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AN ADAPTIVE ALGORITHM FOR EXACT SOLUTION OF AN OVERSTRAINED TUBE

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September 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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An adaptive algorithm to generate an exact solution has been developed for the plane-strain problem of a thick-walled tube overstrained by internal or external pressure. The material obeys the von Mises' yield criterion, the Prandtl-Reuss flow theory and the isotropic hardening rule. The ideally-plastic material is treated as a special case. The formulation is based on the finite-difference

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20. Abstract (CONT'D)

method in conjunction with a scaled incremental-loading approach. One additional grid point will become yielded in each load step. The grid sizes and load increments are determined in the program. For a given percentage of overstrain and a desired solution necessary, the stresses and strains can be obtained in an efficient way.

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INTRODUCTION

In a previous paper[1], a new finite-difference approach was developed for solving the axisymmetric plane-strain problems subjected to internal or external pressure beyond the elastic limit. The material was assumed to obey the von Mises' yield criterion, the Prandtl-Reuss flow theory and the isotropic hardening rule. The ideally-plastic material was treated as a special case. The new formulation is simpler than other finite-difference methods for ideally-plastic materials[2] and strain-hardening materials[3]. The load increments used in all steps were fixed and equal. Accurate numerical results can be obtained by reducing the grid sizes and load increments.

In the present paper, an adaptive algorithm to generate a more accurate solution will be developed for the plane-strain problem of an overstrained tube. The load increments in all steps are varied and determined automatically in the program. One additional grid point will become yielded in each load step. To reach 100% overstrain, the number of steps are equal to the number of grids. For a given percentage of overstrain and a desired solution accuracy, the stresses and strains can be obtained in a much more efficient manner.

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[1]Chen, P. C. T., "A Finite-Difference Approach to Axisymmetric Plane-Strain Problems Beyond the Elastic Limit," Transactions Twenty-Fifth Conference of Army Mathematicians, pp. 455-466, January 1980.

[2]Hodge, P. G. and White, G. N., "A Quantitative Comparison of Flow and Deformation Theories of Plasticity," J. Appl. Mech., Vol. 17, 1950, pp. 180-184.

[3]Chu, S. C., "A More Rational Approach to the Problem of an Elasto-Plastic Thick-Walled Cylinder," J. of the Franklin Institute, Vol. 294, 1972, pp. 57-65.

BASIC EQUATIONS

Assuming small strain and no body forces in the axisymmetric state of plane strain, the radial and tangential stresses, σ_r and σ_θ, must satisfy the equilibrium equation,

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

and the corresponding strains, ε_r and ε_θ, are given in terms of the radial displacement, u, by

$$\varepsilon_r = \partial u/\partial r \quad , \quad \varepsilon_\theta = u/r \quad . \qquad (2)$$

It follows that the strains must satisfy the equation of compatability

$$r(\partial\varepsilon_\theta/\partial r) = \varepsilon_r - \varepsilon_\theta \quad . \qquad (3)$$

The material is assumed to be elastic-plastic, obeying Mises' yield criterion, Prandtl-Reuss flow theory and isotropic hardening law. The complete stress-strain relations can be rewritten in an incremental form[4]

$$d\sigma_i = d_{ij}d\varepsilon_j \quad \text{for} \quad i,j = r,\theta z \qquad (4)$$

and

$$d_{ij}/2G = \nu/(1-2\nu) + \delta_{ij} - \sigma_i'\sigma_j'/S \; , \qquad (5)$$

where E is Young's modulus, ν is Poisson's ratio, δ_{ij} is the Kronecker delta,

$$S = \frac{2}{3}\,(1 + \frac{1}{3}\,H'/G)\sigma^2 \quad , \quad 2G = E/(1+\nu) \quad , \qquad (6)$$

$$\sigma_m = (\sigma_r+\sigma_\theta+\sigma_z)/3 \quad , \quad \sigma_i' = \sigma_i - \sigma_m \quad , \qquad (7)$$

$$\sigma = (1/\sqrt{2})[(\sigma_r-\sigma_\theta)^2 + (\sigma_\theta-\sigma_z)^2 + (\sigma_z-\sigma_r)^2]^{1/2} > \sigma_o \quad , \qquad (8)$$

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[4]Yamada, Y., Yoshimura, N., and Sakurni, T., "Plastic Stress-Strain Matrix and Its Application for the Solution of Elastic-Plastic Problems by the Finite Element Method," Int. J. Mech. Sci., Vol. 10, 1968, pp. 343-354.

and σ_o 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

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

For an ideally-plastic material, $H' = 0$. When $\sigma < \sigma_o$ or $d\sigma < 0$, the state of stress is elastic and the third term in equation (4) disappears. Consider a thick-walled cylinder of inner radius a and external radius b. The tube is subjected to inner pressure p and/or external pressure q. The elastic solution for this problem is well-known

$$\left.\begin{matrix}\sigma_r \\ \sigma_\theta\end{matrix}\right\} = \pm \frac{(q-p)}{b^2/a^2-1}\left(\frac{b}{r}\right)^2 + \frac{p-q(b/a)^2}{b^2/a^2-1} \quad , \tag{9}$$

$$\sigma_z = \nu(\sigma_r+\sigma_\theta) \quad ,$$

and the pressure p* or q* required to cause initial yielding can be determined by using the Mises' yield criterion.

FINITE-DIFFERENCE FORMULATIONS

For pressure beyond the elastic limit, an incremental approach of the finite-difference formulation is used. At the beginning of each incremental loading, Δp or Δq, the distribution of displacements, strains and stresses is assumed to be known and we want to determine Δu, $\Delta\varepsilon_r$, $\Delta\varepsilon_\theta$, $\Delta\sigma_r$, $\Delta\sigma_\theta$, $\Delta\sigma_z$ at all grid points. The cross section of the tube is divided into n rings with

$$r_1 = a, r_2, \ldots, r_k=\rho, \ldots, r_{n+1}=b \tag{10}$$

where ρ is the radius of the elastic-plastic interface.

Since the incremental stresses are related to the incremental strains by the incremental form (Eq. (4)) and $\Delta u = r\Delta\varepsilon_\theta$, there exists only two unknowns at each station that have to be determined for each increment of loading. The unknown variables in the present formulation are $(\Delta\varepsilon_\theta)_i$, $(\Delta\varepsilon_r)_i$, for $i = 1,2,\ldots,n,n+1$.

The equation of equilibrium (Eq. (1)) and the equation of compatibility (Eq. (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 $i = 1,\ldots,n$ are given by

$$(r_{i+1}-2r_i)(\Delta\sigma_r)_i - (r_{i+1}-r_i)(\Delta\sigma_\theta)_i + r_i(\Delta\sigma_r)_{i+1}$$
$$= (r_{i+1}-r_i)(\sigma_\theta-\sigma_r)_i - r_i[(\sigma_r)_{i+1} - (\sigma_r)_i] \qquad (11)$$

for the equation of equilibrium, and

$$(r_{i+1}-2r_i)(\Delta\varepsilon_\theta)_i - (r_{i+1}-r_i)(\Delta\varepsilon_r)_i + r_i(\Delta\varepsilon_\theta)_{i+1}$$
$$= (r_{i+1}-r_i)(\varepsilon_r-\varepsilon_\theta)_i - r_i[(\varepsilon_\theta)_{i+1} - (\varepsilon_\theta)_i] \qquad (12)$$

for the equation of compatibility.

With the aid of the incremental stress-strain relations (Eq. (4)), Eq. (11) can be rewritten as

$$[(r_{i+1}-2r_i)(d_{12})_i + (-r_{i+1}+r_i)(d_{22})_i](\Delta\varepsilon_\theta)_i$$
$$+ [(r_{i+1}-2r_i)(d_{11})_i + (-r_{i+1}+r_i)(d_{21})_i](\Delta\varepsilon_r)_i$$
$$+ r_i(d_{12})_{i+1}(\Delta\varepsilon_\theta)_{i+1} + r_i(d_{11})_{i+1}(\Delta\varepsilon_r)_{i+1}$$
$$= (r_{i+1}-r_i)(\sigma_\theta-\sigma_r)_i - r_i[(\sigma_r)_{i+1} - (\sigma_r)_i] \quad . \qquad (13)$$

The boundary conditions for the problem are

$$\Delta\sigma_r(a,t) = -\Delta p \quad , \quad \Delta\sigma_r(b,t) = -\Delta q \quad . \qquad (14)$$

Using the incremental relations (Eq. (4)), we rewrite Eq. (11) as

$$(d_{12})_1(\Delta\varepsilon_\theta)_1 + (d_{11})_1(\Delta\varepsilon_r)_1 = -\Delta p \quad . \qquad (15)$$

and

$$(d_{12})_{n+1}(\Delta\varepsilon_\theta)_{n+1} + (d_{11})_{n+1}(\Delta\varepsilon_r)_{n+1} = -\Delta q \quad . \tag{16}$$

Now we can form a system of 2(n+1) equations for solving 2(n+1) unknowns, $(\Delta\varepsilon_\theta)_i$, $(\Delta\varepsilon_r)_i$, for $i = 1,2,\ldots,n,n+1$. Equations (15) and (16) are taken as the first and last equations, respectively, and the other 2n equations are set up at $i = 1,2,\ldots,n$ using Eqs. (12) and (13). The final system is an unsymmetric band matrix with the nonzero terms clustered about the main diagonal, two below and one above.

INCREMENTAL LOADING - FIXED VS. SCALED

When the total applied pressure p or q is given, it is natural to divide the loading path into m equal fixed increments with

$$\Delta p = (p-p^*)/m \quad , \quad \Delta q = (q-q^*)/m \quad . \tag{17}$$

These fixed increments need not be equal for all steps and any sequence of m increments can be supplied by the user. The fixed increments are applied until the total pressure or a given percentage of overstrain is reached. The percentage of overstrain is defined as $(\rho-a)/(b-a) \times 100\%$. The accuracy of the numerical results will depend upon the values of m and n used. Large values of m and n will yield better results at greater cost. For each value of n = 20, 50, 100,..., we may set m = n, 2n, 4n, 8n,..., to discuss the convergence. The numerical results suggest that a sequence of decreasing load-increments is a better choice than that of equal increments.

In the following, a method to generate a sequence of load-increments is described. The method is based on a scaled incremental-loading approach.[4] In each step, a dummy load-increment such as Δp is applied and the incremental results $\Delta\sigma_i$ for $i = r,\theta,z$ at all grids are determined. For all grid points at which $\sigma = ||\sigma_i|| < \sigma_o$, we compute the scaler α's by the formula

$$\alpha = \frac{1}{2}\{\Gamma + [\Gamma^2 + 4||\Delta\sigma_i||^2(\sigma_o{}^2 - ||\sigma_i||^2)]^{1/2}\}/||\Delta\sigma_i||^2 \quad , \qquad (18)$$

where

$$\Gamma = ||\sigma_i||^2 + ||\Delta\sigma_i||^2 - ||\sigma_i + \Delta\sigma_i||^2 \quad , \qquad (19)$$

and $||\sigma_i||$, $||\Delta\sigma_i||$, $||\sigma_i + \Delta\sigma_i||^2$ are computed by

$$||\sigma_i||^2 = \frac{1}{2}[(\sigma_r-\sigma_\theta)^2 + (\sigma_\theta-\sigma_z)^2 + (\sigma_z-\sigma_r)^2] \quad . \qquad (20)$$

Let λ be the minimum of the α's. Then λ is the load-increment factor just sufficient to yield one additional point. A sequence of $\lambda^{(j)}$ can be determined for all steps $j = 1,2,\ldots,m$ and the updated results are

$$p^{(j)} = p^{(j-1)} + \lambda^{(j)}\Delta p^{(j)}$$

$$\sigma_i{}^{(j)} = \sigma_i{}^{(j-1)} + \lambda^{(j)}\Delta\sigma_i{}^{(j)} \quad , \quad \text{etc.} \qquad (21)$$

NUMERICAL RESULTS AND DISCUSSIONS

The numerical results for a thick tube with $b/a = 2$, $\nu = .3$ subjected to internal pressure only were obtained. The elastic-perfectly-plastic case ($H' = 0$) as well as strain-hardening case ($H' = E/9$) were considered. Both fixed and scaled incremental loading approaches were used. The pressure p^* required to cause initial yielding is $.4323\ \sigma_o$.

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[4] Yamada, Y., Yoshimura, N., and Sakurni, T., "Plastic Stress-Strain Matrix and Its Application for the Solution of Elastic-Plastic Problems by the Finite Element Method," Int. J. Mech. Sci., Vol. 10, 1968, pp. 343-354.

In order to compare the rate of convergence based on two incremental-loading procedures, we consider an elastic-perfectly-plastic case. The numerical results are shown in Tables I and II. Based on the equal load-increments, the effect of m and n on the internal pressure and bore displacement can be seen in Table I. Larger values of m and n will yield better results except the bore displacement for 100% overstrain. If the scaled incremental-loading approach is used, the load-increments for all steps are calculated and m = n x 100% overstrain. The numerical results for the pressure, displacement, axial stress at the inside and the maximum hoop stress are shown in Table II. A comparison of Tables I and II indicates that the scaled incremental-loading approach is much more accurate and efficient than the equal incremental-loading approach. For example, to reach 50% overstrain with n = 20, 10 scaled load-increments can give better results than 2044 equal load-increments.

Finally, we consider a strain-hardening tube subjected to internal pressure only. The numerical results were based on the scaled incremental loading and the following parameters: $b/a = 2$, $\nu = .3$, $H' = E/9$, $n = 100$. The stresses and strains as functions of overstrain percentage were obtained. In Figures 1 and 2, we show the residual stresses resulting from 50% and 100% overstrain. The effect of favorable residual stresses of an autofrettaged tube is well-known. A simple and efficient approach to compute accurate residual stresses is important.

TABLE I. CONVERGENCE STUDY BASED ON FIXED LOAD-INCREMENTS IN A PLANE-STRAIN TUBE (b/a = 2, ν = .3, H' = 0), Δp = (p-p*)/m

n	m	P/σ_o	$\frac{E}{\sigma_o}\frac{U_a}{a}$	m	P/σ_o	$\frac{E}{\sigma_o}\frac{U_a}{a}$
20	14	.7597	2.1779	18	.8532	4.1528
	30	.7480	2.1382	38	.8322	4.0422
	62	.7422	2.1169	78	.8222	4.2663
	126	.7393	2.0991	159	.8198	5.2851
	252	.7374	2.0924	317	.8161	4.6004
	508	.7369	2.0897	637	.8143	4.1516
	1020	.7367	2.0904	1277	.8134	4.1538
	2044	.7366	2.0898	2556	.8128	4.0463
50	39	.7347	2.0497	50	.8200	3.9683
	77	.7308	2.0387	98	.8123	3.8637
	156	.7269	2.0142	199	.8081	3.8473
	391	.7261	2.0168	497	.8058	4.1184
	793	.7257	2.0152	1006	.8046	3.9444
100	77	.7249	1.9963	99	.8085	3.7437
	154	.7231	1.9913	198	.8062	4.2167
	236	.7235	1.9982	301	.8037	3.7931
	391	.7227	1.9952	498	.8022	3.7641
200	152	.7211	1.9781	196	.8047	4.3750
	311	.7211	1.9831	398	.8018	3.9207
	720	.7203	1.9802	920	.8003	3.8174

TABLE II. CONVERGENCE STUDY BASED ON SCALED LOAD-INCREMENTS IN A PLANE-STRAIN TUBE ($b/a = 2$, $\nu = .3$, $H' = 0$).

O.S.	n	P/σ_o	$\frac{E}{\sigma_o}\frac{U_a}{a}$	Max σ_θ/σ_o	σ_z/σ_o at r=a
	20	.7276	2.0710	.8879	-.1106
	50	.7225	2.0078	.8919	-.1071
50%	100	.7205	1.9877	.8932	-.1056
	200	.7193	1.9776	.8939	-.1047
	400	.7189	1.9731	.8942	-.1045
	20	.8079	3.9786	1.1251	-.2199
	50	.8027	3.7835	1.1251	-.2127
100%	100	.8004	3.7224	1.1251	-.2098
	200	.7990	3.6920	1.2151	-.2081
	400	.7982	3.6770	1.1251	-.2072

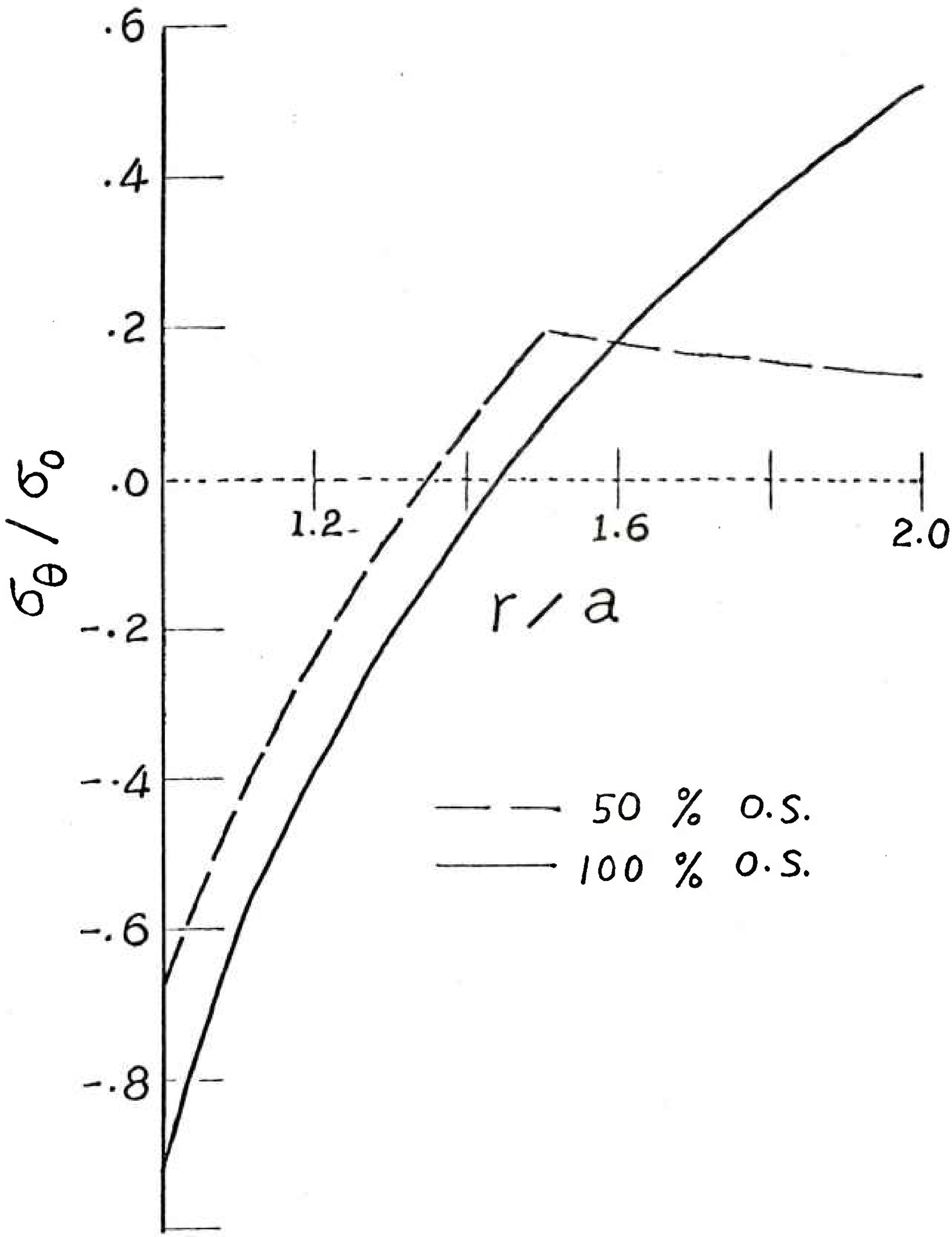

Figure 1. The residual tangential stress distribution in an overstrained tube (b/a = 2.0, ν = 0.3, ω = 0.1, n = 100).

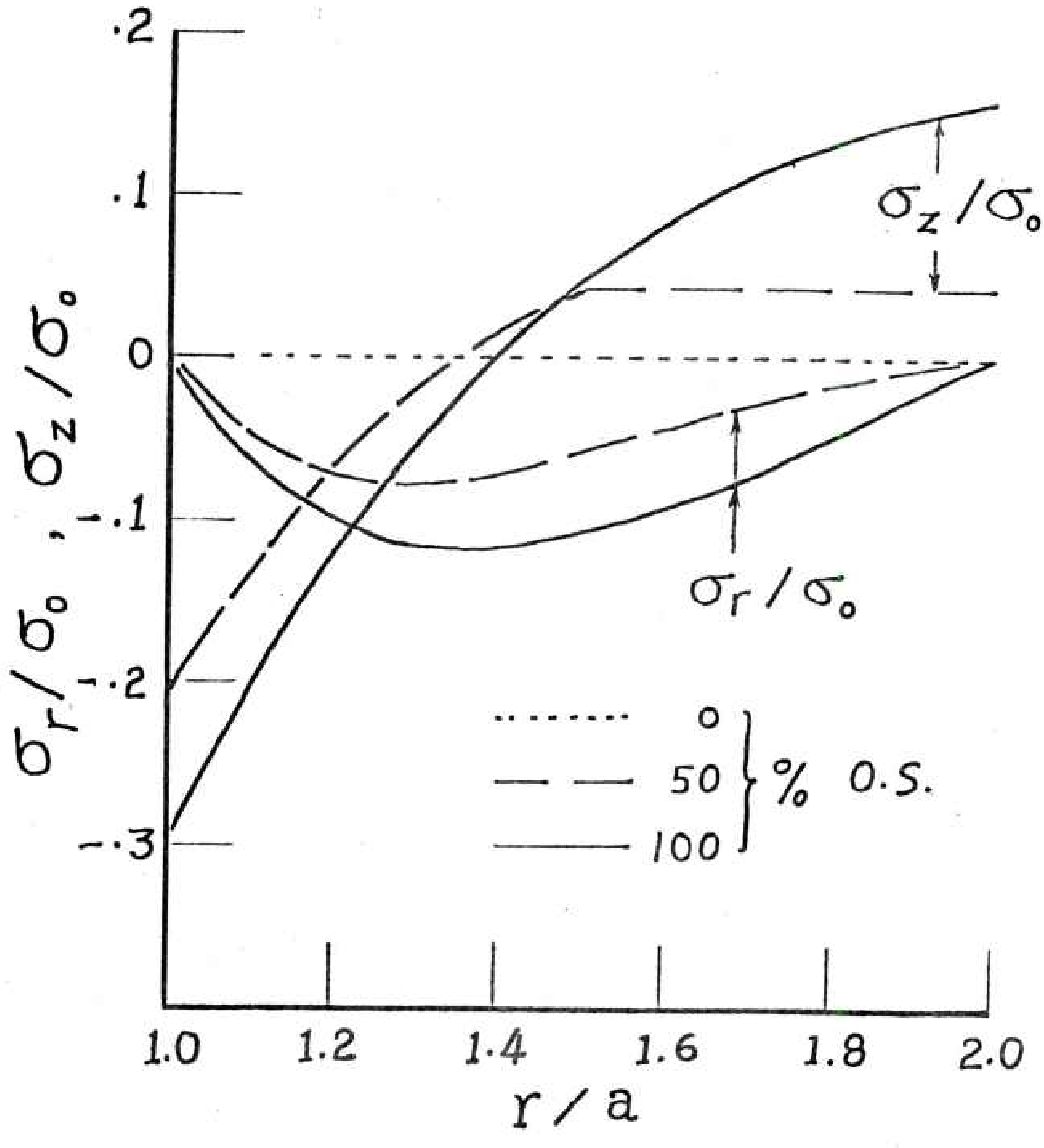

Figure 2. The residual radial and axial stress distribution in an overstrained tube ($b/a = 2.0$, $\nu = 0.3$, $\omega = 0.1$, $n = 100$).

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1. Chen, P. C. T., "A Finite-Difference Approach to Axisymmetric Plane-Strain Problems Beyond the Elastic Limit," Transactions Twenty-Fifth Conference of Army Mathematicians, pp. 455-466, January 1980.

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