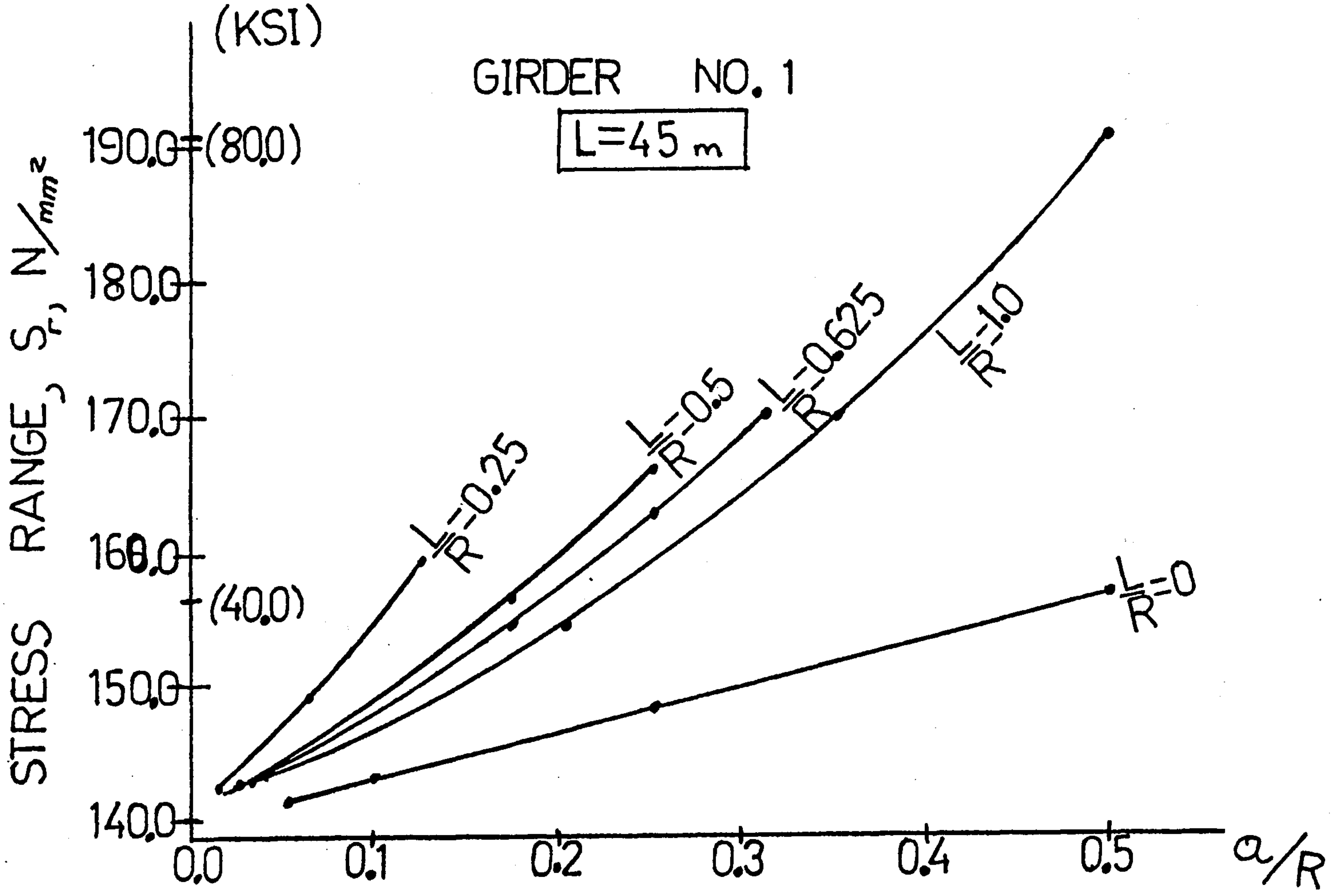


FIG. 27 STRESS RANGE, S_r, (N/mm^2) VS. a/R

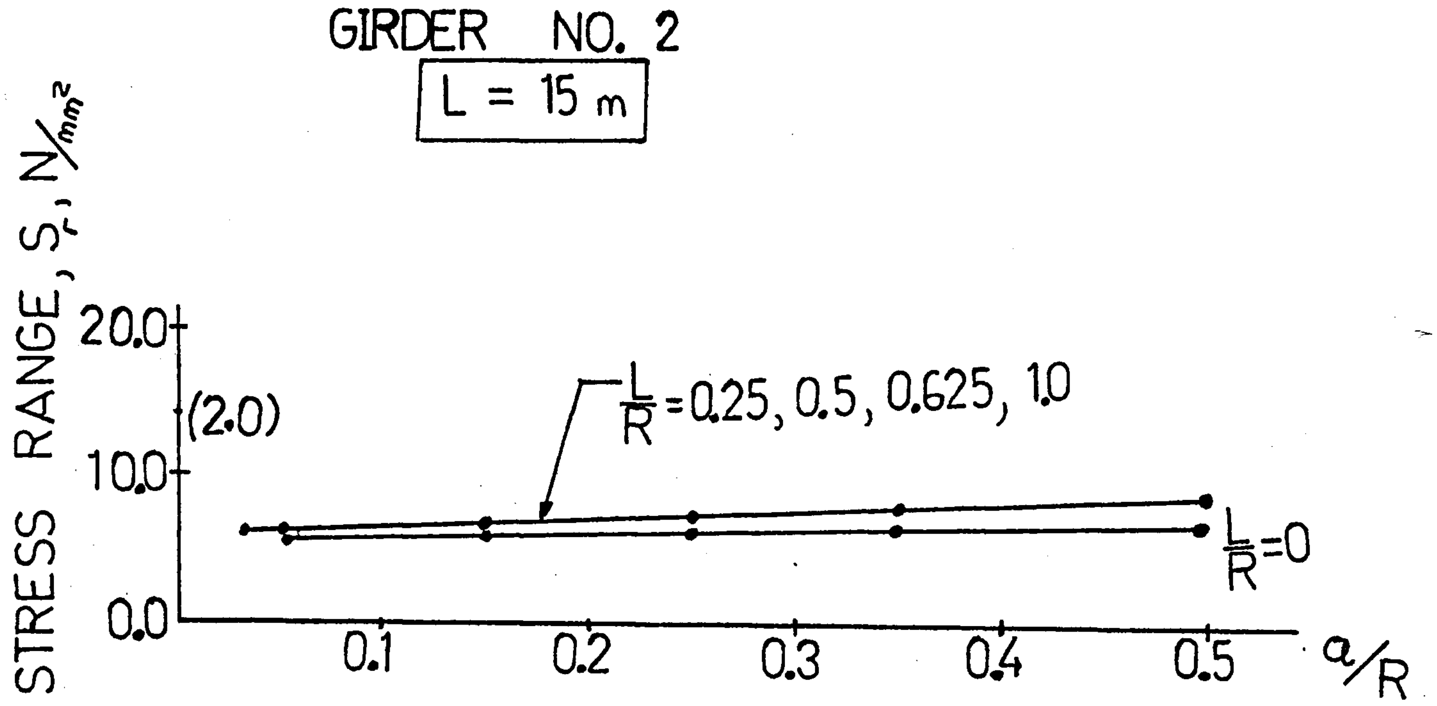


FIG. 28 STRESS RANGE, S_r, (N/mm^2) VS. a/R

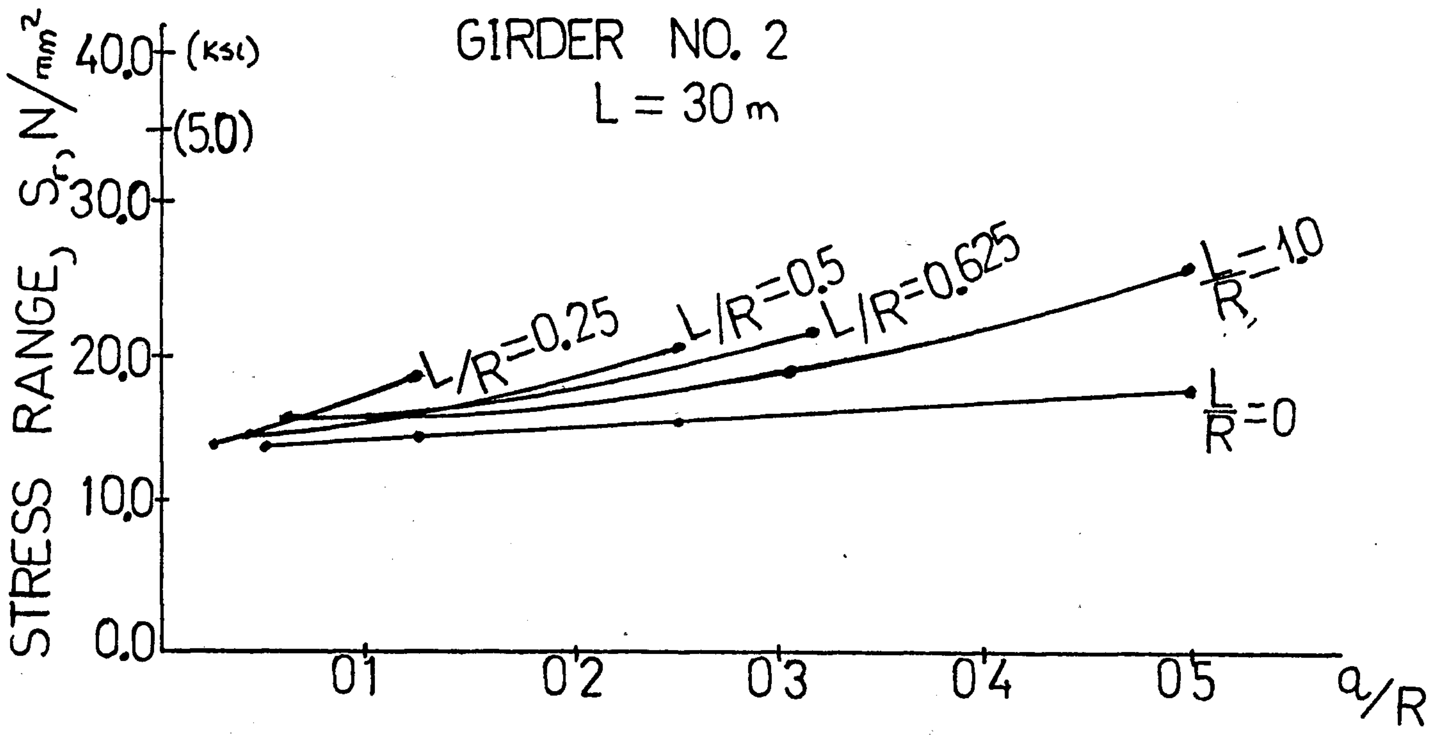


FIG. 2.9 STRESS RANGE, S_r, (N/mm^2) VS. a/R

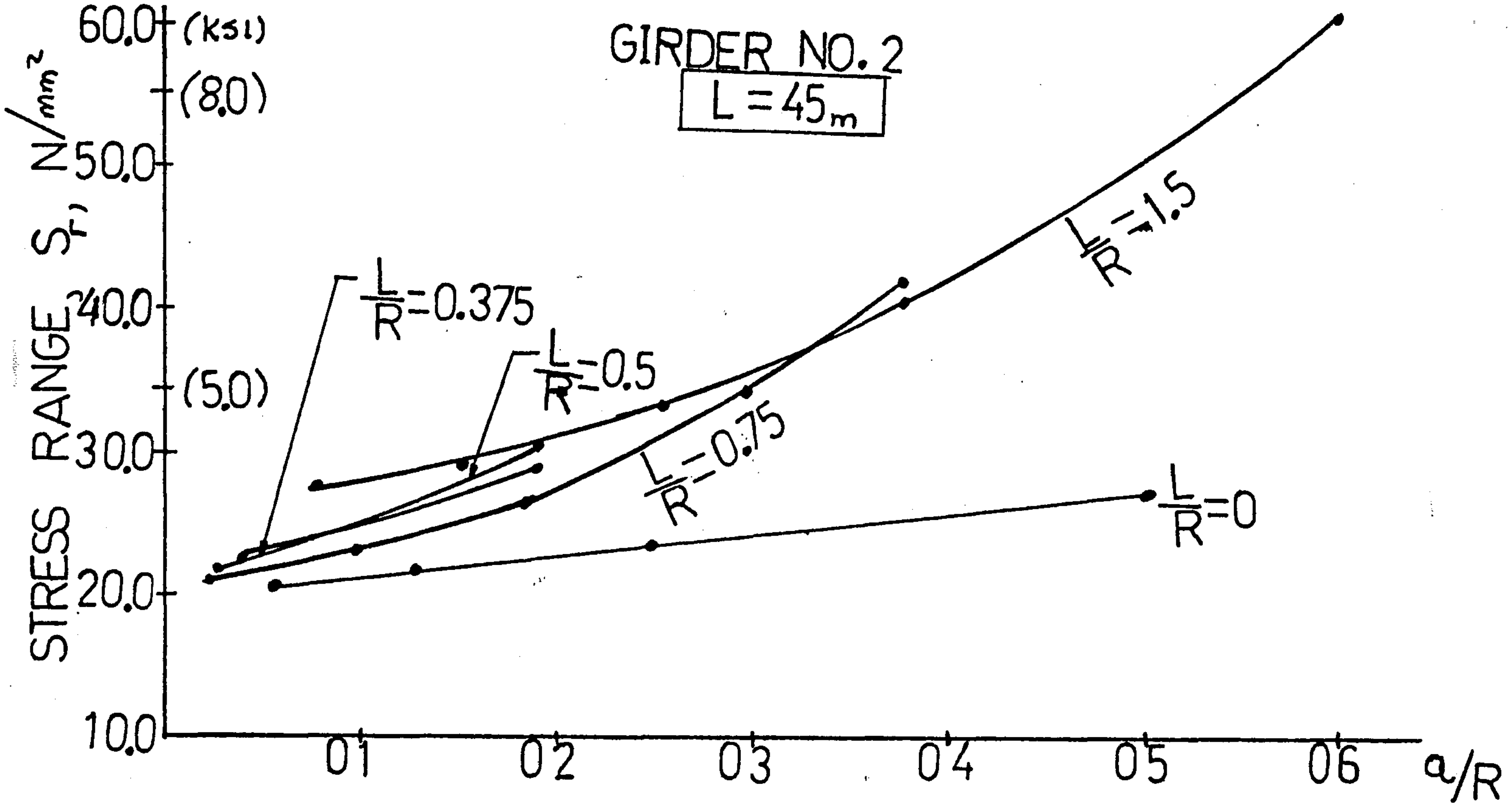
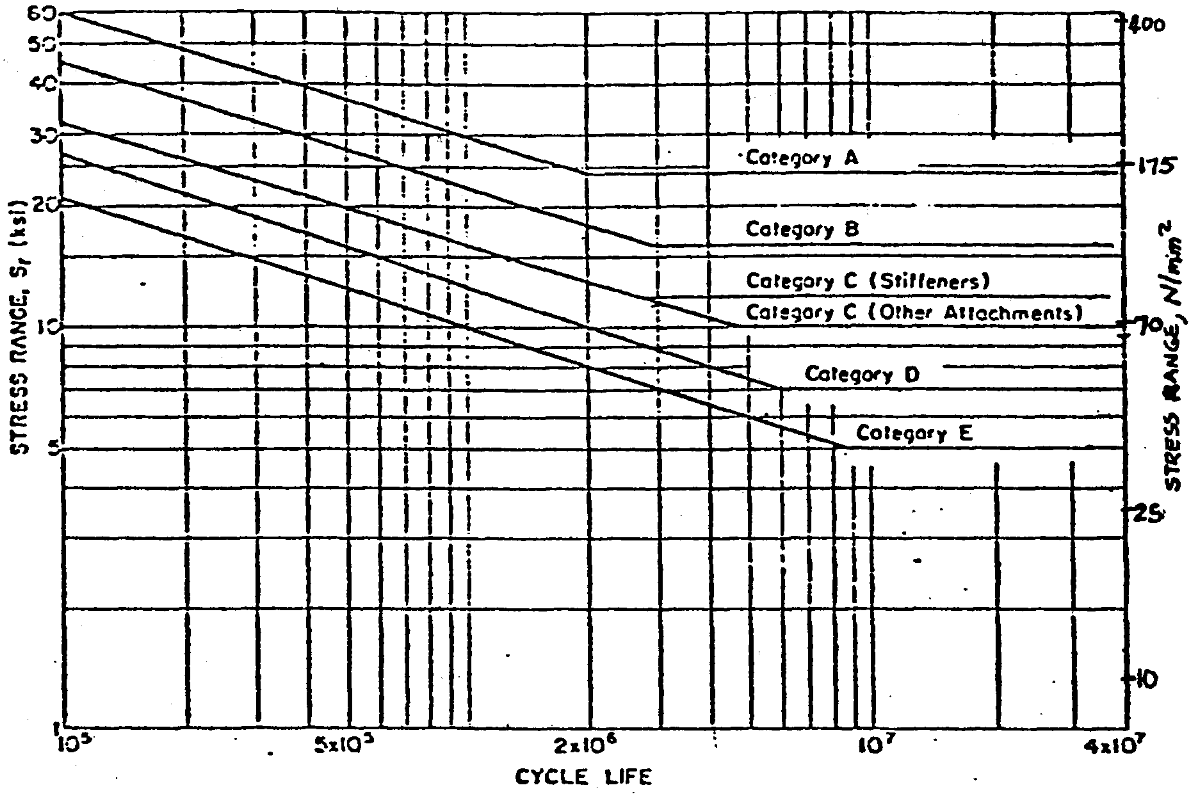


FIG. 30 STRESS RANGE, S_r, (N/mm²) VS. a/R



DESIGN STRESS RANGE CURVES

Category (See Table 1.7.3C)	Allowable Range of Stress, S_r (ksi) N/mm²			
	For 100,000 Cycles	For 500,000 Cycles	For 2,000,000 Cycles	Over 2,000,000 Cycles
A	414(60)	248(36)	166(24)	166(24)
B	310(45)	190(27.5)	124(18)	110(16)
C	221(32)	131(19)	90(13)	69,83(10, 12*)
D	186(27)	110(16)	69(10)	48(7)
E	145(21)	86(12.5)	55(8)	34(5)
F	103(15)	83(12)	62(9)	55(8)

* For transverse stiffener welds on girder webs or flanges.

Fig. 31 AASHTO Fatigue Stress Ranges

REFERENCES

1. Vlasov, V. Z.,
   THIN-WALLED ELASTIC BEAMS, TT61-11400, Office of Technical Services, U. S. Department of Commerce, Israel Program for Scientific Translations, PST. CAT. No. 428, Washington, D. C., 1961.

2. Dabrowski, R.,
   CURVED THIN-WALLED GIRDERS, Translation No. 144, Cement and Concrete Association, London, 1968.

3. Kollbrunner, C. G., and Basler, K.,
   TORSION IN STRUCTURES--AN ENGINEERING APPROACH, Springer Verlag, New York, 1969.

4. Goldberg, J. E. and Leve, H. L.,
   THEORY OF PRISMATIC FOLDED PLATE STRUCTURES, Meinoires, International Association for Bridge and Structural Engineering, Vol. 17, pp. 59-86, 1957.

5. Wright, R. N., Abdel-Samed, S. R. and Robinson, A. R.,
   BEF ANALOGY FOR ANALYSIS OF BOX GIRDERS, Journal of the Structural Division, ASCE, Vol. 94, No. ST7, Proc. Paper 6025, July 1968.

6. Abdel-Samed, S. R., Wright, R. N. and Robinson, A. R.,
   ANALYSIS OF BOX GIRDERS WITH DIAPHRAGMS, Journal of the Structural Division, ASCE, Vol. 94, No. ST10, Proc. Paper 6153, October 1968.

7. Meyer, C. and Scordelis, A. C.,
   ANALYSIS OF CURVED FOLDED PLATE STRUCTURES, Journal of The Structural Division, ASCE, Vol. 97, No. ST10, Proc. Paper 8434, October 1971.

8. Scordelis, A. C.,
   ANALYSIS OF CONTINUOUS BOX GIRDER BRIDGES, Report No. SESM-67-25, Department of Civil Engineering, University of California, Berkeley, CA., November 1967.

9. Subcommittee on Box Girder Bridges of the ASCE-AASHTO Committee on Flexural Members,
   TRENDS IN THE DESIGN OF BOX GIRDER BRIDGES, Journal of the Structural Division, ASCE, Vol. 93, No. ST3, Proc. Paper 5278, June 1967.

REFERENCES (continued)

10. Subcommittee on Box Girder Bridges of the ASCE-AASHTO Committee on Flexural Members,
PROGRESS REPORT ON STEEL BOX GIRDER BRIDGES, Journal of the Structural Division, ASCE, Vol. 97, No. ST4, Proc. Paper 8068, April 1971.

11. Petzold, E. H. and Galambos, T. V.,
BEHAVIOR AND DESIGN OF LARGE STEEL BOX GIRDER BRIDGES, Civil and Environmental Engineering Department Research Report No. 26, Washington University, St. Louis, Mo., December 1973.

12. Oleinik, J. C. and Heins, C. P.,
DIAPHRAGMS FOR CURVED BOX BEAM BRIDGES, Journal of the Structural Division, ASCE, Vol. 101, No. ST10, Proc. Paper 11634, October 1975.

13. Yen, B. T., Hall, J. and Chen, Y. S.,
AFFECT OF DIAPHRAGM SPACING ON BOX GIRDERS, Fritz Engineering Laboratory Report No. 380.13 (in preparation), Department of Civil Engineering, Lehigh University, Bethlehem, Pa.

14. Bathe, K. J., Wilson, E. L. and Peterson, F. E.,
SAP IV, A STRUCTURAL ANALYSIS PROGRAM FOR STATIC AND DYNAMIC RESPONSE OF LINEAR SYSTEMS, Earthquake Engineering Research Center, Report No. EERC 73-11, University of California, Berkeley, California, June 1973.

15. Heins, C. P.,
BENDING AND TORSIONAL DESIGN IN STRUCTURAL MEMBERS, Lexington Books, D. C. Heath and Company, 1975.

16. Fisher, J. W. and Yen, B. T.,
DESIGN, STRUCTURAL DETAILS, AND DISCONTINUITIES IN STEEL, Proc. ASCE Specialty Conference on the Safety and Reliability of Metal Structures, November 1972.

17. Daniels, J. H., Zettlemoyer, N., Abraham, D. and Batcheler, R. P.,
ANALYSIS AND DESIGN OF PLATE GIRDER AND BOX GIRDER TEST ASSEMBLIES, Fritz Engineering Laboratory Report No. 398.1, October 1976.

REFERENCES (continued)

18. Hirt, M. A. and Fisher, J. W.,
FATIGUE CRACK GROWTH IN WELDED BEAMS, Journal of Engineering Fracture Mechanics, Vol. 5, 1973.

19. Fisher, J. W.,
GUIDE TO 1974 AASHTO FATIGUE SPECIFICATIONS, American Institute of Steel Construction, 1974.

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