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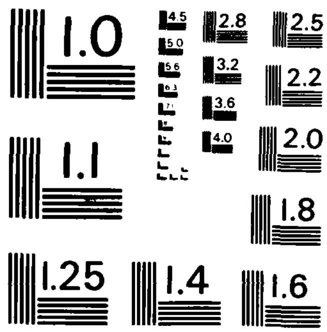


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# ELASTIC-PLASTIC LOADING AND UNLOADING IN A THICK TUBE WITH KINEMATIC HARDENING THEORY

PETER C. T. CHEN

SEPTEMBER 1985



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
LARGE CALIBER WEAPON SYSTEMS LABORATORY
BENÉT WEAPONS LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Using Tresca's yield criterion, its associated flow rule, and the linear hardening law, analytical solutions have been obtained for elastic-plastic loading and unloading problems in a thick tube subjected to uniform internal pressure. Explicit expressions for the displacement, strains, and stresses are presented herein, along with numerical results for a closed-end tube.

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## INTRODUCTION

The importance of the determination of residual stresses in a prestressed thick-walled cylinder is well-known, and elastic-plastic loading response has been extensively studied (refs 1-5). Most of the earlier solutions for residual stresses were based on the assumption of elastic unloading and only a few considered elastic-plastic unloading (refs 2,5). Bland's work (ref 2), which neglects the Bauschinger effect, is based on the Tresca's yield criterion and the isotropic hardening rule. Kinematic hardening is the simplest theory that can model the Bauschinger effect (refs 6,7). If unloading does not occur, there is no difference between the kinematic and isotropic hardening models. For unloading with reverse yielding, the results based on these two models will be different as shown in a recent paper (ref 5) using the ADINA finite element code (ref 8). The von Mises' yield criterion and its associated flow rules were used in both models.

This report states a closed-form solution for elastic-plastic loading and unloading in pressurized thick-walled cylinders using Tresca's yield criterion, its associated flow rule, and the linear kinematic hardening law. Numerical results are presented for a closed-end tube.

## ELASTIC-PLASTIC LOADING

Consider a thick-walled cylinder, internal radius a and external radius b, which is subjected to internal pressure p. The material is assumed to be elastic-plastic, obeying the Tresca's yield criterion, the associated flow theory, and a linear strain-hardening rule. Using the isotropic hardening

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References are listed at the end of this report.

theory, the elastic-plastic solution has been obtained by Bland (ref 2). In order to consider the Bauschinger effect, the kinematic hardening theory is used here. Subject to the condition $\sigma_\theta > \sigma_z > \sigma_r$, Tresca's yield criterion for the Prager-hardening rule (ref 6) states that yielding occurs when

$$(\sigma_\theta-\alpha_\theta) - (\sigma_r-\alpha_r) = K_o \qquad (1)$$

where

$$\alpha_\theta = c\varepsilon_\theta{}^p \quad , \quad \alpha_r = c\varepsilon_r{}^p \qquad (2)$$

define the position of the center of the yield surface; c is a material constant and $K_o$ the initial yield stress. The associated flow rule states that

$$d\varepsilon_\theta{}^p = -d\varepsilon_r{}^p \quad \text{and} \quad d\varepsilon_z{}^p = 0 \qquad (3)$$

For the case of linear strain-hardening, the yield stress curve can be represented by a straight line,

$$K/K_o = 1 + \eta\varepsilon^p \quad \text{and} \quad \eta = (E/K_o)^m/(1-m) \qquad (4)$$

where $\eta$ is a material constant and the equivalent plastic strain $\varepsilon^p$ is defined by

$$\varepsilon^p = \sqrt{2/3} \int \{(d\varepsilon_\theta{}^p)^2 + (d\varepsilon_r{}^p)^2\}^{1/2} = \frac{2}{\sqrt{3}}\varepsilon_\theta{}^p \qquad (5)$$

The elastic-plastic solution for the stresses and displacements can be obtained explicitly. The expressions in the plastic range ($a < r < \rho$) are

$$\begin{matrix}\sigma_r/K_o \\ \sigma_\theta/K_o\end{matrix} = \frac{1}{2}(\mp 1 + \frac{\rho^2}{b^2}) \mp \frac{1}{2}\eta\beta(\frac{\rho^2}{r^2} - 1) - (1 - \eta\beta)\log\frac{\rho}{r} \qquad \begin{matrix}(6)\\(7)\end{matrix}$$

$$\sigma_z/K_o = \nu\rho^2/b^2 - 2\nu(1-\eta\beta)\log\frac{\rho}{r} + E\varepsilon_z/K_o \qquad (8)$$

$$(E/K_o)(u/r) = (1-2\nu)(1+\nu)(\sigma_r/K_o) - \nu E\varepsilon_z/K_o + (1-\nu^2)\rho^2/r^2 \qquad (9)$$

and in the elastic range ($\rho \leq r \leq b$)

$$\left.\begin{array}{l}\sigma_r/K_o \\ \sigma_\theta/K_o\end{array}\right\} = \frac{1}{2}\left(\frac{\rho^2}{b^2} \mp \frac{\rho^2}{r^2}\right) \qquad \begin{array}{r}(10)\\(11)\end{array}$$

$$\sigma_z/K_o = E\varepsilon_z/K_o + \nu\rho^2/b^2 \tag{12}$$

$$(E/K_o)u/r = \frac{1}{2}(1+\nu)[\rho^2/r^2 + (1-2\nu)\rho^2/b^2] - \nu E\varepsilon_z/K_o \tag{13}$$

where

$$E\varepsilon_z/K_o = \frac{(\mu-2\nu)}{(b^2/a^2-1)}(p/K_o) \tag{14}$$

$$\mu = 0 \text{ (open-end)} \quad , \quad 1 \text{ (closed-end)}$$

and

$$\beta^{-1} = \eta + \frac{\sqrt{3}}{2}(E/K_o)/(1-\nu^2) \tag{15}$$

The yield surface moves in translation during plastic deformation as given by

$$\alpha_\theta = -\alpha_r = (\sqrt{3}/2)c\varepsilon^p \quad \text{and} \quad \varepsilon^p = \beta(\rho^2/r^2-1) \tag{16}$$

The elastic plastic surface $\rho$ is related to the internal pressure p by

$$p/K_o = \frac{1}{2}(1-\rho^2/b^2) + (1-\eta\beta)\log \rho/a + \frac{1}{2}\eta\beta(\rho^2/a^2-1) \tag{17}$$

REVERSE YIELDING

If the pressure p given by Eq. (17) is subsequently removed completely with no reverse yielding, the unloading is entirely elastic and the solution is given by

$$\left.\begin{array}{l}\sigma_r' \\ \sigma_\theta'\end{array}\right\} = \frac{p}{b^2/a^2-1}\left[\pm\frac{b^2}{r^2} - 1\right] \qquad \begin{array}{r}(18)\\(19)\end{array}$$

$$\sigma_z' = \nu(\sigma_r'+\sigma_\theta') + E\varepsilon_z' \tag{20}$$

$$E\varepsilon_z' = -(\mu-2\nu)p/(b^2/a^2-1) \tag{21}$$

$$Eu'/r = -[(1-\nu-\mu\nu) + (1+\nu)b^2/r^2]p/(b^2/a^2-1) \tag{22}$$

The residual stress system, which will be denoted by two primes, is the sum of the system produced by loading and that produced by unloading, i.e., $\sigma_r'' = \sigma_r + \sigma_r'$, etc. Assuming the kinematic hardening rule and using Tresca's criterion subject to $\sigma_r'' > \sigma_z'' > \sigma_\theta''$, the reverse yielding will not occur if

$$(\sigma_r''-\alpha_r) - (\sigma_\theta''-\alpha_\theta) \leq K_o \tag{23}$$

Substituting the loading and unloading solution into Eq. (23), we can determine the minimum pressure ($p_m$) for reverse yielding to occur. The equation for $p_m$ is given by

$$p_m/K_o = (1-a^2/b^2) \tag{24}$$

Equating Eqs. (17) to (24), we can determine the maximum amount of overstrain for reverse yielding not to occur.

## ELASTIC-PLASTIC UNLOADING

Now suppose that the loading has been such that the internal pressure is larger than $p_m$ given by Eq. (24). On unloading, yielding will occur for $a \leq r \leq \rho'$ with $\rho' < \rho$. Using the kinematic hardening rule during unloading and assuming $\sigma_r'' \geq \sigma_z'' \geq \sigma_\theta''$, we have

$$(\sigma_r''-\alpha_r'') - (\sigma_\theta''-\alpha_\theta'') = K_o \tag{25}$$

where

$$\alpha_r'' = c\varepsilon_r''^{p} \quad , \quad \alpha_\theta'' = c\varepsilon_\theta''^{p} \tag{26}$$

Since the residual stress system is the sum of two systems produced by loading and unloading, combining Eqs. (1) and (25) leads to

$$(\sigma_r'-\alpha_r') - (\sigma_\theta'-\alpha_\theta') = 2K_o \tag{27}$$

where

$$\alpha_r' = c\varepsilon_r'^{p} \quad , \quad \alpha_\theta' = c\varepsilon_\theta'^{p} \tag{28}$$

During elastic-plastic unloading, the associated flow theory states that

$$d\varepsilon_\theta'^{p} = -d\varepsilon_r'^{p} < 0 \quad \text{and} \quad d\varepsilon_z'^{p} = 0 \tag{29}$$

It has been assumed that the sign of $d\varepsilon_\theta'^{p}$ is the same throughout the unloading process and that is negative. This will be the case when the internal pressure is removed during unloading. Since $\varepsilon_z' = \varepsilon_z'^{e} = -\varepsilon_z$ is known, we can use Hooke's law and the equilibrium equation,

$$d\sigma_r'/dr = (\sigma_\theta' - \sigma_r')/r \tag{30}$$

to express $\sigma_z'$ in terms of $\sigma_r'$

$$\sigma_z' = E\varepsilon_z' + 2\nu\sigma_r' + \nu r(d\sigma_r'/dr) \tag{31}$$

Since the dilation is purely elastic

$$(du'/dr) + u'/r + \varepsilon_z' = E^{-1}(1-2\nu)(\sigma_r' + \sigma_\theta' + \sigma_z') \tag{32}$$

On integration using Eqs. (30) and (31), we obtain

$$ru' = (1-2\nu)(1+\nu)E^{-1}r^2\,\sigma_r' - \nu\varepsilon_z' r^2 + A \tag{33}$$

where A is a constant. The strain components can be expressed in terms of $\sigma_r'$ and $(d\sigma_r'/dr)$. The plastic strain components are

$$\varepsilon_\theta'^{p} = -\varepsilon_r'^{p} = Ar^{-2} - (1-\nu^2)E^{-1}r(d\sigma_r'/dr) \tag{34}$$

Using Eq. (31) together with Eqs. (27) and (28), we have

$$r(d\sigma_r'/dr) = -2(K_o - c\varepsilon_\theta'^{p}) \tag{35}$$

Substituting Eq. (35) into Eq. (34) and determining the constant A by the condition $\varepsilon_\theta'^{p} = 0$ at $\rho'$, we obtain

$$A = -2(1-\nu^2)(K_o/E)\rho'^2 \tag{36}$$

and

$$(E/K_o)\varepsilon_\theta'^{p} = -2(\rho'^2/r^2 - 1)/[2c/E + (1-\nu^2)^{-1}] \tag{37}$$

Equations (35) and (36) with the boundary condition at $r = a$ suffice to determine $\sigma_r'$ in the plastic region. The expressions for the stresses in (a <

$r < \rho'$) are given explicitly by

$$\sigma_r'/K_o = p/K_o - n\beta(\rho'^2/a^2 - \rho'^2/r^2) - 2(1-n\beta)\log(r/a) \tag{38}$$

$$\sigma_\theta'/K_o = \sigma_r'/K_o - 2 - 2n\beta(\rho'^2/r^2 - 1) \tag{39}$$

$$\sigma_z'/K_o = \nu(\sigma_r' + \sigma_\theta')/K_o - E\varepsilon_z/K_o \tag{40}$$

and in ($\rho' < r < b$) given by

$$\left.\begin{array}{l} \sigma_r'/K_o \quad (41) \\ \sigma_\theta'/K_o \quad (42) \end{array}\right\} = \pm\,(\rho'^2/r^2 \mp \rho'^2/b^2)$$

$$\sigma_z'/K_o = -2\nu\rho'^2/b^2 - E\varepsilon_z/K_o \tag{43}$$

The continuity condition of $\sigma_r'$ determines the relation between $\rho'$ and $\rho$ as given by

$$1 - \rho'^2/b^2 + 2(1-n\beta)\log\frac{\rho'}{a} + n\beta(\rho'^2/a^2 - 1)$$
$$= \frac{1}{2}(1-\rho^2/b^2) + (1-n\beta)\log(\rho/a) + \frac{1}{2}n\beta(\rho^2/a^2 - 1) \tag{44}$$

The yield surface moves in translation during elastic-plastic unloading according to

$$\alpha_\theta' = -\alpha_r' = c\varepsilon_\theta'^{\,p} \tag{45}$$

where $\varepsilon_\theta'^{\,p}$ is given by Eq. (37).

## NUMERICAL RESULTS AND DISCUSSIONS

Consider a closed-end thick-walled cylinder with the following parameters: $b/a = 3$, $\nu = 0.3$, and $E/K_o = 200$. The numerical results for the displacements, strains, and stresses during elastic-plastic loading and unloading have been calculated. Figure 1 shows the relationship between the internal pressure factor ($p/K_o$) and the dimensionless elastic-plastic interface ($\rho/a$) for various values of the hardening parameter, $m = 0$, 0.05, 0.1, and 0.2. The displacements at the inside and outside boundaries of the tube ($U_a$ and $U_b$) are shown in Figure 2 as functions of the elastic-plastic interface for $m = 0.1$. The solid and dotted curves represent the displacements during loading and after unloading, respectively. Figure 3 shows the distribution of hoop stresses ($\sigma_\theta$) during loading for $\rho/a = 1.0, 1.5, 2.0, 2.5$, and 3.0. After complete unloading from different stages of loading, the corresponding residual hoop stresses ($\sigma_\theta''$) are shown in Figure 4. Reverse yielding occurs in a strain-hardening tube with $m = 0.1$ only when the plastic portion ($\rho$) is larger than 1.652 a. In order to show the effect of hardening parameters (m) on the residual stress distribution, the numerical results are presented in Figure 5 for $m = 0$, 0.05, and 0.10. As can be seen in the figure, larger values of hardening parameter (m) tend to reduce the beneficial residual hoop stress at the bore.

All the results presented in Figures 1 through 5 are based on the kinematic theory. We have also calculated the results based on the isotropic hardening theory (ref 2). Figure 6 shows a comparison of two hardening rules for the residual hoop stresses in a closed-end thick-walled cylinder. The dotted curves represent the isotropic hardening model with no Bauschinger effect. According to this model, there is no reverse yielding. The solid curves show the Bauschinger effect, and reverse yielding occurs in both cases, $\rho'/a = 1.098, 1.336$, for $\rho/a = 2.0, 3.0$, respectively. The residual hoop stresses at the bore are $\sigma_\theta''/K_o = -0.729, -0.327$ for $\rho/a = 2.0, 3.0$, respectively. According to the isotropic hardening rule, those values of $\sigma_\theta''/K_o$ should be $-1.060, -1.318$ for $\rho/a = 2.0, 3.0$, respectively. These numerical results indicate that the effect of hardening rules on the residual hoop stresses is quite significant, especially near the bore. Many plasticity theories for reverse yielding have been proposed and reviewed (ref 9), and many computer programs have been developed (ref 10). It is believed that the numerical results based on other theories will fall within the limits obtained by using the kinematic and isotropic hardening models.

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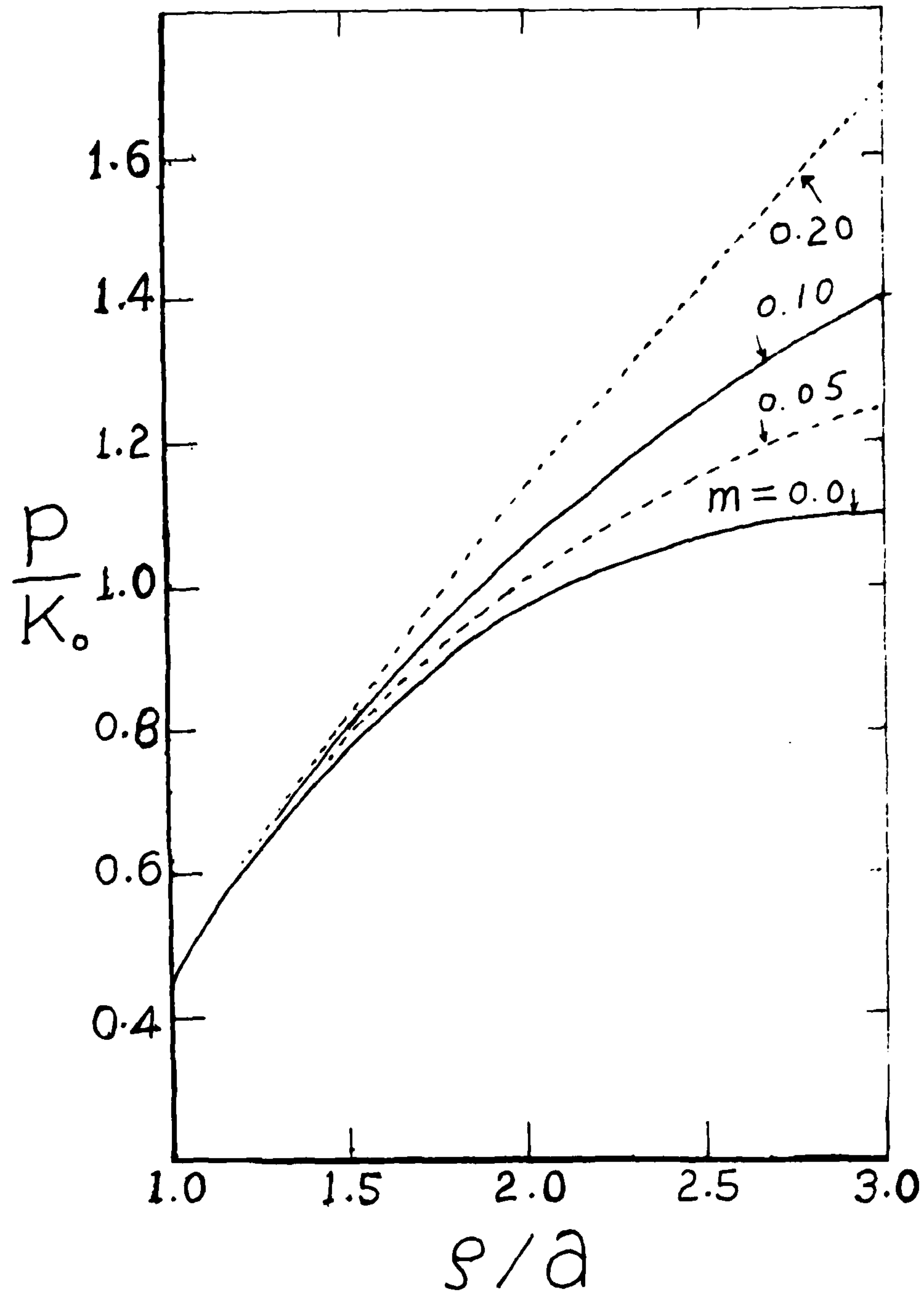


Figure 1. Effect of hardening on the relation between internal pressure and elastic-plastic interface.

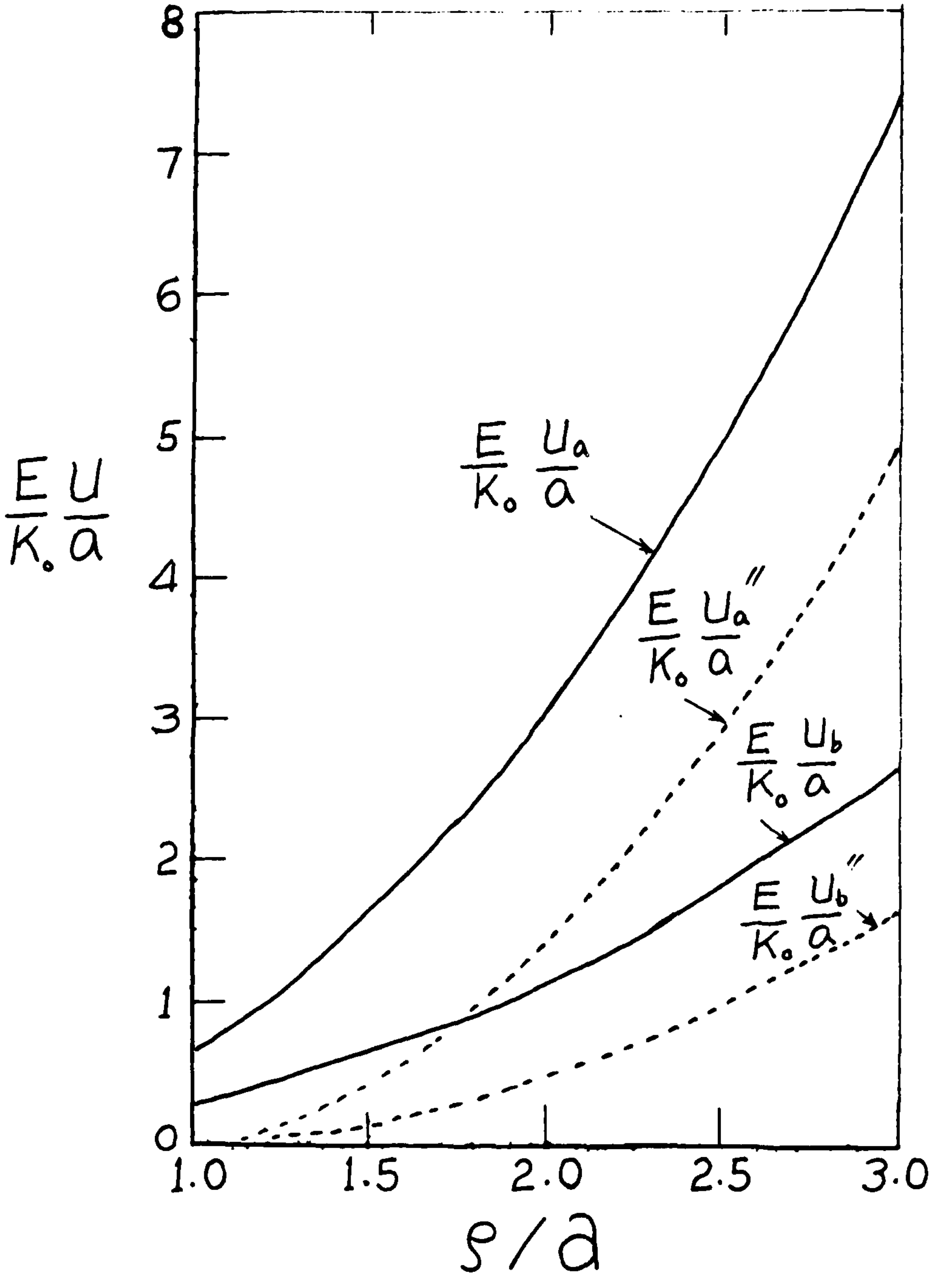


Figure 2. Boundary displacement during loading and after unloading.

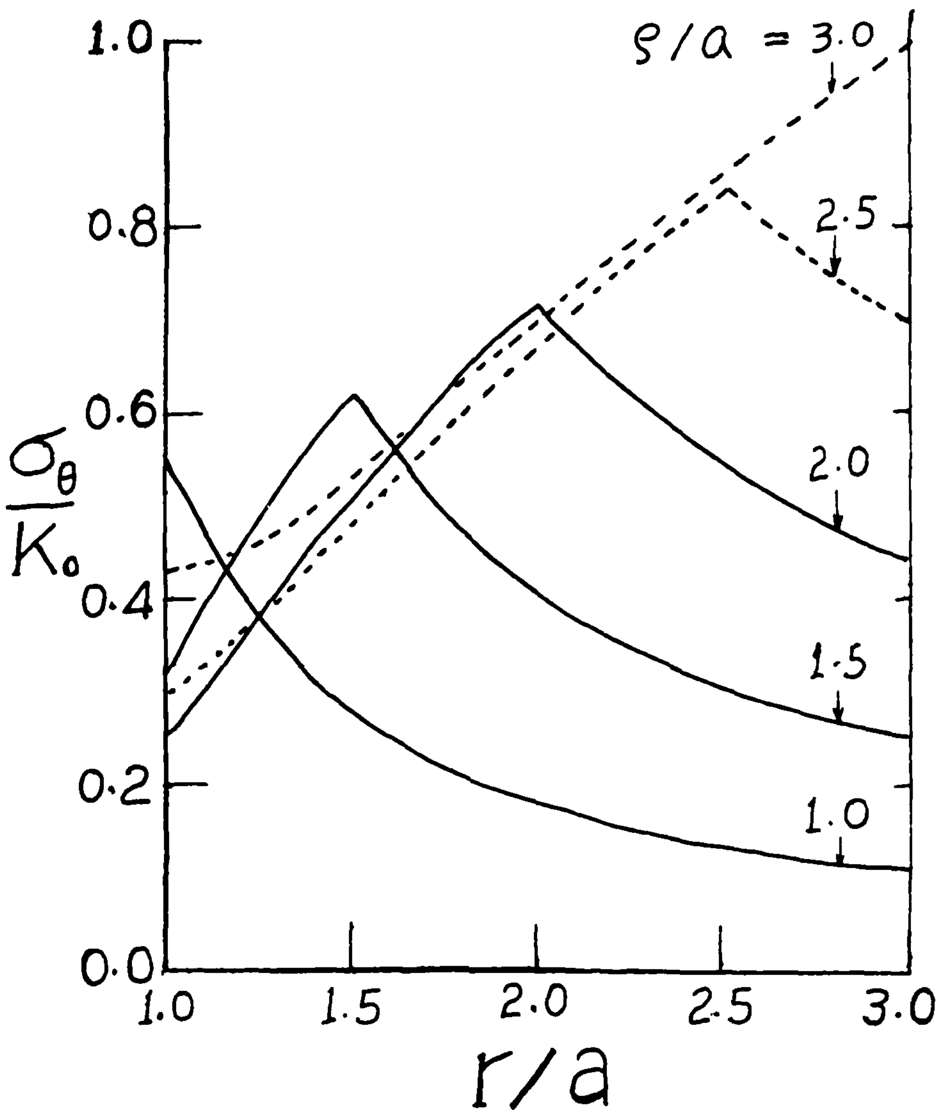


Figure 3. Distribution of hoop stresses during loading.

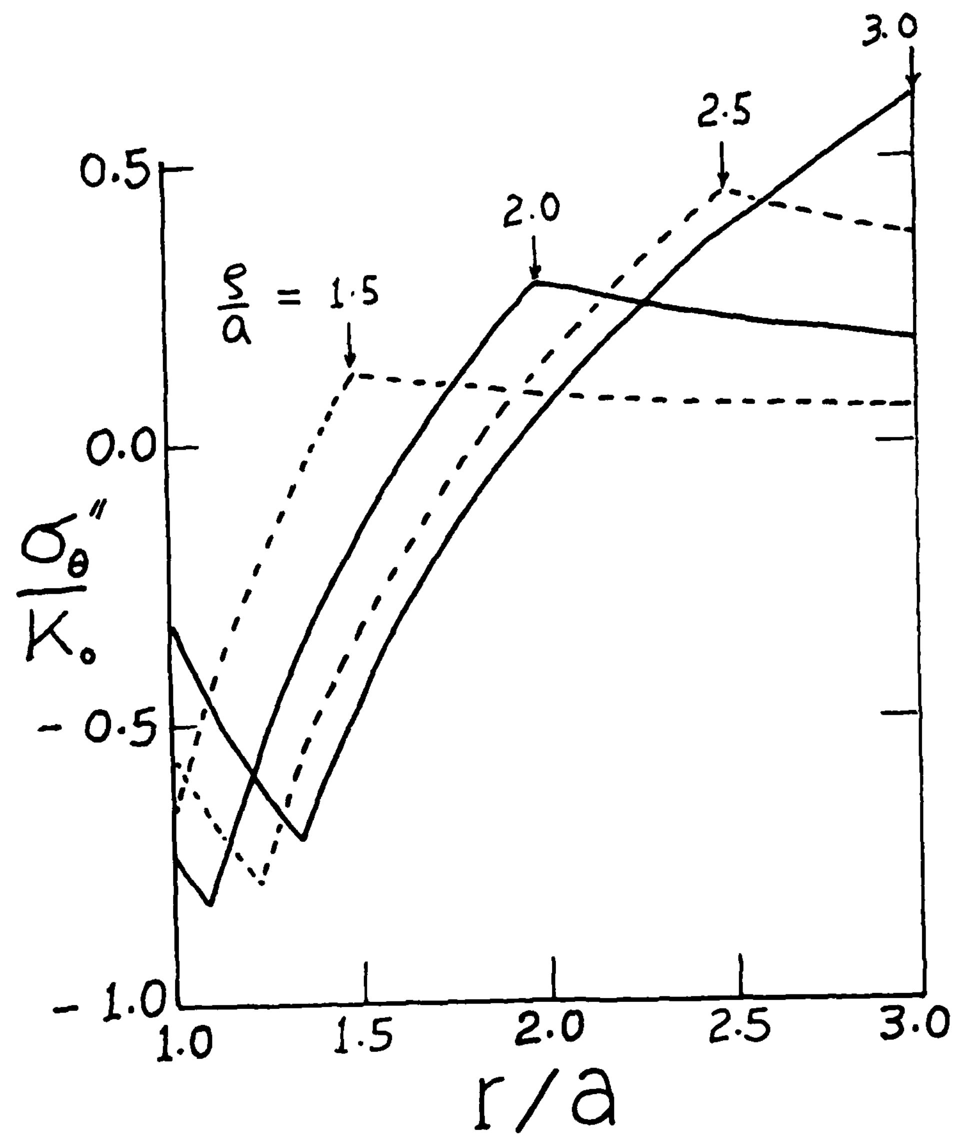


Figure 4. Distribution of residual hoop stresses.

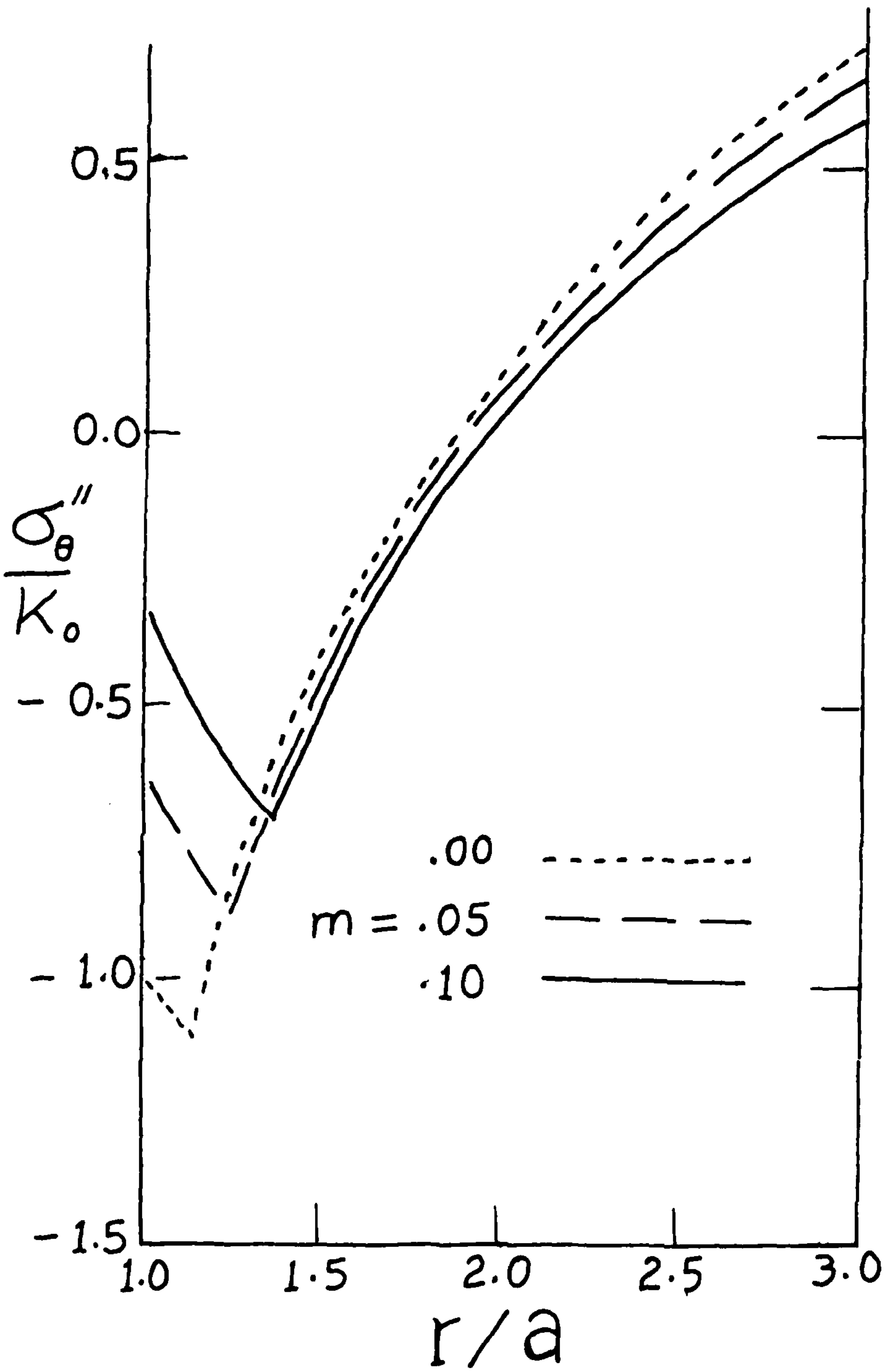


Figure 5. Effect of hardening parameter on residual stress distribution.

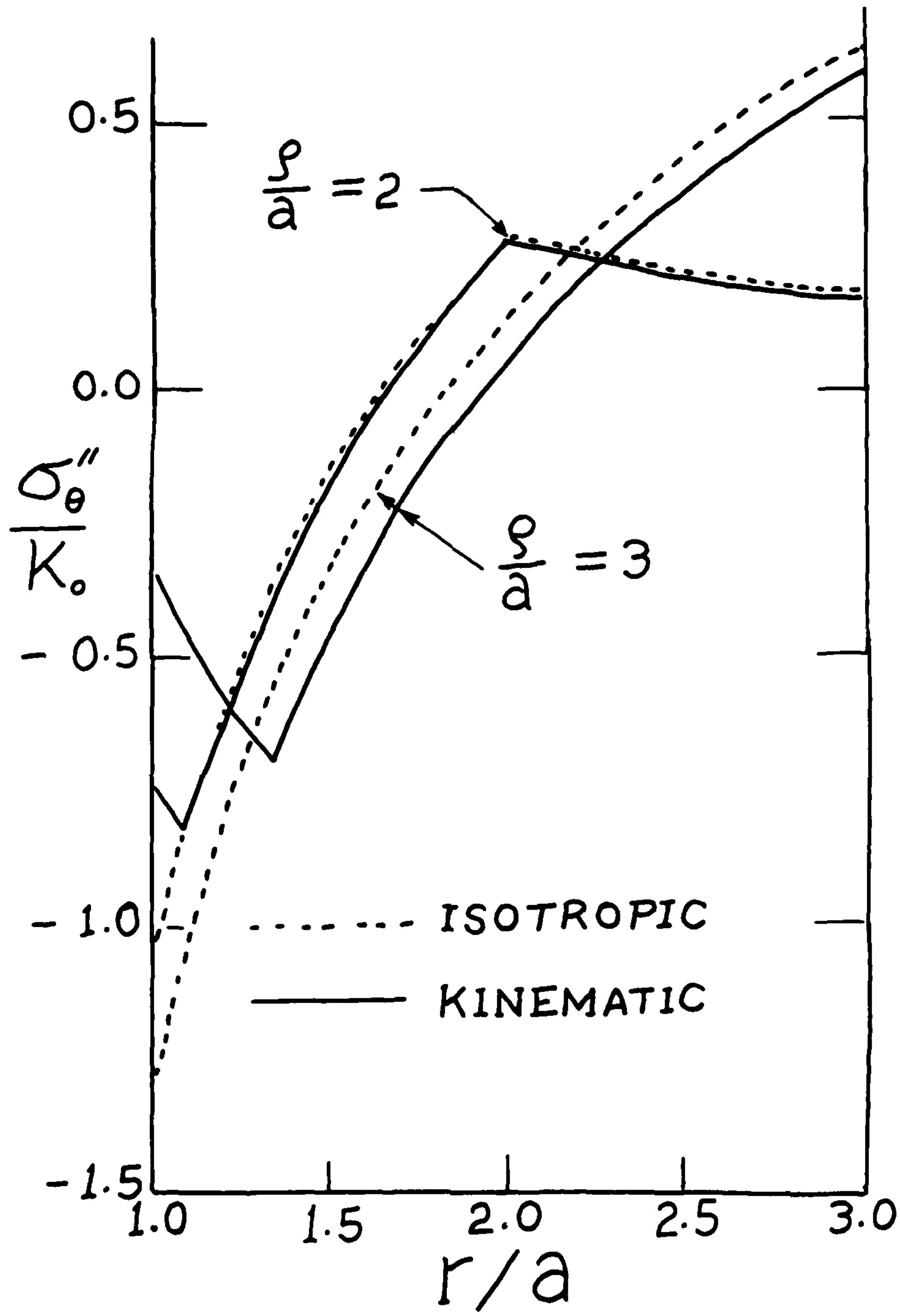


Figure 6. Effect of hardening rules on residual stress distribution.

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| DIRECTOR<br>US NAVAL RESEARCH LAB<br>ATTN: DIR, MECH DIV<br>CODE 26-27, (DOC LIB)<br>WASHINGTON, D.C. 20375 | 1<br>1 |
| COMMANDER<br>AIR FORCE ARMAMENT LABORATORY<br>ATTN: AFATL/DLJ<br>AFATL/DLJG<br>EGLIN AFB, FL 32542 | 1<br>1 |
| METALS & CERAMICS INFO CTR<br>BATTELLE COLUMBUS LAB<br>505 KING AVENUE<br>COLUMBUS, OH 43201 | 1 |

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH AND DEVELOPMENT CENTER, US ARMY AMCCOM, ATTN: BENET WEAPONS LABORATORY, SMCAR-LCB-TL, WATERVLIET, NY 12189, OF ANY ADDRESS CHANGES.

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