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GENERALIZED PLANE-STRAIN PROBLEMS IN AN  
ELASTIC-PLASTIC THICK-WALLED CYLINDER

P. C. T. Chen

July 1980



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND  
LARGE CALIBER WEAPON SYSTEMS LABORATORY  
BENÉT WEAPONS LABORATORY  
WATERVLIET, N. Y. 12189

AMCMS No. 36KA7000204

DA Project No. 156401813GRN

PRON No. 1A0215641A1A

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARLCB-TR-80028	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) GENERALIZED PLANE-STRAIN PROBLEMS IN AN ELASTIC-PLASTIC THICK-WALLED CYLINDER		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) P. C. T. Chen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Benet Weapons Laboratory Watervliet Arsenal, Watervliet, NY 12189 DRDAR-LCB-TL		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 36KA7000204 DA Project No. 156401813GRN PRON No. 1A0215641A1A
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research and Development Command Large Caliber Weapon Systems Laboratory Dover, NJ 07801		12. REPORT DATE July 1980
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)  UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Presented at the 26th Conference of Army Mathematicians, Cold Regions Research and Engineering Lab, Hanover, New Hampshire, 10-12 June 1980. To be published in proceedings of the conference.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Autofrettage Elastic-Plastic Deformation Finite-Difference Method Gun Tube		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A new finite-difference approach has been developed for solving the generalized plane-strain problems of partially-plastic thick-walled cylinders made of strain-hardening or ideally-plastic materials. The tube is assumed to obey the Von Mises' criterion, the Prandtl-Reuss flow theory and the isotropic- hardening rule. The forces include internal pressure, external pressure, and end force. An incremental approach is used and no iteration is needed for each increment. The approach is simpler than others yet quite general and accurate. CONT'D ON REVERSE		

20. Abstract (CONT'D)

The desired accuracy can be achieved by reducing the grid sizes and load increments. Some numerical results for the stresses and displacements in partially-plastic thick-walled cylinders with either open-end or closed-end conditions are presented.

## TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
BASIC EQUATIONS	2
FINITE-DIFFERENCE FORMULATION	4
NUMERICAL RESULTS AND DISCUSSIONS	6
REFERENCES	8

## LIST OF ILLUSTRATIONS

1. Radial displacement at the bore as a function of internal pressure for cases 1, 2, and 4.	10
2. Elastic-plastic boundary as a function of internal pressure for cases 1, 2, and 4.	11
3. Distributions of radial and tangential stresses for case 1 ( $\alpha = 0$ , $\mu = 0$ , $b/a = 2$ ).	12
4. Distributions of radial and tangential stresses for case 2 ( $\alpha = 0$ , $\mu = 1$ , $b/a = 2$ ).	13
5. Distributions of axial stress for cases 1 and 2.	14

## INTRODUCTION

It is well known that the closed-form elastoplastic solutions of the generalized plane-strain problems can only be obtained by Hencky's total stress-strain relations or Tresca's yield criterion.<sup>1,2</sup> Based on the detailed studies reported in reference 3, more realistic material model for thick-walled tube under very high pressure operation is an elastic-plastic material which obeys the Mises' yield criterion and the Prandtl-Reuss incremental stress-strain relations. And, in such situations, one has to rely on numerical methods. Both the finite-difference method<sup>4-6</sup> and the finite-element method<sup>7,8</sup> have been used to solve the elastoplastic problem considered here. The finite-element method is more powerful and can be used to solve more general elastoplastic problems.<sup>8-10</sup> Since the displacement function is assumed and the programming is complicated, the accuracy of the finite-element approach has to be verified. This is usually done by comparison with more rigorous solutions to simpler problems. For the problem considered here, rigorous solutions based on the finite-difference method were obtained for ideally-plastic materials in references 4 and 5 and for strain-hardening materials in reference 6.

In the present paper, a new finite-difference approach is developed for solving the generalized plane-strain problems of thick-walled cylinders subjected to internal pressure, external pressure, or end force beyond the elastic limit. An incremental approach is used and no iteration is needed for each increment. The numerical scheme is stable for ideally-plastic as well as

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References are listed at the end of this report.

strain-hardening materials. The approach is simpler than others yet quite general and accurate. The desired accuracy can be achieved by reducing the grid size and load increments.

#### BASIC EQUATIONS

Assuming small strain and no body forces in the axisymmetric state of generalized plane strain, the radial and tangential stresses,  $\sigma_r$  and  $\sigma_\theta$ , must satisfy the equilibrium equation,

$$r(\partial\sigma_r/\partial r) = \sigma_\theta - \sigma_r ; \quad (1)$$

and the corresponding strains,  $\epsilon_r$  and  $\epsilon_\theta$ , are given in terms of the radial displacement,  $u$ , by

$$\epsilon_r = \partial u/\partial r \quad , \quad \epsilon_\theta = u/r \quad . \quad (2)$$

It follows that the strains must satisfy the equation of compatibility

$$r(\partial\epsilon_\theta/\partial r) = \epsilon_r - \epsilon_\theta \quad . \quad (3)$$

Whereas the differential equations (1), (2), and (3) hold throughout the tube regardless of the material properties, the constitution equations assume various forms according to the adopted form of yield function, hardening rule, total or incremental theory of plasticity. In the present paper, the material is assumed to be elastic-plastic, obeying the Mises' yield criterion, the Prandtl-Reuss flow theory and the isotropic hardening law. The complete stress-strain relations are:

$$d\epsilon_i' = d\sigma_i'/2G + (3/2)\sigma_i'd\sigma/(\sigma H') \quad (4)$$

$$d\sigma \geq 0 \quad \text{for } i = r, \theta, z$$

$$d\epsilon_m = E^{-1}(1-2\nu)d\sigma_m \quad (5)$$

where  $E$ ,  $\nu$  Young's modulus, Poisson's respectively,

$$2G = E/(1+\nu)$$

$$\epsilon_m = (\epsilon_r + \epsilon_\theta + \epsilon_z)/3 \quad , \quad \epsilon_i' = \epsilon_i - \epsilon_m \quad ,$$

$$\sigma_m = (\sigma_r + \sigma_\theta + \sigma_z)/3 \quad , \quad \sigma_i' = \sigma_i - \sigma_m \quad ,$$

$$\sigma = (1/\sqrt{2})[(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2]^{1/2} > \sigma_0 \quad , \quad (6)$$

and  $\sigma_0$  is the yield stress in simple tension or compression. For a strain-hardening material,  $H'$  is the slope of the effective stress/plastic strain curve

$$\sigma = H(\int d\epsilon^p) \quad . \quad (7)$$

For an ideally-plastic material ( $H' = 0$ ), the quantity  $(3/2)d\sigma/(\sigma H')$  is replaced by  $d\lambda$ , a positive factor of proportionality. When  $\sigma < \sigma_0$  or  $d\sigma < 0$ , the state of stress is elastic and the second term in equation (4) disappears.

Following Yamada et al,<sup>9</sup> equations (4) and (5) can be rewritten in an incremental form

$$d\sigma_i = d_{ij}d\epsilon_j \quad \text{for } i, j = r, \theta, z$$

and

$$d_{ij}/2G = \nu/(1-2\nu) + \delta_{ij} - \sigma_i'\sigma_j'/S \quad , \quad (8)$$

where

$$S = \frac{2}{3} \left(1 + \frac{1}{3} H'/G\right) \sigma^2 \quad , \quad H'/E = \alpha/(1-\alpha) \quad , \quad (9)$$

$\alpha E$  is the slope of the effective stress-strain curve, and  $\delta_{ij}$  is the Kronecker delta.

This form was used in the finite-element formulation for solving elastic-plastic thick-walled tube problems.<sup>7</sup> In the following section, the incremental stress-strain matrix will be used in the finite-difference formulation.



## FINITE-DIFFERENCE FORMULATION

Consider an open-end or closed-end thick-walled cylinder of inner radius  $a$  and external radius  $b$ . The tube is subjected to inner pressure  $p$ , external pressure  $q$ , and end force  $f$ . The elastic solution for this problem is well-known and the pressure  $p^*$ ,  $q^*$ , or  $f^*$  required to cause initial yielding can be determined by using the Mises' yield criterion. For loading beyond the elastic limit, an incremental approach of the finite-difference formulation is used. The analysis starts with the applied pressure  $p$ ,  $q$ , or  $f$  and the loading path is divided into  $m$  increments with

$$\Delta p = (p-p^*)/m \quad , \quad \Delta q = (q-q^*)/m \quad , \quad \Delta f = (f-f^*)/m \quad . \quad (10)$$

The cross section of the tube is divided into  $n$  rings with

$$r_1=a, r_2, \dots, r_k=\rho, \dots, r_{n+1}=b \quad , \quad (11)$$

where  $\rho$  is the radius of the elastic-plastic interface. At the beginning of each increment of loading, the distribution of displacements, strains and stresses is assumed to be known and we want to determine  $\Delta u$ ,  $\Delta \epsilon_r$ ,  $\Delta \epsilon_\theta$ ,  $\Delta \epsilon_z$ ,  $\Delta \sigma_r$ ,  $\Delta \sigma_\theta$ ,  $\Delta \sigma_z$  at all grid points. Since the incremental stresses are related to the incremental strains by the incremental form (Eq. (8)) and  $\Delta u = r \Delta \epsilon_\theta$ , there exists only three unknowns at each station that have to be determined for each increment of loading. Accounting for the fact that the axial strain  $\epsilon_z$  is independent of  $r$ , the unknown variables in the present formulation are  $(\Delta \epsilon_\theta)_i$ ,  $(\Delta \epsilon_r)_i$ , for  $i = 1, 2, \dots, n, n+1$ , and  $\Delta \epsilon_z$ .

The equation of equilibrium (1) and the equation of compatibility (3) are valid for both the elastic and the plastic regions of a thick-walled tube. The finite-difference forms of these two equations at  $i = 1, \dots, n$  are given in reference 6 by

$$\begin{aligned}
& (r_{i+1}-2r_i)(\Delta\sigma_r)_i - (r_{i+1}-r_i)(\Delta\sigma_\theta)_i + r_i(\Delta\sigma_r)_{i+1} \\
& = (r_{i+1}-r_i)(\sigma_\theta-\sigma_r)_i - r_i[(\sigma_r)_{i+1} - (\sigma_r)_i]
\end{aligned} \tag{12}$$

for the equation of equilibrium, and

$$\begin{aligned}
& (r_{i+1}-2r_i)(\Delta\varepsilon_\theta)_i - (r_{i+1}-r_i)(\Delta\varepsilon_r)_i + r_i(\Delta\varepsilon_\theta)_{i+1} \\
& = (r_{i+1}-r_i)(\varepsilon_r-\varepsilon_\theta)_i - r_i[(\varepsilon_\theta)_{i+1} - (\varepsilon_\theta)_i]
\end{aligned} \tag{13}$$

for the equation of compatibility. With the aid of the incremental stress-strain relations (Eq. (8)), equation (12) can be rewritten as

$$\begin{aligned}
& [(r_{i+1}-2r_i)(d_{12})_i + (-r_{i+1}+r_i)(d_{22})_i](\Delta\varepsilon_\theta)_i \\
& + [(r_{i+1}-2r_i)(d_{11})_i + (-r_{i+1}+r_i)(d_{21})_i](\Delta\varepsilon_r)_i \\
& + r_i(d_{12})_{i+1}(\Delta\varepsilon_\theta)_{i+1} + r_i(d_{11})_{i+1}(\Delta\varepsilon_r)_{i+1} \\
& + [(r_{i+1}-2r_i)(d_{13})_i + (-r_{i+1}+r_i)(d_{23})_i + r_i(d_{13})_{i+1}]\Delta\varepsilon_z \\
& = (r_{i+1}-r_i)(\sigma_\theta-\sigma_r)_i - r_i[(\sigma_r)_{i+1} - (\sigma_r)_i] .
\end{aligned} \tag{14}$$

The boundary conditions for the problem are

$$\begin{aligned}
& \Delta\sigma_r(a,t) = -\Delta p \quad , \quad \Delta\sigma_r(b,t) = -\Delta q \quad , \\
& \pi \sum_{i=1}^n [r_i(\Delta\sigma_z)_i + r_{i+1}(\Delta\sigma_z)_{i+1}](r_{i+1}-r_i) = \mu\pi\alpha^2\Delta p + \Delta f \quad ,
\end{aligned} \tag{15}$$

where  $\mu$  is 0 for open-end tubes and 1, for closed-end tubes. Using the incremental relations (Eq. (8)), we rewrite equation (15) as

$$(d_{12})_1(\Delta\varepsilon_\theta)_1 + (d_{11})_1(\Delta\varepsilon_r)_1 + (d_{13})_1\Delta\varepsilon_z = -\Delta p \quad , \tag{16}$$

$$(d_{12})_{n+1}(\Delta\varepsilon_\theta)_{n+1} + (d_{11})_{n+1}(\Delta\varepsilon_r)_{n+1} + (d_{13})_{n+1}\Delta\varepsilon_z = -\Delta q \quad , \tag{17}$$

and

$$\begin{aligned}
& \sum_{i=1}^n (r_{i+1}-r_i)\{r_i[(d_{23})_i(\Delta\varepsilon_\theta)_i + (d_{13})_i(\Delta\varepsilon_r)_i] + r_{i+1}[(d_{23})_{i+1}(\Delta\varepsilon_\theta)_{i+1} \\
& + (d_{13})_{i+1}(\Delta\varepsilon_r)_{i+1}]\} + \sum_{i=1}^n (r_{i+1}-r_i)[r_i(d_{33})_i + r_{i+1}(d_{33})_{i+1}]\Delta\varepsilon_z \\
& = \mu a^2\Delta p + \Delta f/\pi \quad .
\end{aligned} \tag{18}$$

Now we can form a system of  $2n+3$  equations for solving  $2n+3$  unknowns,  $(\Delta\epsilon_\theta)_i$ ,  $(\Delta\epsilon_r)_i$ , at  $i = 1, 2, \dots, n, n+1$  and  $\Delta\epsilon_z$ . Equations (16), (17), and (18) are taken as the first and last two equations, respectively, and the other  $2n$  equations are set up at  $i = 1, 2, \dots, n$  using (13) and (14). The final system is an unsymmetric matrix of arrow type with the nonzero terms appearing in the last row and column and others clustered about the main diagonal, two below and one above.

In the computer program which was developed, the dimensionless quantities  $r/a$ ,  $E\epsilon_r/\sigma_0$ ,  $E\epsilon_\theta/\sigma_0$ ,  $E\epsilon_z/\sigma_0$ ,  $\sigma_r/\sigma_0$ ,  $\sigma_\theta/\sigma_0$ ,  $\sigma_z/\sigma_0$ ,  $p/\sigma_0$ ,  $q/\sigma_0$ ,  $f/(\pi a^2 \sigma_0)$  were used in the formulation and the Gaussian elimination method was used to solve these equations. All calculations were carried out on IBM 360/Model 44 with double precision to reduce round-off errors.

#### NUMERICAL RESULTS AND DISCUSSIONS

The generalized plane-strain problems of thick-walled cylinders subjected to internal pressure  $p$  beyond the elastic limit were solved. The elastic-perfectly-plastic as well as strain-hardening materials were considered for open-end or closed-end conditions. The numerical results were based on the following parameters:  $b/a = 2$ ,  $\nu = 0.3$ ,  $\alpha = 0.05$ ,  $\mu = 0$  or  $1$ . Various values of  $m$  and  $n$  were used to test the convergence of the numerical results. The incremental loadings were applied until the fully plastic state was reached. The value for  $p$  corresponding to this final state was denoted by  $p^{**}$ . It was found that the results of these values for all four cases converge by increasing  $m$  and/or  $n$ . For  $n = 100$ ,  $\Delta p/\sigma_0 = 0.0004$ , we have  $p^{**}/\sigma_0 = 0.7802$  ( $\alpha = 0$ ,  $\mu = 0$  as case 1);  $0.8038$  ( $\alpha = 0$ ,  $\mu = 1$  as case 2);  $0.8222$  ( $\alpha = 0.05$ ,  $\mu = 0$  as case 3);  $0.8618$  ( $\alpha = 0.05$ ,  $\mu = 1$  as case 4). Additional results are

shown in Figures 1 to 5. Figure 1 shows the bore radial displacements as functions of internal pressure for cases 1, 2, and 4. Figure 2 shows the relations between internal pressure and elastic-plastic boundary for cases 1, 2, and 4. The effects of end conditions and strain hardening can also be seen in these two figures. The distributions of radial and tangential stresses for  $\rho/a = 1.0, 1.2, 1.4, 1.6, \text{ and } 1.8$  are shown in Figure 3 for case 1 and in Figure 4 for case 2. Finally the distributions of axial stress for  $\rho/a = 1.0, 1.4, \text{ and } 1.8$  are shown in Figure 5 for cases 1 and 2. The effect of end conditions and elastic-plastic boundary on the axial stress is quite significant.

The present approach determines  $\Delta\epsilon_z$  directly for each step of incremental loadings whereas in reference 6, many iterations were needed because a value of  $\Delta\epsilon_z$  was assumed. In addition, the computer storage needed in this approach was only 35% of that in reference 6, and much larger  $n$  can be used to yield better results. The present approach is simpler yet more general than the other finite-difference approaches because both ideally-plastic<sup>4,5</sup> and strain-hardening<sup>6</sup> materials can be considered in a unified manner. Furthermore, very accurate numerical results can be obtained and used to verify the accuracy of the finite-element programs.<sup>7,8,10</sup>

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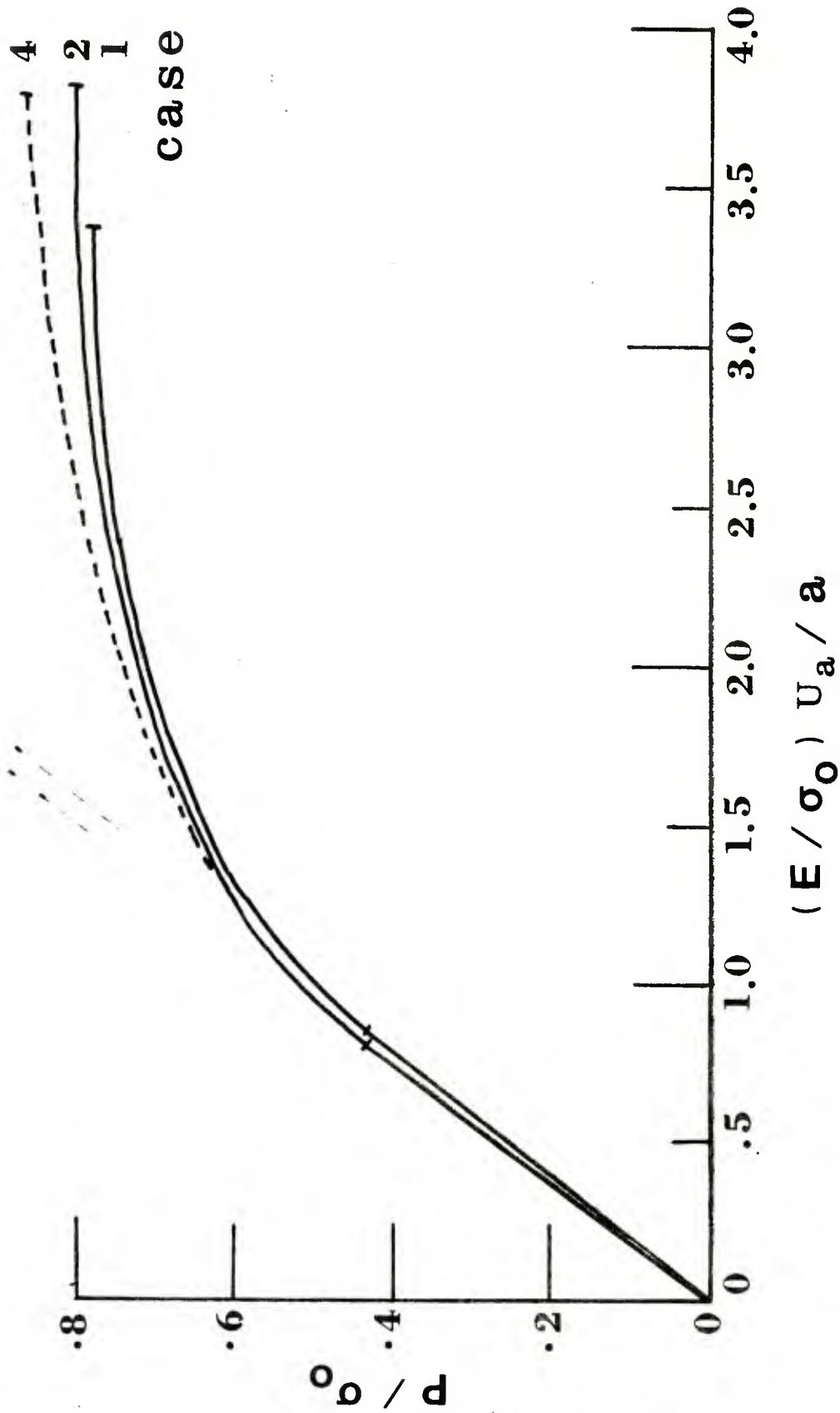


Figure 1. Radial displacement at the bore as a function of internal pressure for cases 1, 2, and 4.

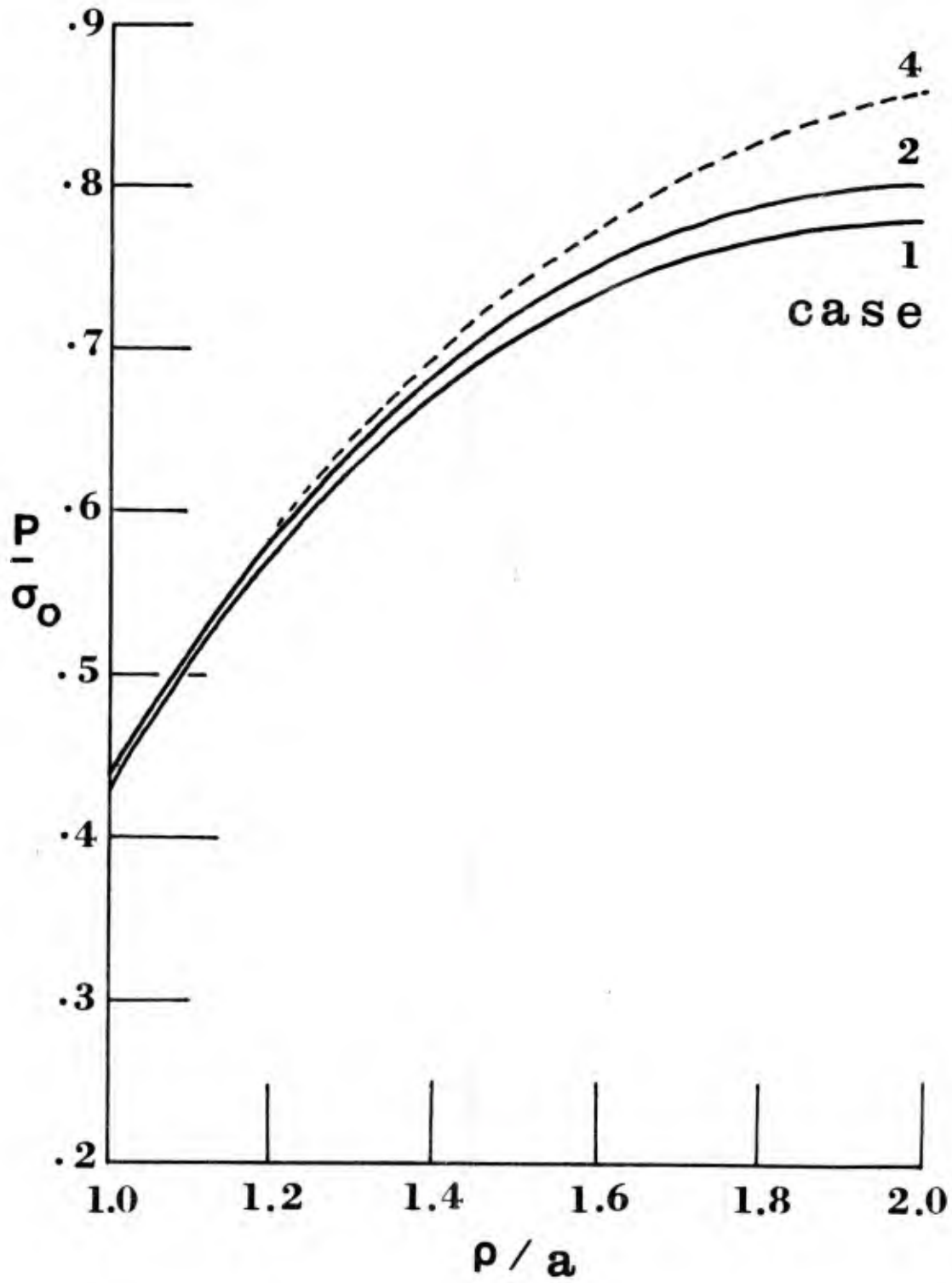


Figure 2. Elastic-plastic boundary as a function of internal pressure for cases 1, 2, and 4.



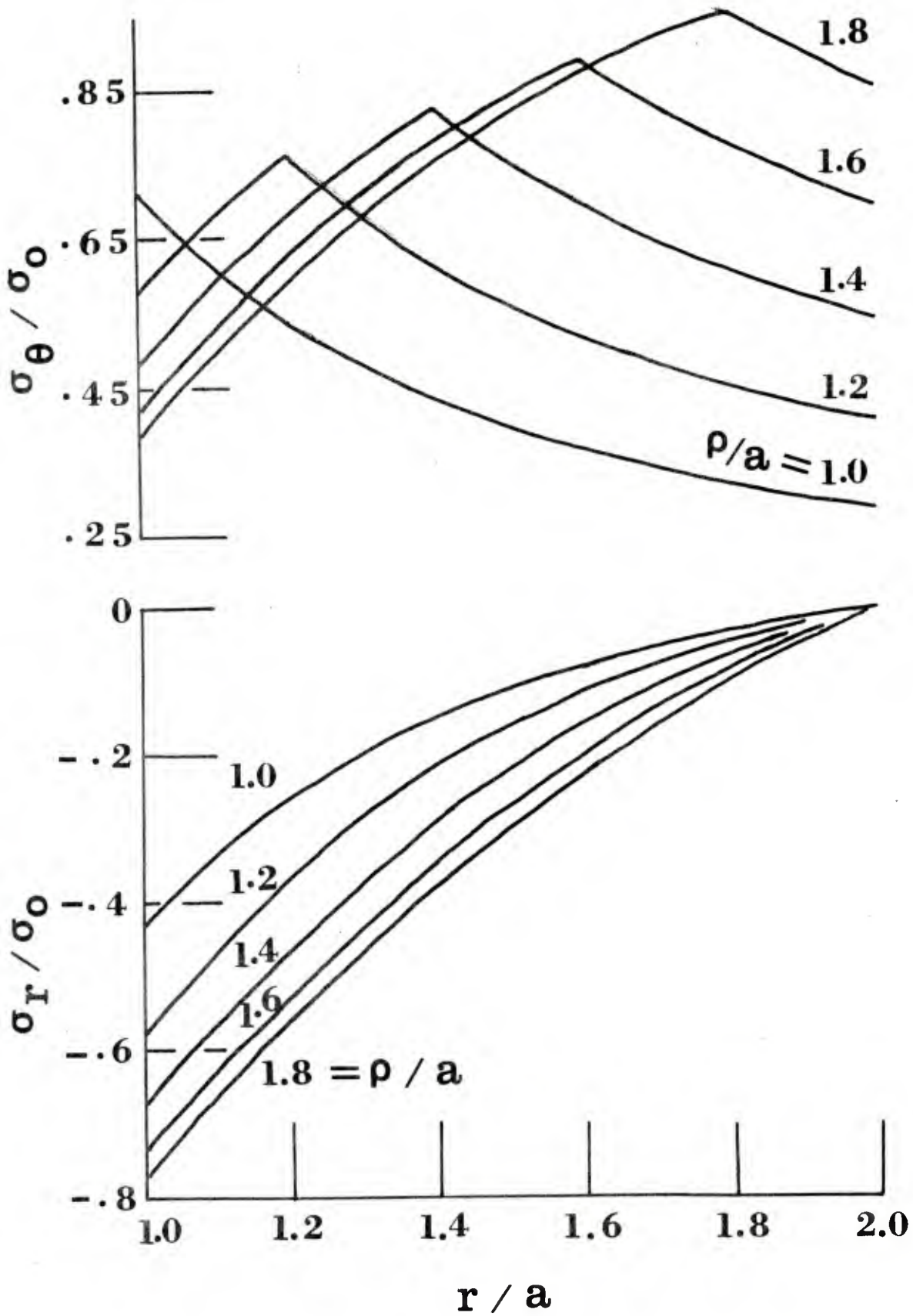


Figure 3. Distributions of radial and tangential stresses for case 1 ( $\alpha = 0, \mu = 0, b/a = 2$ ).

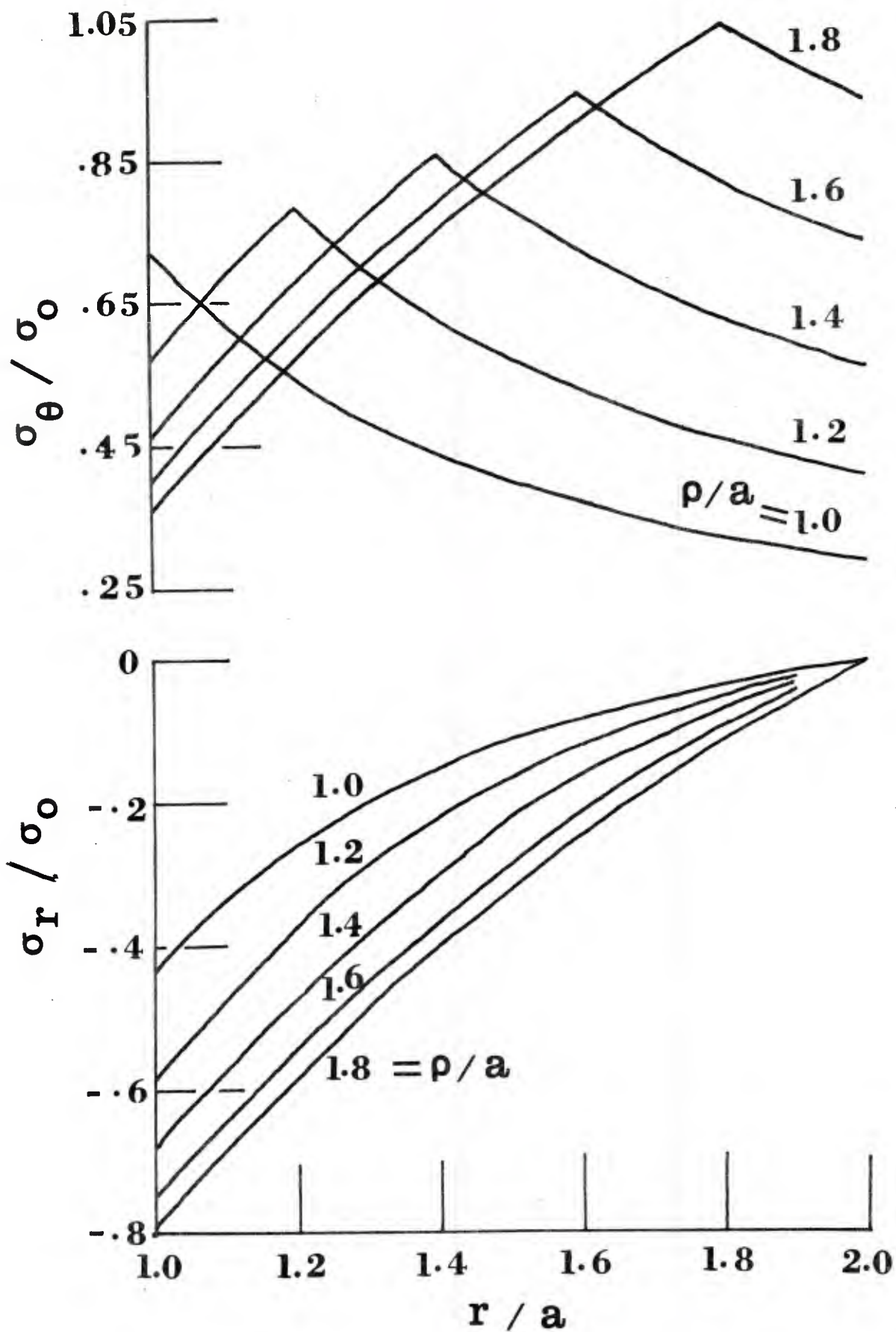


Figure 4. Distributions of radial and tangential stresses for case 2 ( $\alpha = 0$ ,  $\mu = 1$ ,  $b/a = 2$ ).

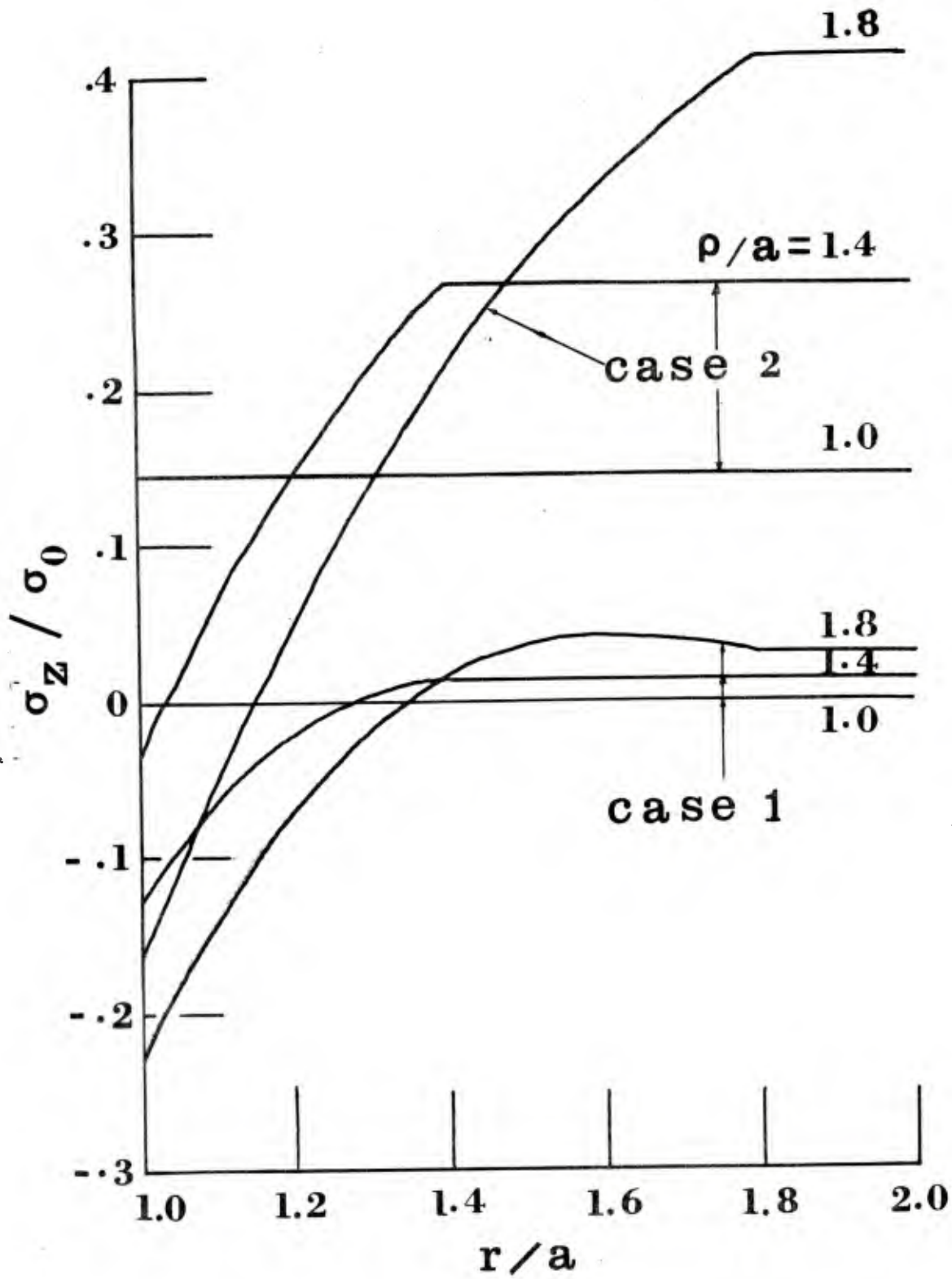


Figure 5. Distributions of axial stress for cases 1 and 2.

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