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TECHNICAL REPORT ARCCB-TR-91033

**RESIDUAL STRESSES IN A PRESTRESSED
STEEL PRESSURE VESSEL WRAPPED
WITH MULTILAYERED COMPOSITES**

PETER C. T. CHEN

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**US ARMY ARMAMENT RESEARCH,
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13. ABSTRACT (Maximum 200 words) This report presents an analytical solution for predicting residual stresses in a steel pressure vessel wrapped with a multilayered composite jacket. The numerical results for the hoop stresses before and after complete unloading are obtained for a subscale test tube. The steel liner is elastic-plastic, and the composite layup (O ₂ 9O ₂) ₄ consists of 16 layers made of graphite-bismaleimide produced by Fiberite Corporation.				
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INTRODUCTION

In recent years there has been increasing emphasis on the use of composite materials in armament structures. A current problem in Army cannon design is to replace a portion of the steel wall thickness with a lighter material. The inner portion, steel liner, maintains the tube projectile interface and shields the composite from the extremely hot gases. The outer portion, composite jacket, is made of single or multilayered graphite-bismaleimide wound and wrapped on the steel liner. Two subscale models have been fabricated and tested (refs 1,2). An analytical elastic-plastic solution for the model with a single-layered composite jacket has been presented in a recent paper (ref 3). This report covers a complete stress analysis for the model with a multilayered composite jacket. The composite layup is made of two longitudinal layers alternating with two circumferential layers. Sixteen layers were applied in this way. The total thickness of the composite jacket is 0.12 inch and the steel liner is of inner radius 1 inch and outer radius 1.17 inches. Analytical solutions are presented for loading within and beyond the elastic range up to failure. Numerical results for the residual stresses in the steel liner and composite jacket are presented.

COMPOSITE JACKET

The composite jacket is made of n layers bounded by radii $(r_1, r_2, \dots, r_n, r_{n+1})$. Each layer is elastically orthotropic but with different material properties. The strain-stress relations for the k -th layer in cylindrical coordinates are given by

$$\begin{Bmatrix} \epsilon_r(k) \\ \epsilon_\theta(k) \\ \epsilon_z(k) \end{Bmatrix} = \begin{bmatrix} 1/E_r & , & -\nu_{\theta r}/E_\theta & & -\nu_{zr}/E_z \\ -\nu_{r\theta}/E_r & , & 1/E_\theta & & -\nu_{z\theta}/E_\theta \\ -\nu_{rz}/E_r & , & -\nu_{\theta z}/E_\theta & & 1/E_z \end{bmatrix}^{(k)} \begin{Bmatrix} \sigma_r(k) \\ \sigma_\theta(k) \\ \sigma_z(k) \end{Bmatrix} \quad (1)$$

or

$$\epsilon_i^{(k)} = S_{ij}^{(k)} \sigma_j^{(k)} \quad (i, j = r, \theta, z) \quad (2)$$

where $S_{ij}^{(k)}$ are components of the compliance matrix. The superscript k refers to the k -th layer. In plane-strain conditions, the above strain-stress relations modify to

$$\begin{Bmatrix} \epsilon_r^{(k)} \\ \epsilon_\theta^{(k)} \end{Bmatrix} = \begin{bmatrix} \beta_{rr}^{(k)} & \beta_{r\theta}^{(k)} \\ \beta_{r\theta}^{(k)} & \beta_{\theta\theta}^{(k)} \end{bmatrix} \begin{Bmatrix} \sigma_r^{(k)} \\ \sigma_\theta^{(k)} \end{Bmatrix} \quad (3)$$

where

$$\begin{aligned} \beta_{rr}^{(k)} &= (1 - \nu_{rz}^{(k)} \nu_{zr}^{(k)}) / E_r^{(k)} \\ \beta_{r\theta}^{(k)} &= -(\nu_{\theta r}^{(k)} + \nu_{\theta z}^{(k)} \nu_{zr}^{(k)}) / E_\theta^{(k)} \\ \beta_{\theta\theta}^{(k)} &= (1 - \nu_{\theta z}^{(k)} \nu_{z\theta}^{(k)}) / E_\theta^{(k)} \end{aligned} \quad (4)$$

The normal traction acting on the interface between $(k-1)$ th and k -th layers is denoted by q_k . Then the general elastic solution for the k -th layer bounded by radii (r_k, r_{k+1}) and subjected to interface pressure (q_k, q_{k+1}) is given by (ref 4)

$$\begin{aligned} \sigma_r^{(k)} &= (-a_k q_k + c_k q_{k+1}) (r_{k+1}/r)^{g_k+1} + (a_k q_k - b_k q_{k+1}) (r/r_{k+1})^{g_k-1} \\ \sigma_\theta^{(k)} &= g_k (a_k q_k - c_k q_{k+1}) (r_{k+1}/r)^{g_k+1} + g_k (a_k q_k - b_k q_{k+1}) (r/r_{k+1})^{g_k-1} \\ u^{(k)} &= r (\beta_{r\theta}^{(k)} \sigma_r^{(k)} + \beta_{\theta\theta}^{(k)} \sigma_\theta^{(k)}) \end{aligned} \quad (5)$$

where

$$\begin{aligned} d_k &= r_{k+1}/r_k, \quad g_k = (\beta_{rr}^{(k)} / \beta_{\theta\theta}^{(k)})^{1/2} \\ c_k &= (d_k^{2g_k-1})^{-1}, \quad b_k = c_k d_k^{2g_k}, \quad a_k = c_k d_k^{g_k-1} \end{aligned} \quad (6)$$

At the two ends of the k -th layer the expressions for the displacements and hoop stresses are

$$\begin{aligned}
u_{k+1} &= (A_k q_k - B_k q_{k+1}) r_{k+1} \\
u_k &= (C_k q_k - D_k q_{k+1}) r_k \\
\sigma_\theta(k) &= 2a_k g_k q_k - (b_k + c_k) g_k q_{k+1} \quad \text{at } r_{k+1} \\
\sigma_\theta(k) &= (b_k + c_k) g_k q_k - 2a_k d_k^2 g_k q_{k+1} \quad \text{at } r_k
\end{aligned} \tag{7}$$

where

$$\begin{aligned}
A_k &= 2a_k g_k \beta_{\theta\theta}(k) \quad , \quad B_k = \beta_{r\theta}(k) + (b_k + c_k) g_k \beta_{\theta\theta}(k) \\
C_k &= -\beta_{r\theta}(k) + (b_k + c_k) g_k \beta_{\theta\theta}(k) \quad , \quad D_k = 2a_k d_k^2 g_k \beta_{\theta\theta}(k)
\end{aligned} \tag{8}$$

At the interfaces ($r_k, k=2, \dots, n$) the displacements should be continuous and these require

$$A_{k-1} q_{k-1} - B_{k-1} q_k = C_k q_k - D_k q_{k+1} \tag{9}$$

Let $\bar{Q}_k = q_k/q_n$ for all k , then $\bar{Q}_{n+1} = 0$, $\bar{Q}_n = 1$, and we can calculate \bar{Q}_{k-1} backward for $k = n$ to 2 by

$$\bar{Q}_{k-1} = A_{k-1}^{-1} [(B_{k-1} + C_k) \bar{Q}_k - D_k \bar{Q}_{k+1}]$$

Normalizing by \bar{Q}_1 leads to

$$\bar{q}_k = q_k/q_1 \quad \text{for } k = 1, 2, \dots, n \tag{10}$$

i.e., the relative values for the interface pressures when $q_1 = 1$. We can also obtain the corresponding displacements $\bar{u}_1, \dots, \bar{u}_n, \bar{u}_{n+1}$ at r_1, \dots, r_n, r_{n+1} .

STEEL LINER

The steel liner of inside radius a and outer radius b is elastic-plastically isotropic and assumed to obey Tresca's yield criterion, the associated flow rule, and linear strain-hardening. The elastic solution for the steel liner subjected to internal pressure p and external pressure q is

$$\begin{aligned}
\sigma_r &= \{ \mp(p-q)(b/r)^2 + p-q \ b^2/a^2 \} / (b^2/a^2 - 1) \\
\sigma_\theta & \\
u/r &= E^{-1}(1+\nu) [(p-q)(b/r)^2 + (1-2\nu)(p-q \ b^2/a^2)] / (b^2/a^2 - 1)
\end{aligned} \tag{11}$$

When the internal pressure p is large enough, part of the steel liner ($a \leq r \leq \rho$) will become plastic and ρ is the elastic-plastic interface. The elastic-plastic solution can be written in the elastic portion ($\rho \leq r \leq b$) as

$$\begin{aligned} \frac{E}{\sigma_0} \frac{u}{r} &= \frac{1+\nu}{2} \frac{\rho^2}{r^2} + (1-\nu-2\nu^2) \left[\frac{1}{2} \frac{\rho^2}{b^2} - \frac{q}{\sigma_0} \right] \\ \frac{\sigma_r}{\sigma_0} &= \frac{1}{2} \left(\mp \frac{\rho^2}{r^2} + \frac{\rho^2}{b^2} \right) - \frac{q}{\sigma_0} \\ \frac{\sigma_\theta}{\sigma_0} &= \frac{1}{2} \left(\mp \frac{\rho^2}{r^2} + \frac{\rho^2}{b^2} \right) - \frac{q}{\sigma_0} \\ \frac{\sigma_z}{\sigma_0} &= \nu \frac{\rho^2}{b^2} - 2\nu \frac{q}{\sigma_0} \end{aligned} \quad (12)$$

and in the plastic portion ($a \leq r \leq \rho$)

$$\begin{aligned} \frac{E}{\sigma_0} \frac{u}{r} &= (1-\nu-2\nu^2) \frac{\sigma_r}{\sigma_0} + (1-\nu^2) \frac{\rho^2}{r^2} \\ \frac{\sigma_r}{\sigma_0} &= \mp \frac{1}{2} (1-\eta\beta + \eta\beta \frac{\rho^2}{r^2}) + \frac{1}{2} \frac{\rho^2}{b^2} - (1-\eta\beta) \ln \frac{\rho}{r} - \frac{q}{\sigma_0} \\ \frac{\sigma_\theta}{\sigma_0} &= \mp \frac{1}{2} (1-\eta\beta + \eta\beta \frac{\rho^2}{r^2}) + \frac{1}{2} \frac{\rho^2}{b^2} - (1-\eta\beta) \ln \frac{\rho}{r} - \frac{q}{\sigma_0} \\ \frac{\sigma_z}{\sigma_0} &= \nu \frac{\rho^2}{b^2} - 2\nu(1-\eta\beta) \ln \frac{\rho}{r} - 2\nu \frac{q}{\sigma_0} \\ \bar{\epsilon}^p &= \beta(\rho^2/r^2 - 1) \quad , \quad \eta\beta = \frac{m}{m + \frac{3}{4} \frac{(1-m)}{(1-\nu^2)}} \\ \eta &= \frac{2}{\sqrt{3}} \frac{E}{\sigma_0} \frac{m}{1-m} \quad , \quad m = \frac{E_t}{E} \quad , \quad \sigma = \sigma_0(1 + \eta \bar{\epsilon}^p) \end{aligned} \quad (13)$$

where σ_0 is the initial tensile yield stress and E_t is the tangent modulus in the plastic range of the stress-strain curve.

When the internal pressure is further increased, the steel liner will become fully-plastic. Using Tresca's yield criterion, the associated flow rule, and assuming linear strain-hardening, the fully-plastic solution derived in Reference 3 is given below.

Subject to $\sigma_\theta \geq \sigma_z \geq \sigma_r$, the analytical expressions for the stresses and displacement are

$$\begin{aligned}
\sigma_r &= -p + \sigma_0(1-\eta\beta)\ln\left(\frac{r}{a}\right) + \frac{1}{2} \frac{\eta\beta}{(1-\nu^2)} \left[\frac{b^2}{a^2} - \frac{b^2}{r^2}\right] E\phi \\
\sigma_\theta &= \sigma_r + \sigma_0(1+\eta\epsilon^p) \\
ru &= E^{-1}(1-2\nu)(1+\nu)r^2\sigma_r + \phi b^2
\end{aligned} \tag{14}$$

where

$$\begin{aligned}
\phi &= u_b/b + (1-2\nu)(1+\nu)E^{-1}q \\
\epsilon^p &= \frac{2}{\sqrt{3}} \left[\phi b^2/r^2 - (1-\nu^2)\sigma_0/E \right] / \left[1 + \frac{2}{\sqrt{3}} (1-\nu^2)\eta\sigma_0/E \right]
\end{aligned}$$

COMPOUND CYLINDER

The compound cylinder consists of an inner steel liner and an outer composite jacket. The steel liner of inside radius a and outer radius b is wrapped by a multilayered composite jacket. The displacement and normal traction at the interface between the liner and jacket should be continuous, i.e., $q = q_1$ and $u_b = u_1$. From these conditions we can determine the relations between p and q .

When the internal pressure p is small, an explicit functional relation exists

$$\frac{2p}{q} = \frac{(b^2/a^2 - 1)}{(1-\nu^2)} [E(C_1 - D_1\bar{q}_2) + (1-\nu-2\nu^2)] + 2 \tag{15}$$

where every term in the right-hand side is known. The displacement at the bore can also be expressed as an explicit function of p

$$\left(\frac{b^2}{a^2} - 1\right) \frac{E}{p} \frac{u_a}{a} = (1+\nu) \frac{b^2}{a^2} + (1-\nu-2\nu^2) - 2(1-\nu^2) \frac{b^2}{a^2} \frac{q}{p} \tag{16}$$

When the internal pressure is large enough, part of the steel liner will become plastic. The elastic-plastic solution is given in terms of the parameter ρ . The conditions of continuity require

$$\frac{q}{\sigma_0} = \frac{(1-\nu^2)\rho^2/b^2}{(1-\nu-2\nu^2) + E(C_1 - D_1\bar{q}_2)} \tag{17}$$

This, together with

$$\frac{p_-}{\sigma_0} = \frac{q_-}{\sigma_0} + \frac{1}{2}(1 - \frac{p_-^2}{b^2}) + (1 - \eta\beta) \ln \frac{p_-}{a} + \frac{\eta\beta}{2} (\frac{p_-^2}{a^2} - 1) \quad (18)$$

serves to give an implicit relation between p and q . By letting $p = a$ and b , we can determine the lower limits p^* , q^* , u_a^* , u_b^* and the upper limits p^{**} , q^{**} , u_a^{**} , u_b^{**} , respectively.

When the internal pressure p is further increased, i.e., $p > p^{**}$, $u_a > u_a^{**}$, $u_b > u_b^{**}$, the conditions of continuity lead to

$$\phi = q[(C_1 - D_1 \bar{q}_2) + (1 - \nu - 2\nu^2)/E] \quad (19)$$

and

$$\frac{p_-}{\sigma_0} = (1 - \eta\beta) \ln \frac{b}{a} + \frac{q_-}{\sigma_0} \left\{ 1 + \frac{\eta\beta(b^2/a^2 - 1)}{2(1 - \nu^2)} [E(C_1 - D_1 \bar{q}_2) + (1 - \nu - 2\nu^2)] \right\} \quad (20)$$

It should be pointed out that the pressure q and the displacement u_b at the interface are linear functions of internal pressure p . The bore displacement u_a can be written as

$$\frac{u_a}{a} = -(1 - 2\nu)(1 + \nu) \frac{p}{E} + \frac{b^2}{a^2} \phi \quad (21)$$

which is also a linear function of internal pressure p .

RESIDUAL STATE

If the pressure p is subsequently removed completely with no reverse yielding, the unloading is entirely elastic and the solution, denoted by a prime, is given by $p' = -p$.

$$q' = 2p' / \left\{ \frac{(b^2/a^2 - 1)}{(1 - \nu^2)} [E(C_1 - D_1 \bar{q}_2) + (1 - \nu - 2\nu^2)] + 2 \right\}$$

$$\begin{aligned} \sigma_r' &= \{ \mp (p' - q')(b/r)^2 + p' - q' b^2/a^2 \} / (b^2/a^2 - 1) \\ \sigma_\theta' & \end{aligned}$$

and

$$U'/r = E^{-1}(1 + \nu) [(p' - q')(b/r)^2 + (1 - 2\nu)(p' - q' b^2/a^2)] / (b^2/a^2 - 1) \quad (22)$$

The residual state system, denoted by two primes, is the sum of the system produced by loading and that produced by unloading, i.e.,

$$\sigma_{\theta}'' = \sigma_{\theta} + \sigma_{\theta}' , \text{ etc.} \quad (23)$$

Assuming no Bauschinger effect and using Tresca's yield criterion subject to $\sigma_r'' > \sigma_z'' > \sigma_{\theta}''$, the reverse yielding will not occur if

$$\sigma_r'' - \sigma_{\theta}'' \leq \sigma'' = \sigma_0[1 + m\xi/(1-m)] \quad (24)$$

Unloading solution considering reverse yielding but neglecting Bauschinger effect was first obtained by Bland (ref 5). If we need to consider the Bauschinger effect during unloading, analytical solutions given in References 6 and 7 can be used.

NUMERICAL RESULTS

Given any value of internal pressure, we can obtain numerical results for the stresses and strains in the radial and tangential directions and also for the displacement at any radial position in a steel pressure vessel wrapped with multilayered composites. The steel liner for the subscale test specimens (ref 1) had an inner diameter of 2.0 inches and an outer diameter of 2.34 inches. The steel was 4130 seamless mechanical tubing heat treated to a hardness of 34 to 36 Rockwell "C." A standard ASTM tensile test was conducted to determine the 0.1 percent offset yield strength (120 Ksi) and the ultimate tensile strength (140 Ksi). The composite jacket is a graphite-bismaleimide produced by Fiberite Corporation. Its cure temperature is 450°F, and it is wound and wrapped on the steel liner in the same manner as the full-scale gun tube specimen denoted as CTL III. The layup $(0_290_2)_4$ is approximately half-scale and made up of two longitudinal layers alternating with two circumferential layers. Sixteen layers are applied in this way. Lamina properties for this material are

given in Table I. The total thickness of the composite jacket is 0.12 inch, and the steel liner is assumed to be linear strain-hardening with $a = 1$ inch, $b = 1.17$ inches, $\sigma_0 = 120$ Ksi, $m = 0.04$.

TABLE I. ELASTIC CONSTANTS OF STEEL AND COMPOSITE MATERIALS

Material	E_{θ} $\times 10^6$ psi	E_r $\times 10^6$ psi	E_z $\times 10^6$ psi	ν_{rz}	$\nu_{r\theta}$	$\nu_{z\theta}$
Hoop lamina Im6	21.0	1.0	1.0	0.40	0.02	0.02
Axial lamina G50	1.3	1.3	31.0	0.01	0.39	0.39
Steel 4130	30.8	30.8	30.8	0.30	0.30	0.30

The pressure at the interface between the liner and jacket has been obtained as a function of internal pressure, and the result is shown in Figure 1. The results of the hoop strains at the bore, interface between the liner and jacket, and outside surface are shown in Figure 2 as functions of internal pressure. The complete (including elastic, elastic-plastic, and fully-plastic) ranges of loadings have been considered. These numerical results for the strains are presented here for future comparisons with experimental results. The distribution of hoop stresses in the liner and jacket can be obtained at any given value of internal pressure. In Figure 3 we present the numerical results at three values of internal pressure, i.e., $p = p^*$, p^{**} , and $p = 21.33$ Ksi when half of the liner is plastic. The values of two limits for the elastic-plastic solution are $p^* = 18.80$ Ksi and $p^{**} = 22.60$ Ksi. If the pressure p is subsequently removed completely, the residual displacements, strains, and stresses can be obtained. In Figure 4, we show the distributions of residual hoop stresses in the liner and jacket corresponding to three values of internal pressure before unloading. When the jacket consists of alternating axial-hoop

lamina, the hoop stresses before and after unloading become discontinuous not only at the interface between the liner and jacket but also at all other interfaces between axial and hoop lamina.

CONCLUSION

A method for predicting residual stresses in a steel pressure vessel wrapped with multilayered composites has been developed. Analytical expressions are presented for loading in the elastic-plastic as well as the fully-plastic range.

REFERENCES

1. M.A. Scavullo, M.D. Witherell, K. Miner, T.E. O'Brien, and W. Yaiser, "Experimental and Analytical Investigation of a Steel Pressure Vessel Overwrapped With Graphite Bismaleimide," ARDEC Technical Report ARCCB-TR-87013, Benet Weapons Laboratory, Watervliet, NY, May 1987.
2. M.D. Witherell and M.A. Scavullo, "An Investigation of Stresses and Strains in an Internally Pressurized, Composite-Jacketed Steel Cylinder," ARDEC Technical Report ARCCB-TR-88042, Benet Laboratories, Watervliet, NY, November 1988.
3. P.C.T. Chen, "Elastic-Plastic Analysis of a Thick-Walled Composite Tube Subjected to Internal Pressure," Transactions of the Seventh Army Conference on Applied Mathematics and Computing, February 1990, pp. 589-598.
4. S.W. Tsai, Composite Design, 3rd Edition, Think Composites, Dayton, OH, 1987.
5. D.R. Bland, "Elastoplastic Thick-Walled Tubes of Work-Hardening Material Subject to Internal and External Pressures and to Temperature Gradients," Journal of the Mechanics and Physics of Solids, Vol. 4, 1956, pp. 209-229.
6. P.C.T. Chen, "Bauschinger and Hardening Effects on Residual Stresses in Autofrettaged Thick-Walled Cylinders," Journal of Pressure Vessel Technology, Vol. 108, February 1986, pp. 108-112.
7. P.C.T. Chen, "Stress and Deformation Analysis of Autofrettaged High Pressure Vessels," ASME Pressure Vessels and Piping, Vol. 110, July 1986, pp. 61-67.

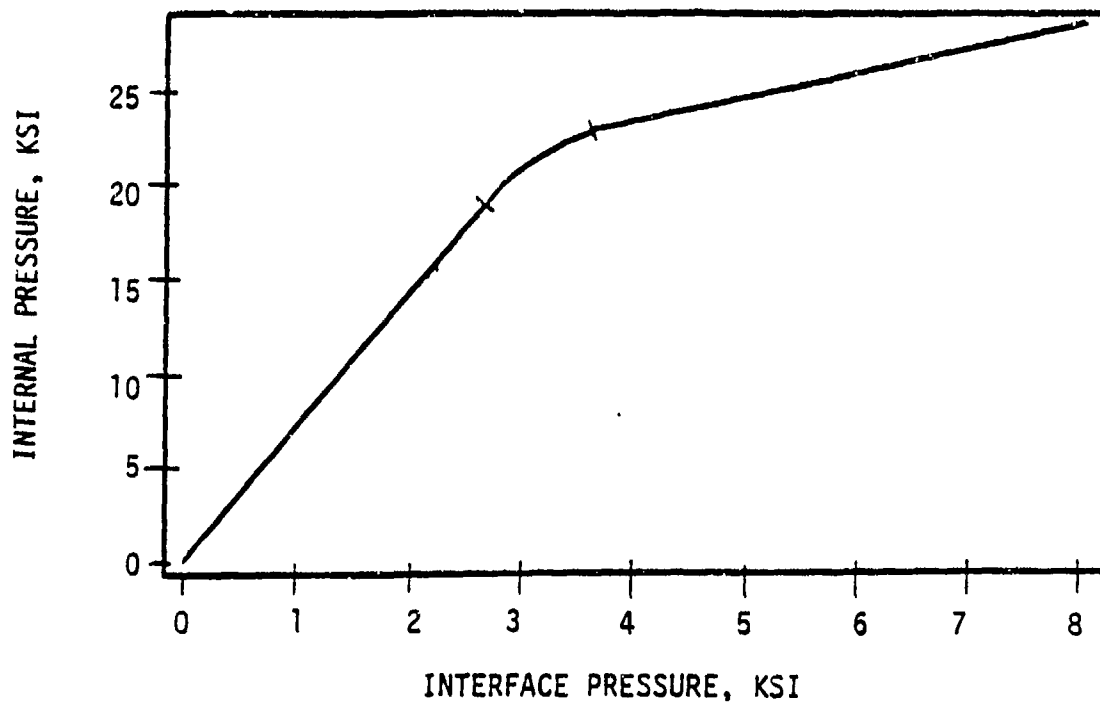


Figure 1. Interface pressure as a function of internal pressure.

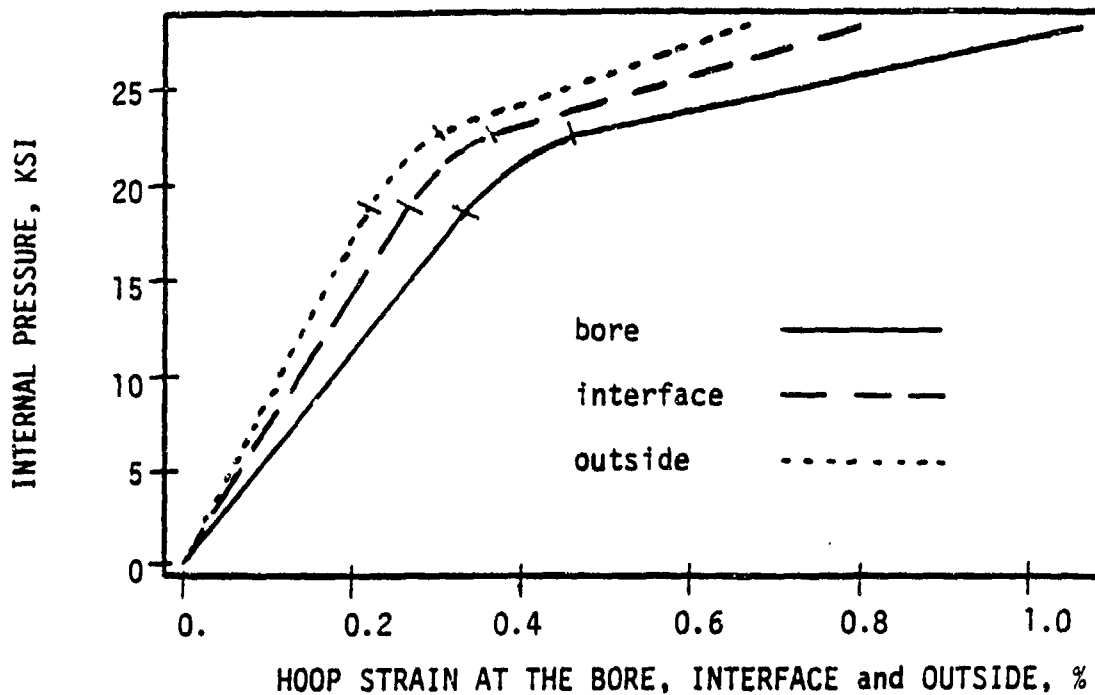


Figure 2. Hoop strains at the bore, interface, and outside as functions of internal pressure.

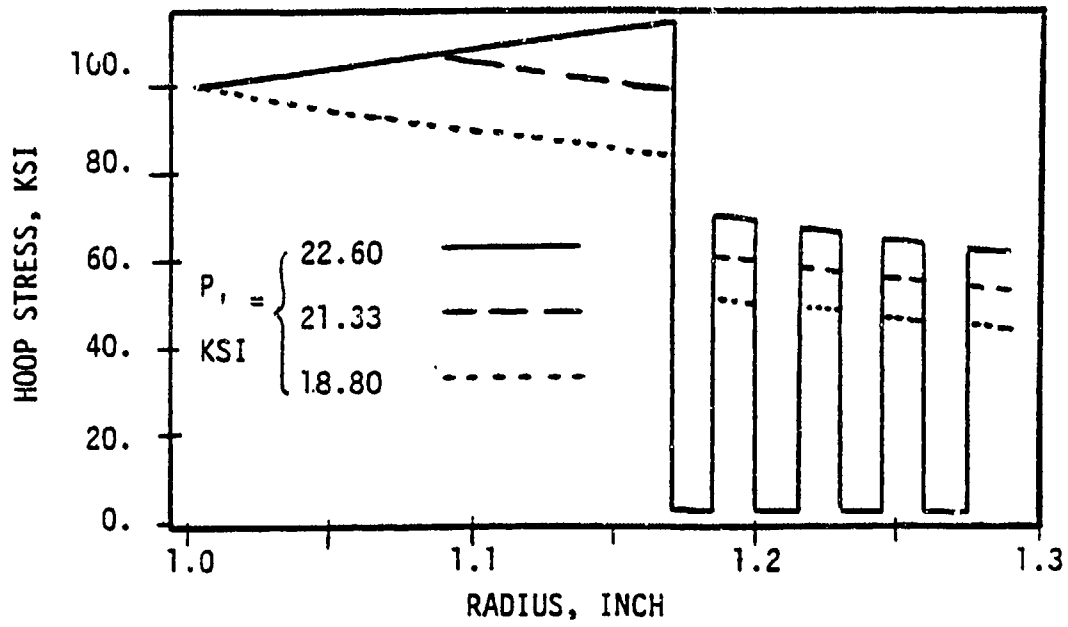


Figure 3. Distribution of hoop stresses in the liner and jacket.

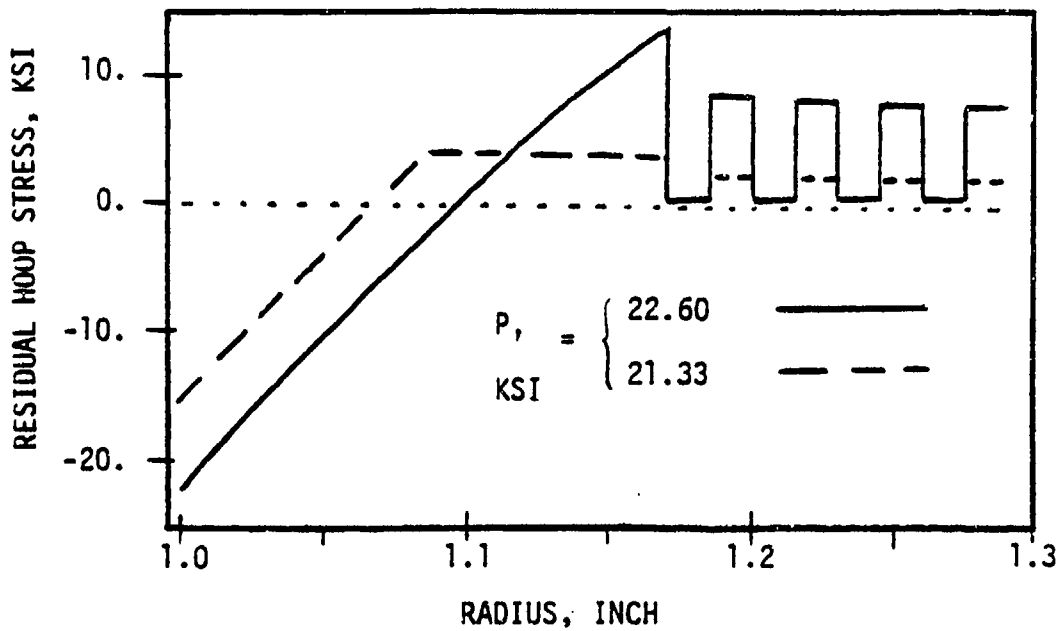


Figure 4. Distribution of residual hoop stresses in the liner and jacket.

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