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NUMERICAL SOLUTION TO AN AUTOFRETTAGED TUBE WITH CONSTRAINING WALLS AND END CLOSURES

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June 1982

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This report presents a numerical study of a container autofrettage process. This process uses internal hydraulic pressure to expand the tube, restraining containers to control the amount of tube expansion and the press force to hold the end closures. The incremental finite-difference approach developed recently by the author is extended to obtain numerical results. The effects of restraining walls and the press force on the displacements and stresses are discussed.

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INTRODUCTION

The importance of favorable residual stresses in an autofrettaged tube is well known.[1] The container method is one of the autofrettage processes currently being used for gun tubes. It uses internal hydraulic pressure to expand the tube. Restraining containers or dies are used to control the amount of tube expansion by means of a small, predetermined clearance between the inside of the containers and the outside of the tube. The press is used to simply hold the end closures or seals in the ends of the tube and to support the forces of the internal pressure on the closures.

Many methods for solving the partially autofrettaged problem in a gun tube have been reported.[2-6] However, the effects of constraining walls and end closures on the residual stresses have never been discussed. This report presents a numerical study of the container autofrettage process. The finite-difference approach developed recently by the author[6] is extended to

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[1]Davidson, T. E. and Kendall, D. P., "The Design of Pressure Vessels For Very High Pressure Operation," Watervliet Arsenal Report WVT-6917. Also in Mechanical Behavior of Materials Under Pressure (edited by Pugh, H.L.D.), Elsevier Co., 1970, Chapter 2.

[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 Elastoplastic Thick-Walled Cylinder," J. of the Franklin Institute, Vol. 294, 1972, pp. 57-65.

[4]Chen, P. C. T., "The Finite Element Analysis of Elastic-Plastic Thick-Walled Tubes," Proc. of Army Symposium on Solid Mechanics, 1972, The Role of Mechanics in Design-Ballistic Problems, pp. 243-253.

[5]Elder, A. S., Tomkins, R. C., and Mann, T. L., "Generalized Plane Strain in an Elastic, Perfectly Plastic Cylinder, With Reference to the Hydraulic Autofrettage Process," Trans. 21st Conference of Army Mathematicians, 1975, pp. 623-659.

[6]Chen, P. C. T., "Generalized Plane-Strain Problems in an Elastic-Plastic Thick-Walled Cylinder," Trans. 26th Conference of Army Mathematicians, 1980, pp. 265-275.

obtain the numerical results. The material is assumed to obey the von Mises' yield criterion and the Prandtl-Reuss incremental stress-strain relations.

FINITE-DIFFERENCE FORMULATION

Consider a long, open-end thick-walled cylinder of inner radius a and external radius b. The inside surface of the tube is subjected to hydraulic pressure p and and end force ($p\pi a^2$) is applied to simply hold the end closures or seals. The additional force f on the end closures will press against the tube. The amount of tube expansion is restricted by means of restraining containers of inside radius C. The cross section of the tube is divided into n rings with $r_1 = a, r_2, \ldots, r_k = \rho, \ldots, r_{n+1} = b$, where ρ is the radius of the elastic-plastic interface. Since the material behavior is nonlinear, an incremental approach is used. At the beginning of each incremental loading, the distribution of displacements, strains, and stresses is assumed to be known and we want to determine Δu, $\Delta\varepsilon_r$, $\Delta\varepsilon_\theta$, $\Delta\varepsilon_z$, $\Delta\sigma_r$, $\Delta\sigma_\theta$, $\Delta\sigma_z$ at all grid points. According to the Prandtl-Reuss flow theory, the incremental stresses are related to the incremental strains by

$$\{\Delta\sigma_i\} = [d_{ij}]\ \{\Delta\varepsilon_j\} \text{ for } i,j = r,\theta,z \tag{1}$$

and

$$[d_{ij}] = 2G[\nu/(1-2\nu) + \delta_{ij} - \sigma_i'\sigma_j'/s] \tag{2}$$

where

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

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

$$\sigma = (1/\sqrt{2})[(\sigma_r-\sigma_\theta)^2 + (\sigma_\theta-\sigma_z)^2 + (\sigma_z-\sigma_r)^2]^{1/2} > \sigma_o \tag{3}$$

E is Young's modulus, ν is Poisson's ratio, δ_{ij} is the Kronecker delta, αE is the slope of the effective stress-strain curve, and σ_0 is the yield stress in simple tension or compression. When $\sigma < \sigma_0$ or $d\sigma < 0$, the state of stress is elastic and the last term in Eq. (2) disappears. Since the incremental stresses are related to the incremental strains by Eq. (1) and $\Delta u = r\Delta\varepsilon_\theta$, 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 e_z is independent of r, the unknown variables in the present formulation are $(\Delta\varepsilon_\theta)_i$, $(\Delta\varepsilon_r)_i$, for $i = 1,2,\ldots,n,n+1$, and $\Delta\varepsilon_z$.

The equation of equilibrium and the equation of compatibility 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[6]

$$\begin{aligned}&[(r_{i+1}-2r_i)(d_{12})_i + (-r_{i+1}+r_i)(d_{22})_i](\Delta\varepsilon_\theta)_i\\&+ [(r_{i+1}-2r_i)(d_{11})_i + (-r_{i+1}+r_i)(d_{21})_i](\Delta\varepsilon_r)_i\\&+ r_i(d_{12})_{i+1}(\Delta\varepsilon_\theta)_{i+1} + r_i(d_{11})_{i+1}(\Delta\varepsilon_r)_{i+1}\\&+ [(r_{i+1}-2r_i)(d_{13}) + (-r_{i+1}+r_i)(d_{23})_i + r_i(d_{13})_{i+1}]\Delta\varepsilon_z\\&= (r_{i+1}-r_i)(\sigma_\theta-\sigma_r)_i - r_i[(\sigma_r)_{i+1} - (\sigma_r)_i]\end{aligned} \tag{4}$$

for the equation of equilibrium, and

$$\begin{aligned}&(r_{i+1}-2r_i)(\Delta\varepsilon_\theta)_i - (r_{i+1}-r_i)(\Delta\varepsilon_r)_i + r_i(\Delta\varepsilon_\theta)_{i+1}\\&= (r_{i+1}-r_i)(\varepsilon_r-\varepsilon_\theta)_i - r_i[(\varepsilon_\theta)_{i+1} - (\varepsilon_\theta)_i]\end{aligned} \tag{5}$$

for the equation of compatibility.

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[6]Chen, P. C. T., "Generalized Plane-Strain Problems in an Elastic-Plastic Thick-Walled Cylinder," Trans. 26th Conference of Army Mathematicians, 1980, pp. 265-275.

BOUNDARY CONDITIONS AND INCREMENTAL LOADING

The three boundary conditions for the problem are

(i) $$(d_{12})(\Delta\varepsilon_\theta)_1 + (d_{11})_1(\Delta\varepsilon_r)_1 + (d_{13})_1\Delta\varepsilon_z = -\Delta p \quad (6)$$

(ii) $$(d_{12})_{n+1}(\Delta\varepsilon_\theta)_{n+1} + (d_{11})_{n+1}(\Delta\varepsilon_r)_{n+1} + (d_{13})_{n+1}\Delta\varepsilon_z = 0 \quad (7a)$$

before contact or $(\Delta\varepsilon_\theta)n+1 = 0$ after contact , (7b)

(iii)

$$\sum_{i=1}^{n} (r_{i+1}-r_i)\{r_i[(d_{23})_i(\Delta\varepsilon_\theta)_i + (d_{13})_i(\Delta\varepsilon_r)_i] + r_{i+1}[(d_{23})_{i+1}(\Delta\varepsilon_\theta)_{i+1} + (d_{13})_{i+1}(\Delta\varepsilon_r)_{i+1}]\} + \sum_{i=1}^{n} (r_{i+1}-r_i)[r_i(d_{33})_i + r_{i+1}(d_{33})_{i+1}]\Delta\varepsilon_z = \Delta f/\pi \quad (8)$$

Now we can form a system of 2n+3 equations for solving 2n+3 unknowns, $(\Delta\varepsilon_\theta)_i$, $(\Delta\varepsilon_r)_i$, at $i = 1,2,\ldots,n,n+1$ and $\Delta\varepsilon_z$. Equations (6), (7), and (8) are taken as the first and the last two equations, respectively, and the other 2n equations are set up at $i = 1,2,\ldots,n$ using Eqs. (4) and (5). 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 order to increase the efficiency of the program, an adaptive algorithm based on a scaled incremental-loading approach has been implemented. 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 g's by the formula

$$g = \frac{1}{2} \{\Gamma + [\Gamma^2 + 4||\Delta\sigma_i||^2(\sigma_o{}^2-||\sigma_i||^2)^{1/2}\}/||\Delta\sigma_i||^2 \quad (9)$$

where

$$\Gamma = ||\sigma_i||^2 + ||\Delta\sigma_i||^2 - ||\sigma_i + \Delta\sigma_i||^2 \quad (10)$$

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

$$||\sigma_i||^2 = \frac{1}{2}\,[(\sigma_r-\sigma_\theta)^2 + (\sigma_\theta-\sigma_z)^2 + (\sigma_z-\sigma_r)^2] \tag{11}$$

Let λ be the minimum of the g'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

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

$$\sigma_i^{(j)} = \sigma_i^{(j-1)} + \lambda^{(j)}\Delta\sigma_i^{(j)} \quad \text{, etc.} \tag{12}$$

NUMERICAL RESULTS

The numerical results are obtained on the basis of the following parameters: $a = 1.895"$, $b = 3.21"$, $c = 3.2275"$, $n = 50$, $E = 30\times10^6$ psi, $\nu = 0.3$, $\sigma_o = 17\times10^4$ psi and $H' = 0$. The maximum internal pressure applied is 13×10^4 psi (max. p) and the maximum end force applied against the tube is $f = -0.6p\pi(b^2-a^2)$. Introducing the dimensionless quantity $\bar{f} = f/[\pi(b^2-a^2)p]$, we have $-0.6 < \bar{f} < 0$. Since the end force required to simply hold the end closures or scales is $-p\pi a^2$, the total end force applied on the end closures is $F = p\pi a^2[-1 + \bar{f}(b^2/a^2-1)]$. In order to discuss the effect of end force f, the numerical results have been obtained for two extreme cases, i.e. $\bar{f} = 0$ and -0.6.

(a) $\bar{f} = 0$. In this case the total end force applied on the end closures is $F = -p\pi a^2$, just enough to support the forces of the internal pressure on the closures. Therefore, there is no force applied at the end of the tube. The maximum internal pressure ($p = 13\times10^4$ psi) is applied incrementally in three different stages. The displacements u_a, u_b at the inside, outside surface as functions of internal pressure p are shown in Figure 1. In stage one, the elastic solution due to a dummy internal pressure is applied and the scaled factor to cause initial yielding is determined. The closed form elastic solution together with the von Mises' yield criterion may be used, and the pressure factor corresponding to initial yielding is $p^*/\sigma_0 = 0.36875$. In the second stage, scaled incremental-loading approach is used until the maximum allowable outside displacement (c-b) is reached. At the instant when the contact between the tube and container first occurs, the pressure p/σ_0 is 0.57916 and 96 percent of the tube has been yielded. In the third stage, there is no outside displacement and internal pressure is increased in 20 equal steps until the maximum $p/\sigma_0 = 0.76471$ has been reached. The relation between pressure and inside displacement is almost linear in this stage as shown in Figure 1. The results of the displacements at the end of three stages are represented by the points 1, 2, and 3. The corresponding results of the stress distributions for σ_r, σ_θ, and σ_z are shown in Figures 2 through 4, respectively. It can be seen that the stress distributions at the end of three loading stages are quite different.

The residual stresses after unloading completely from the end of three loading stages have also been obtained. The results for the residual hoop stresses for three stages and the residual axial stress for the last stage are shown in Figure 5. The differences in residual stresses between stage two and three are much smaller than those before unloading. Thus a further increase in internal pressure is possible in the presence of restraining container, but the increased pressure makes little differences in the residual stresses. The purpose of the outside container is to prevent occurrence of large displacements.

(b) $\bar{f} = -0.6$. In this case the total end force applied on the end closures is $F = -p\pi a^2(0.4 + 0.6\ b^2/a^2)$. This end force is larger than that required to support the forces of the internal pressure on the closures. Therefore, the end force applied at the end of the tube is $f = -0.6\ p\pi(b^2-a^2)$. For this case the maximum internal pressure is applied incrementally in four different stages. The displacements u_a, u_b at the inside, outside surface as functions of internal pressure p are shown in Figure 6. The points 1 to 4 represent the corresponding results at the end of each loading stage. At the end of the first stage, initial yielding solution has been obtained and the pressure required is $p = 0.34594\ \sigma_o$. In the second stage, 50 scaled incremental-loading steps are applied until the entire tube becomes yielded. At the end of the second stage, the pressure factor p/σ_o is 0.50194 and the outside displacement is still smaller than the clearance, i.e., $u_b = 0.86126\ b\ \sigma_o/E < 0.0175''$. Since the material is assumed to be ideally plastic, the tube would collapse if there were no outside restraining containers. A very small increase in internal pressure, say $\Delta p/\sigma_o = 0.0001$, will close the clearance between the tube and container. The instant when the contact first occurs is the end of loading stage three. After the contact we increase the internal pressure in 29 equal steps until the maximum pressure has been reached. The relation between pressure and internal displacement is approximately linear in this stage as shown in Figure 6. The stress distributions for σ_r, σ_θ at the end of four loading stages are shown in Figures 7 and 8 respectively, and that for σ_z shown in Figure 4. The change in stresses during the third loading stage is too small to be shown graphically in these figures but the differences in displacements are large as shown in Figure 6.

The residual stresses due to complete unloading from the end of each loading stage have also been obtained and some of the results are shown in Figure 9. It can be seen that the differences in stresses during loading stages three and four are quite large but the corresponding residual stresses are very close. This also shows that the effect of outside containers and end forces on the residual stresses is small but their effects on the displacement and stresses during loading are large. In the presence of the press force on the tube end, the axial stress distributions change drastically as shown in Figure 4 and as compared with the case of no end force. By comparing the results for the residual axial stresses as shown in Figures 5 and 9, we can see two different stress patterns, one is almost the reverse of the other. As a result of extra press force on the tube end, the final residual stresses can change signs.

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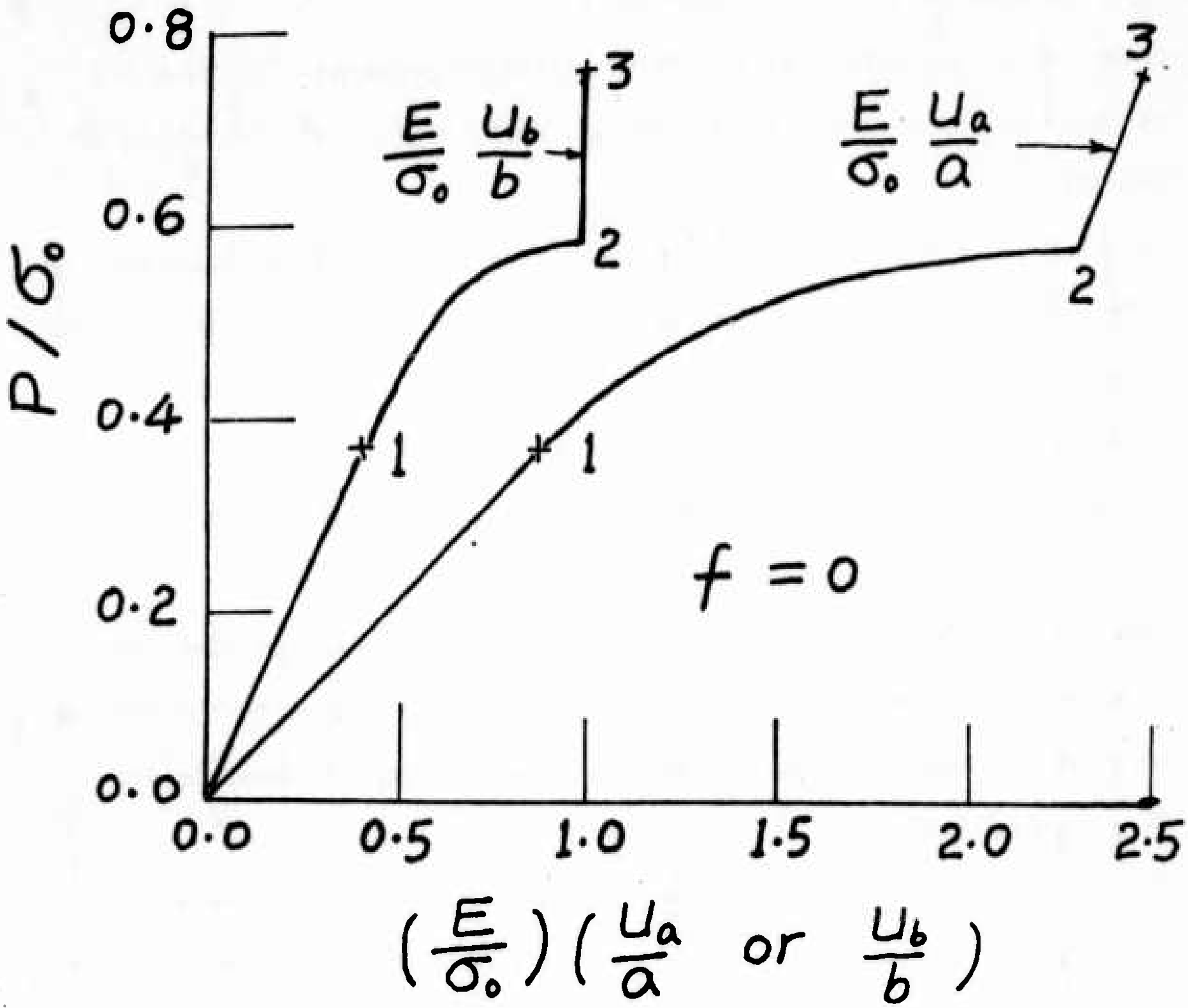

Figure 1. The boundary displacements u_a, u_b as functions of internal pressure p with no end force f.

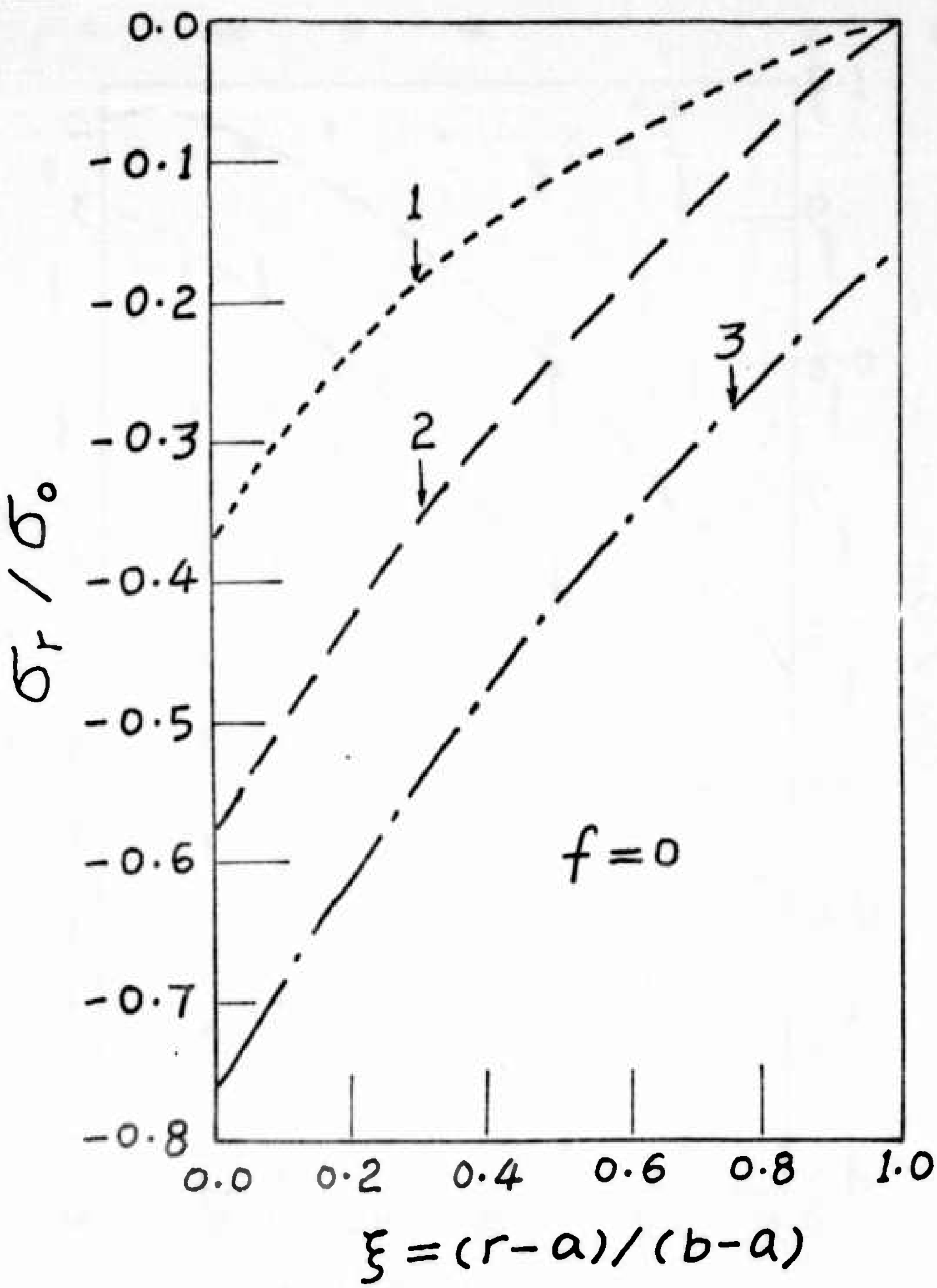

Figure 2. The radial stress distributions during loading with no end force f.

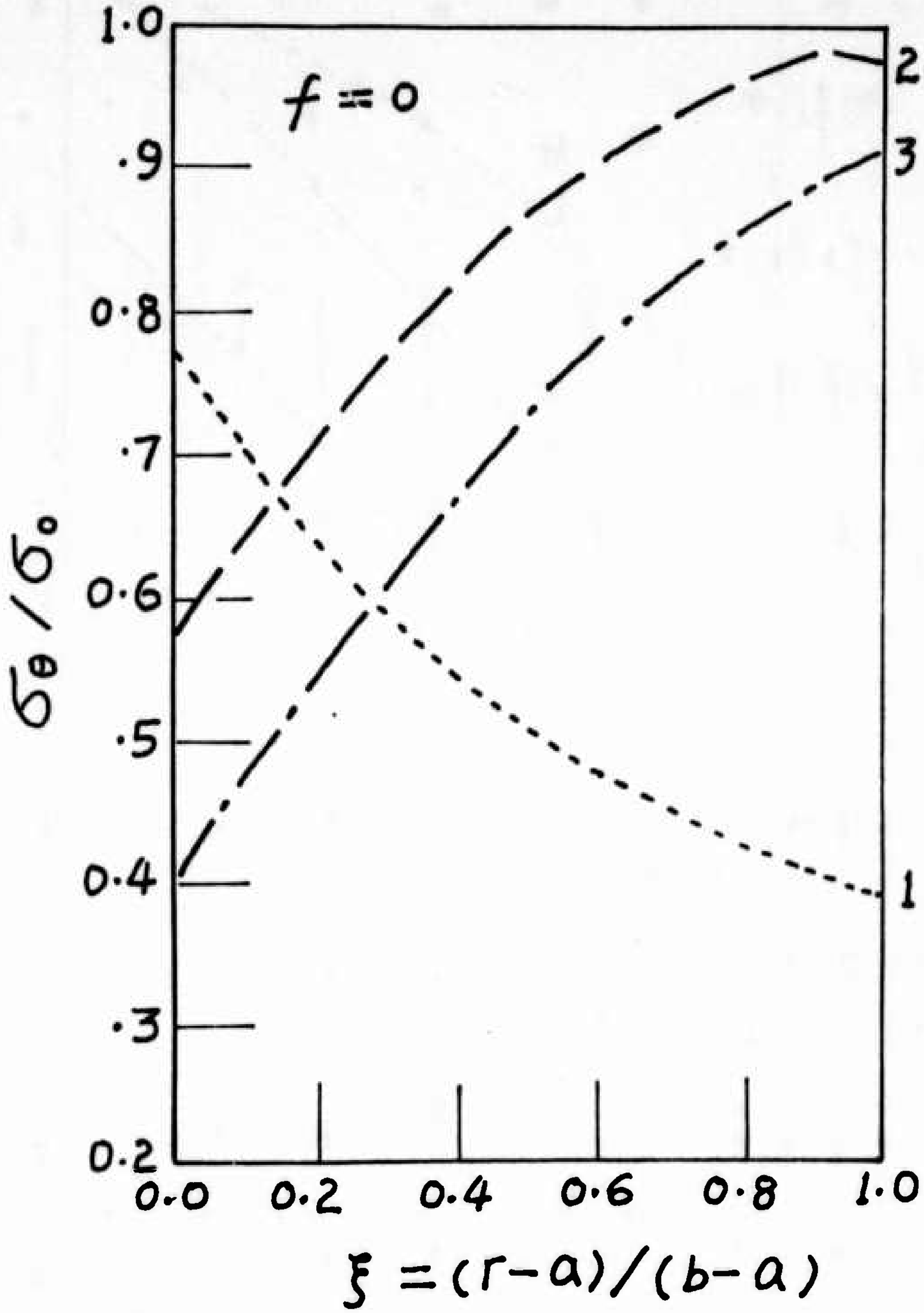

Figure 3. The hoop stress distributions during loading with no end force f.

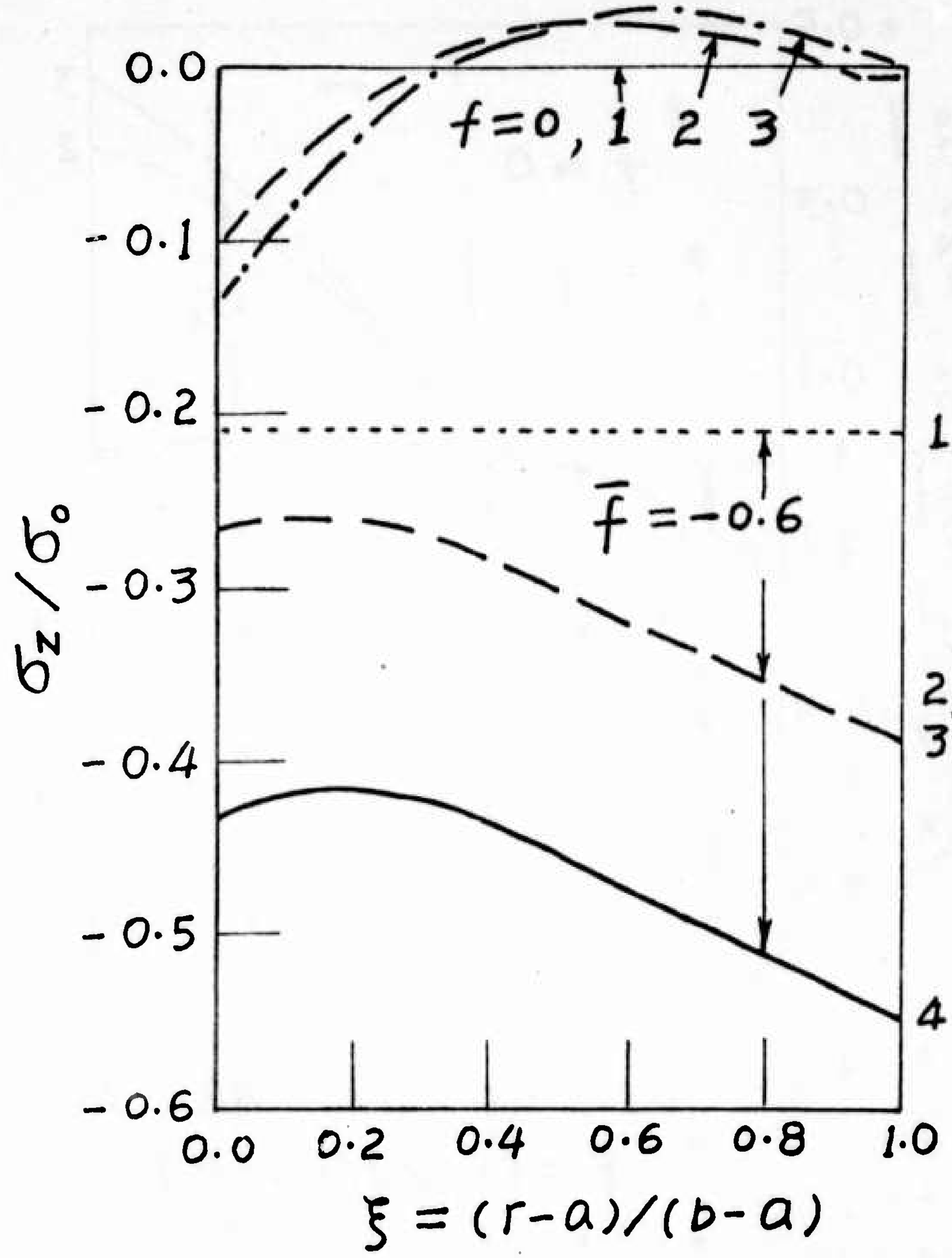

Figure 4. The axial stress distributions during loading with $\bar{f}$ = 0 and -0.6.

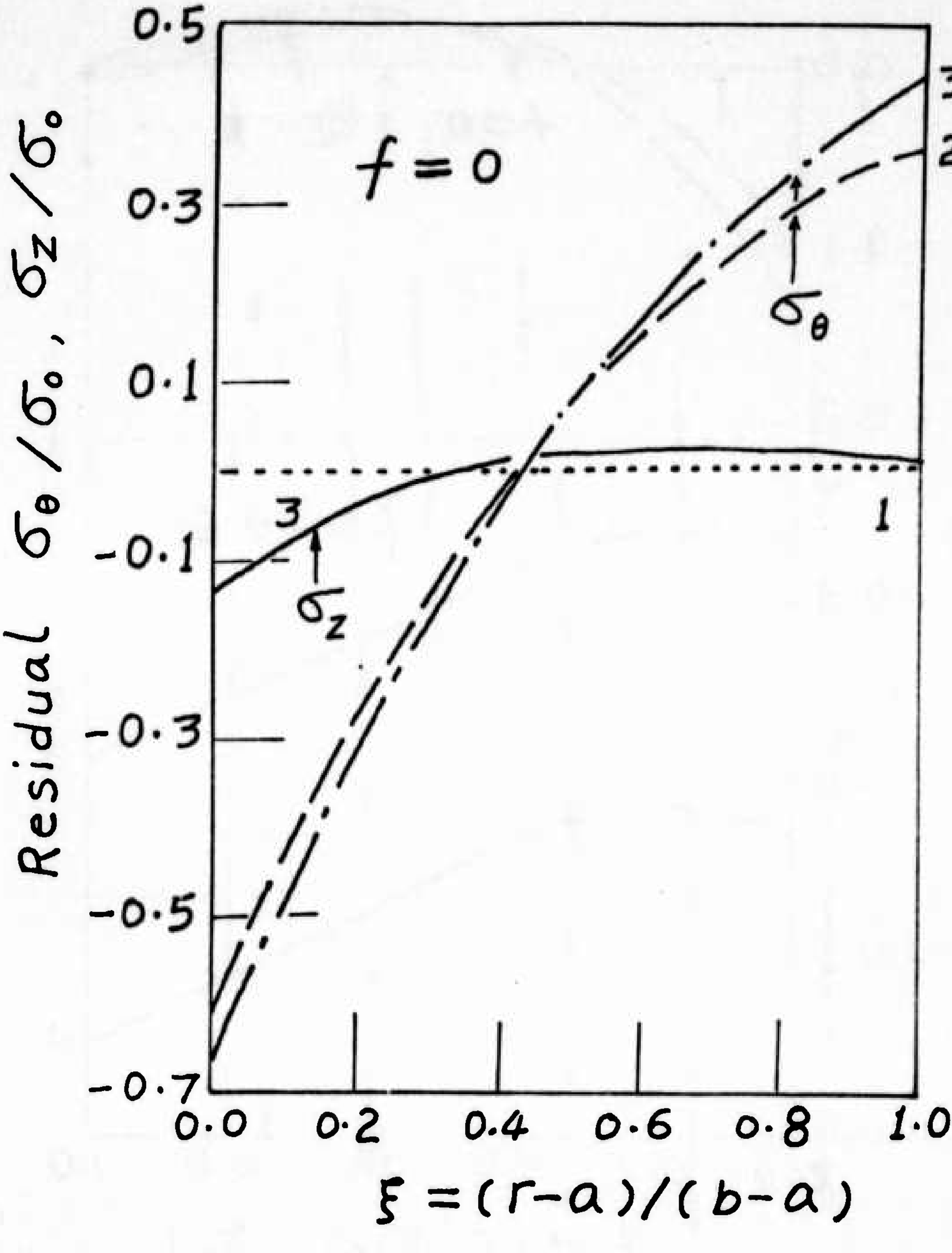

Figure 5. The residual stresses due to complete unloading from different stages with no end force.

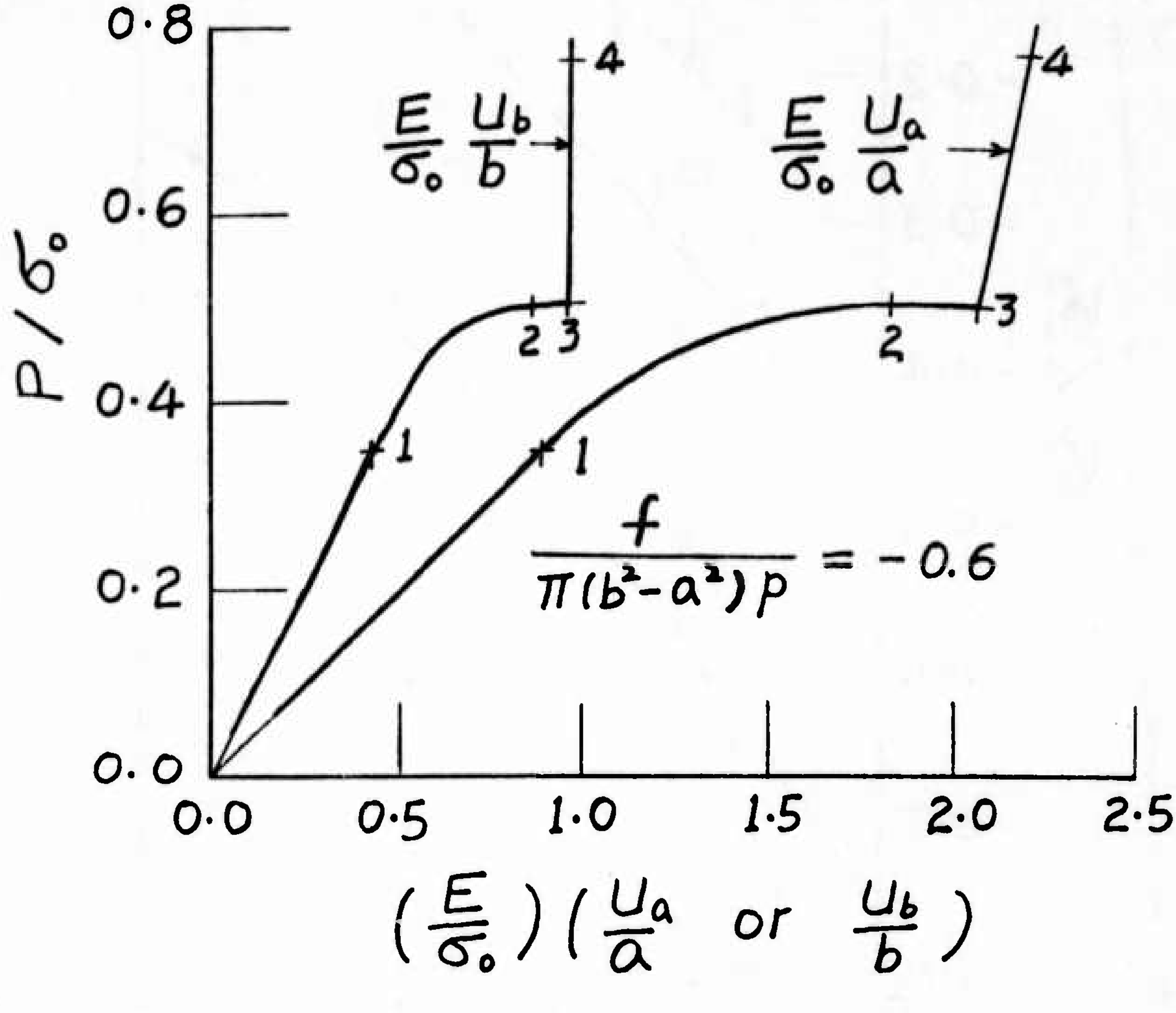

Figure 6. The boundary displacements u_a, u_b as functions of internal pressure p with $\bar{f} = -0.6$.

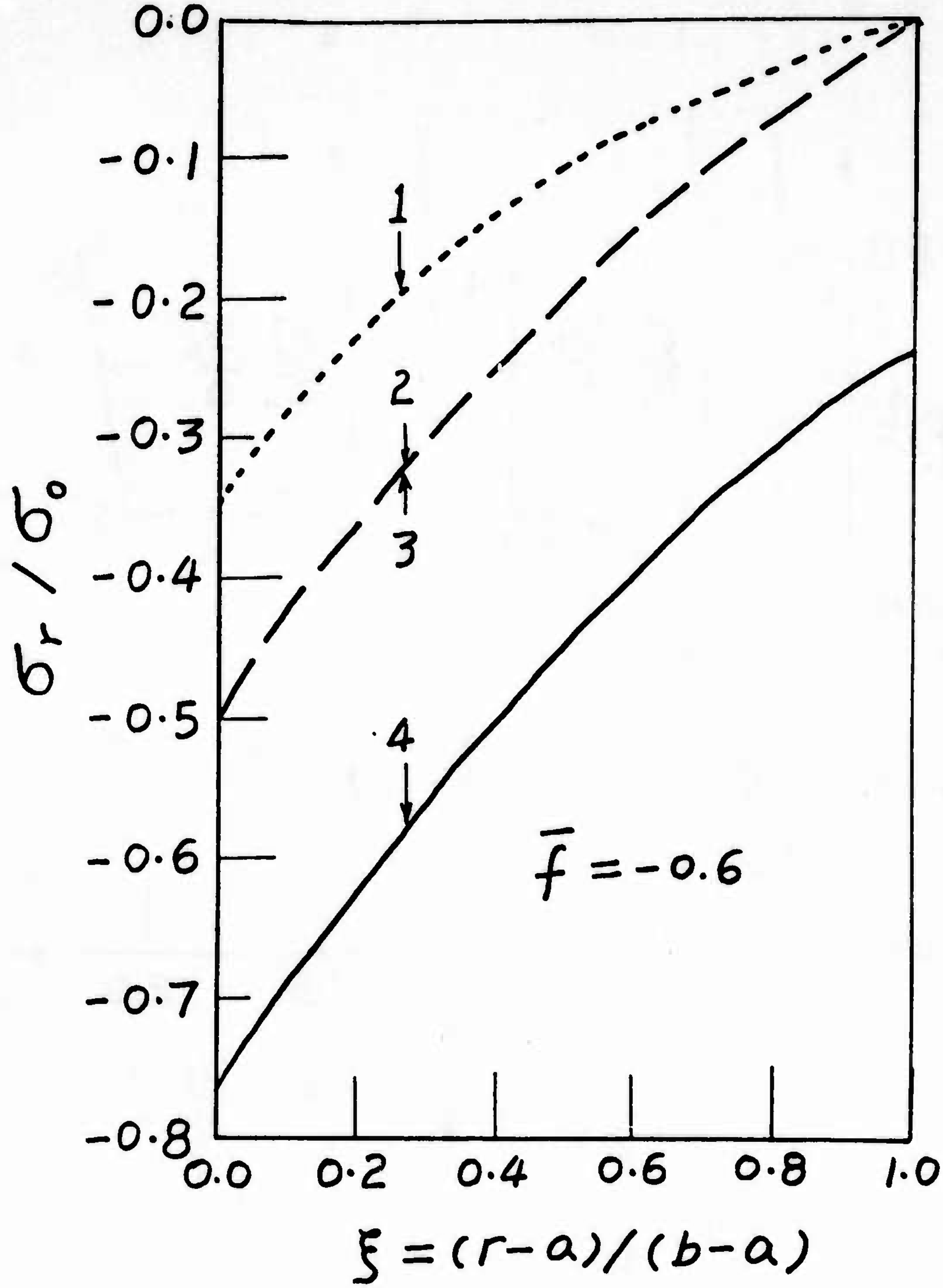

Figure 7. The radial stress distributions during loading with $\bar{f}$ = -0.6.

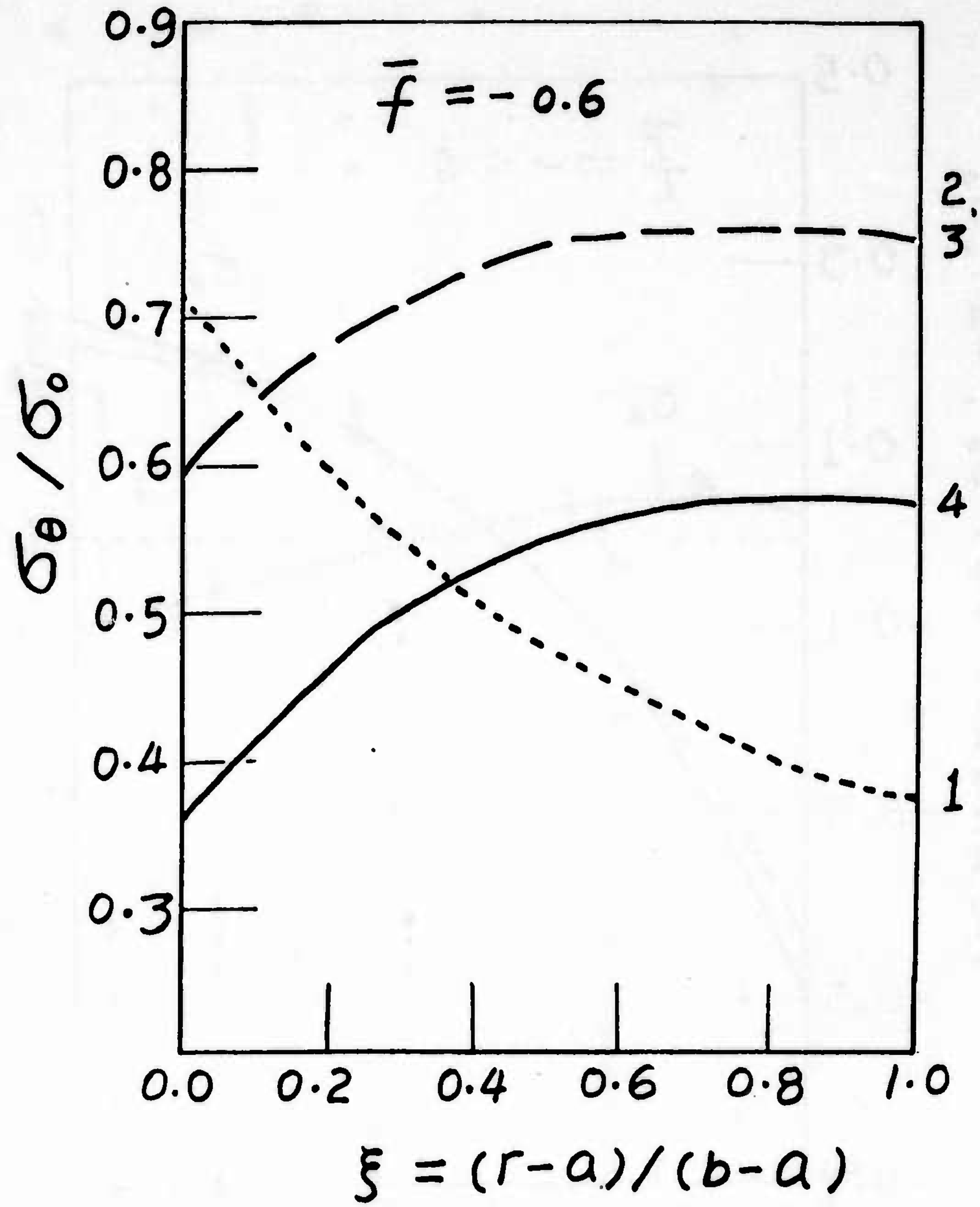

Figure 8. The hoop stress distributions during loading with $\bar{f}$ = -0.6.

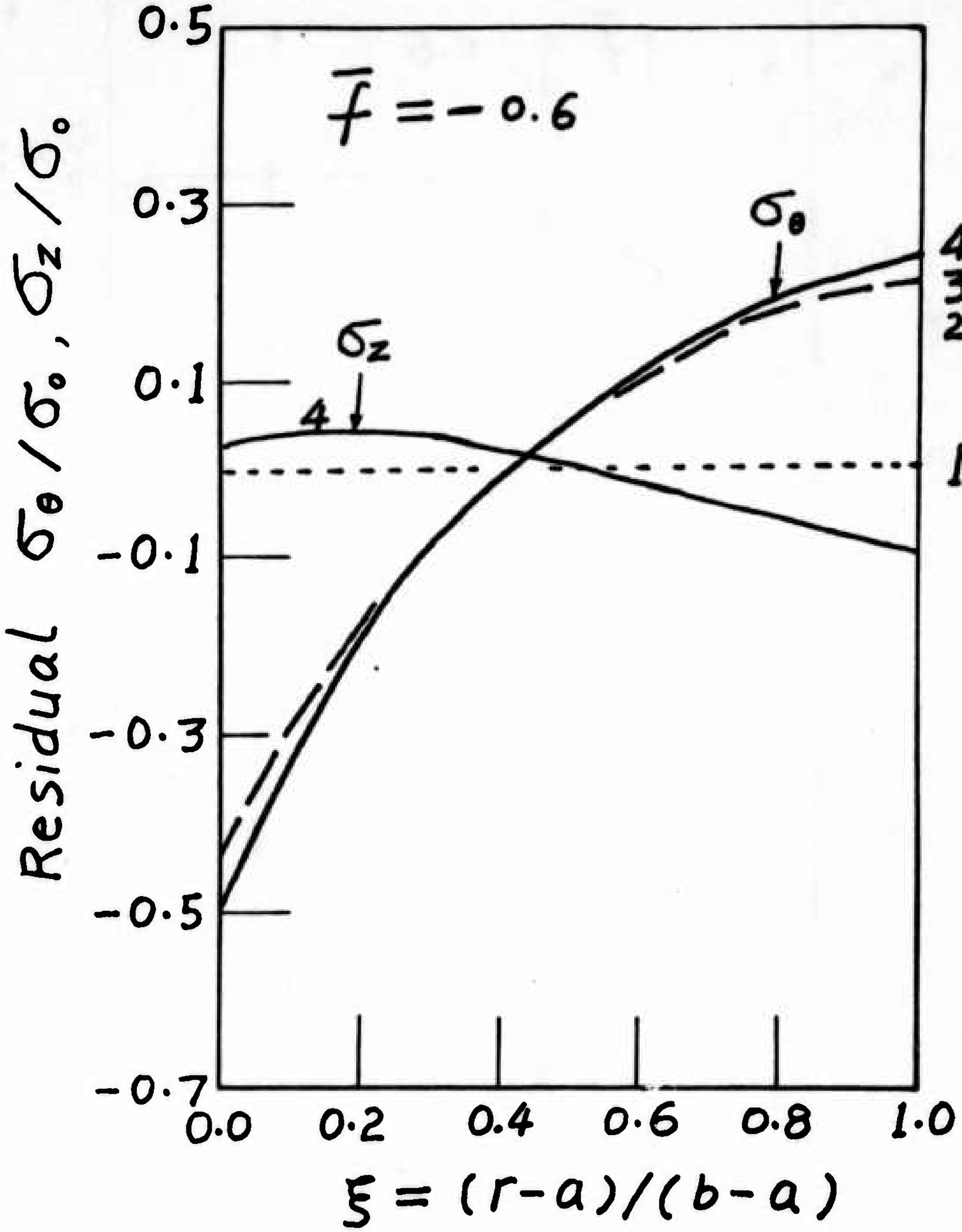

Figure 9. The residual stresses due to complete unloading from different stages with $\bar{f}$ = -0.6.

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MECHANICAL PROPERTIES DATA CTR BATTELLE COLUMBUS LAB 505 KING AVE COLUMBUS, OHIO 43201	1
MATERIEL SYSTEMS ANALYSIS ACTV ATTN: DRXSY-MP ABERDEEN PROVING GROUND MARYLAND 21005	1

NOTE: PLEASE NOTIFY COMMANDER, ARRADCOM, ATTN: BENET WEAPONS LABORATORY, DRDAR-LCB-TL, WATERVLIET ARSENAL, WATERVLIET, N.Y. 12189, OF ANY REQUIRED CHANGES.