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TECHNICAL REPORT ARCCB-TR-92026

NONLINEAR ANALYSIS OF A PRESSURIZED STEEL CYLINDER JACKETED WITH METAL MATRIX COMPOSITE

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JUNE 1992

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
NONLINEAR ANALYSIS OF A PRESSURIZED STEEL CYLINDER JACKETED WITH METAL MATRIX COMPOSITE

5. FUNDING NUMBERS
AMCMS No. 6111.01.91A1.1

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-92026

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Accepted for presentation at the American Society for Composites 7th Technical Conference on Composite Materials to be held 13-15 October 1992, The Pennsylvania State University, University Park, PA. Accepted for publication in the Conference Proceedings.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report presents a nonlinear analysis of a thick-walled compound tube subjected to internal pressure. The compound tube is constructed of a steel liner and a metal matrix composite outer shell. Analytical expressions for the stresses, strains, and displacements are derived for loading ranges including elastic, elastic-plastic, fully plastic, and unloading. Numerical results for the stresses and strains are obtained as functions of internal pressure.

14. SUBJECT TERMS
Metal Matrix Composite, Compound Tube, Steel Liner, Elastic-Plastic, Fully Plastic, Residual Stresses, Internal Pressure

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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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, the steel liner, maintains the tube projectile interface and shields the composite from the extremely hot gases. The outer portion, the composite jacket, is made of organic composite or metal matrix composite materials. Steel liners wrapped with single or multilayered organic composite (graphite-bismaleimide) were fabricated and tested (refs 1,2). Analytical nonlinear solutions including residual stresses in prestressed steel pressure vessels wrapped with multilayered composites are presented (refs 3,4).

This report covers a nonlinear analysis of a pressurized steel cylinder jacketed with metal matrix composite (MMC). The fabrication and laboratory pressure testing of MMC-jacketed cylinders was summarized in a recent Benet Laboratories report (ref 5). The cylinder is ASTM A723 steel forging approximately 1 foot long, with a bore diameter of 4.5 inches, a steel liner thickness of 0.4 inch, and an MMC jacket thickness of 0.2 inch. This composition results in the steel liner having 64 percent of the total volume and 82 percent of the total weight. The total component weight savings of the compound cylinder compared to an all-steel cylinder is 22 percent. The liner was directly wrapped with the MMC jacket in an all-hoop direction, and 6061 aluminum alloy matrix was applied by plasma spray. The reinforcing fibers were continuous monofilament silicon carbide (SiC) (Textron designation: SCS-2) 0.0056 inch in diameter. Volume fraction of the SiC was approximately 47 percent. The cylinder was pressurized in increments over various pressure ranges and followed by autofrettage operation. In this report, analytical expressions for the stresses, strains, and displacements in the compound tube are developed for complete ranges of loading including elastic, elastic-plastic, fully plastic, and unloading. Numerical results for the stresses and strains in the steel liner and composite jacket are obtained as functions of internal pressure. The distributions of hoop stresses before and after complete unloading are presented.

ELASTIC ANALYSIS

The compound tube consists of an inner steel "liner" and an outer composite "jacket." The steel liner of inside radius a and outer radius b is wrapped in the circumferential direction with an MMC of outside radius c. The strain-stress relations for the composite jacket in cylindrical coordinates are given by

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

where E_r, E_θ, E_z, $\upsilon_{r\theta}$, $\upsilon_{\theta z}$, and υ_{zr} are elastic material constants.

When the composite tube is subjected to internal pressure p in the elastic range, the general solutions in the plane-strain condition for the isotropic liner ($a \le r \le b$) are

$$\begin{matrix} \sigma_r \\ \sigma_\theta \end{matrix} = \left\{ \mp(p-q)\left(\frac{b}{r}\right)^2 + p-q\ b^2/a^2 \right\} \Big/ \left(\frac{b^2}{a^2} - 1\right) \qquad \begin{matrix} (2) \\ (3) \end{matrix}$$

$$\frac{u}{r} = E^{-1}(1+\nu)\left[(p-q)\left(\frac{b}{r}\right)^2 + (1-2\nu)\left(p-q\,\frac{b^2}{a^2}\right)\right]\Big/\left(\frac{b^2}{a^2}-1\right) \tag{4}$$

and for the orthotropic jacket ($b \le r \le c$),

$$\sigma_r = q\left[-\left(\frac{c}{b}\right)^{k-1}\left(\frac{c}{r}\right)^{k+1} + \left(\frac{r}{b}\right)^{k-1}\right]\Big/\left[\left(\frac{c}{b}\right)^{2k}-1\right] \tag{5}$$

$$\sigma_\theta = kq\left[\left(\frac{c}{b}\right)^{k-1}\left(\frac{c}{r}\right)^{k+1} + \left(\frac{r}{b}\right)^{k-1}\right]\Big/\left[\left(\frac{c}{b}\right)^{2k}-1\right] \tag{6}$$

$$\frac{u}{r} = \epsilon_\theta = \alpha_{12}\sigma_r + \alpha_{22}\sigma_\theta \tag{7}$$

where q is the pressure at the interface, $k = (\alpha_{11}/\alpha_{22})^{1/2}$,

$$\begin{aligned} \alpha_{11} &= (1-\nu_{rz}\nu_{zr})/E_r \\ \alpha_{12} &= (\nu_{\theta r}+\nu_{\theta z}\nu_{zr})/E_\theta \\ \alpha_{22} &= (1-\nu_{\theta z}\nu_{z\theta})/E_\theta \end{aligned} \tag{8}$$

By requiring the displacement to be continuous at the interface, the interface pressure q can be expressed as a linear function of internal pressure p,

$$\frac{2p}{q} = \left(\frac{b^2}{a^2}-1\right)\left[Ak\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} + B\right] + \frac{b^2}{a^2} + 1 \tag{9}$$

where

$$A = E\alpha_{22}/(1-\nu^2)\ , \ B = -E\alpha_{12}/(1-\nu^2) - \nu/(1-\nu) \tag{10}$$

Now all the stresses, strains, and displacements in the tube ($a \le r \le c$) can be determined as functions of p. In particular, the expressions for the displacements at the bore (u_a), interface (u_b), and outside surface (u_c) are

$$\left(\frac{b^2}{a^2}-1\right)\frac{E}{p}\frac{u_a}{a} = (1+\nu)\frac{b^2}{a^2} + (1-\nu-2\nu^2) - \frac{4(1-\nu^2)(b^2/a^2)}{\left(\frac{b^2}{a^2}-1\right)\left[Ak\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1}+B\right]+\frac{b^2}{a^2}+1} \tag{11}$$

$$\frac{u_b}{b} = q\left[k\alpha_{22}\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} - \alpha_{12}\right] \tag{12}$$

$$\frac{u_c}{c} = \frac{2qka_{22}(c/b)^{k-1}}{(c/b)^{2k}-1} \tag{13}$$

ELASTIC-PLASTIC ANALYSIS

When the internal pressure p is large enough, part of the steel liner will become plastic. Using Tresca's yield criterion, the associated flow rule, and assuming linear strain-hardening, the elastic-plastic solution based on Bland can be used (refs 6,7). Let ρ be the elastic-plastic interface.

The solution can be written in the elastic portion ($\rho \le r \le b$) as

$$\frac{E}{\sigma_o}\frac{u}{r} = \frac{1+\nu}{2}\frac{\rho^2}{r^2} + (1-\nu-2\nu^2)\left[\frac{1}{2}\frac{\rho^2}{b^2} - \frac{q}{\sigma_o}\right] \tag{14}$$

$$\begin{aligned} \sigma_r/\sigma_o \\ \sigma_\theta/\sigma_o \end{aligned} = \frac{1}{2}\left(\mp\frac{\rho^2}{r^2} + \frac{\rho^2}{b^2}\right) - \frac{q}{\sigma_o} \qquad \begin{aligned} (15) \\ (16) \end{aligned}$$

$$\sigma_z/\sigma_o = \nu\frac{\rho^2}{b^2} - 2\nu\frac{q}{\sigma_o} \tag{17}$$

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

$$\frac{E}{\sigma_o}\frac{u}{r} = (1-\nu-2\nu^2)\frac{\sigma_r}{\sigma_o} + (1-\nu^2)\frac{\rho^2}{r^2} \tag{18}$$

$$\begin{aligned} \sigma_r/\sigma_o \\ \sigma_\theta/\sigma_o \end{aligned} = \mp\frac{1}{2}\left(1-\eta\beta+\eta\beta\frac{\rho^2}{r^2}\right) + \frac{1}{2}\frac{\rho^2}{b^2} - (1-\eta\beta)\ln\frac{\rho}{r} - \frac{q}{\sigma_o} \qquad \begin{aligned} (19) \\ (20) \end{aligned}$$

$$\sigma_z/\sigma_o = \nu\frac{\rho^2}{b^2} - 2\nu(1-\eta\beta)\ln\frac{\rho}{r} - 2\nu\frac{q}{\sigma_o} \tag{21}$$

$$\bar{\epsilon}^p = \beta\left(\frac{\rho^2}{r^2}-1\right), \quad \eta\beta = \frac{m}{m + \frac{3}{4}\frac{(1-m)}{(1-\nu)^2}} \tag{22}$$

$$\eta = \frac{2}{\sqrt{3}}\frac{E}{\sigma_o}\frac{m}{1-m}, \quad m = \frac{E_t}{E}, \quad \sigma = \sigma_o(1+\eta\epsilon^p) \tag{23}$$

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.

Using Eqs. (12) and (14) and the requirement of displacement continuity at the interface, i.e., u_{b-} (liner) = u_{b+} (jacket), we obtain the expression for the interface pressure q as

$$\frac{q}{\sigma_o} = \frac{(1-\nu^2)\rho^2/b^2}{(1+\nu)(1-2\nu) + E\left[\alpha_{22}k\,\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} - \alpha_{12}\right]} \tag{24}$$

Given any value of ρ in $a \le \rho \le b$, we can now determine q, u, and all the stresses and strains in the tube. In particular, the expressions for internal pressure and for displacements at the bore and the interfaces are

$$\frac{p}{\sigma_o} = \frac{q}{\sigma_o} + \frac{1}{2}\left(1-\frac{\rho^2}{b^2}\right) + (1-\eta\beta)\ln\frac{\rho}{a} + \frac{1}{2}\eta\beta\left(\frac{\rho^2}{a^2}-1\right) \tag{25}$$

$$\frac{E}{\sigma_o}\frac{u_a}{a} = -(1-\nu-2\nu^2)\frac{p}{\sigma_o} + (1-\nu^2)\frac{\rho^2}{a^2} \tag{26}$$

$$\frac{E}{\sigma_o}\frac{u_b}{b} = (1-\nu^2)\frac{\rho^2}{b^2} - (1-\nu-2\nu^2)\frac{q}{\sigma_o} \tag{27}$$

By letting ρ = a and b, we can determine the lower limits p^*, q^*, u_a^*, u_b^*, u_c^*, and the upper limits p^{**}, q^{**}, u_a^{**}, u_b^{**}, u_c^{**}, respectively.

FULLY-PLASTIC ANALYSIS

When the internal pressure p is further increased, i.e., $p > p^{**}$, the steel liner will become fully-plastic. The composite jacket remains elastic as long as the failure pressure is not reached. Using Tresca's yield criterion, the associated flow rule, and assuming linear strain-hardening, a fully-plastic solution can be obtained (ref 3). The result is presented here for completeness. The explicit expressions for the displacement, strains, and stresses in the plane-strain case subject to $\sigma_\theta \ge \sigma_z \ge \sigma_r$ are

$$ru = E^{-1}(1-2\nu)(1+\nu)r^2\sigma_r + \phi b^2 \tag{28}$$

$$\sigma_r = -p+\sigma_o(1-\eta\beta)\ln\left(\frac{r}{a}\right) + \frac{1}{2}\frac{\eta\beta}{(1-\nu^2)}\left[\frac{b^2}{a^2} - \frac{b^2}{r^2}\right]E\phi \tag{29}$$

$$\sigma_\theta = \sigma_r + \sigma_o(1+\eta\bar{\epsilon}^p) \tag{30}$$

where σ_o, η, and $\bar{\epsilon}^p$ are the initial yield stress, hardening parameter, and equivalent plastic strain, respectively, and

$$\bar{\epsilon}^p = \frac{2}{\sqrt{3}}[\phi\,\frac{b^2}{r^2}-(1-\nu^2)\sigma_o/E]/\left[1+\frac{2}{\sqrt{3}}(1-\nu^2)\eta\sigma_o/E\right] \tag{31}$$

$$\phi = \left[E\alpha_{22}k\,\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} - E\alpha_{12}+(1-2\nu)(1+\nu)\right]q/E \tag{32}$$

$$p = \sigma_o(1-\eta\beta)\ln\frac{b}{a}+q\left\{1+\frac{1}{2}\eta\beta\left(\frac{b^2}{a^2}-1\right)\left[Ak\,\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} + B+1\right]\right\} \tag{33}$$

It is interesting to point out that p is a linear function of q. Similarly, when evaluating u at the bore from Eq. (28), we obtain

$$\frac{u_a}{a} = -(1-2\nu)(1+\nu)P/E + \phi\,\frac{b^2}{a^2} \tag{34}$$

which can also be expressed as a linear function of q with the aid of Eqs. (32) and (33). Since the relation between q and u_b is linear from Eq. (12), p and u_a given by Eqs. (33) and (34), respectively, can be expressed as linear functions of u_b.

UNLOADING ANALYSIS

If the pressure q 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.

$$q' = 2p'/\left(\frac{b^2}{a^2}-1\right)\left[Ak\frac{(c/b)^{2k}+1}{(c/b)^{2k}-1} +B\right] + \frac{b^2}{a^2}+1 \tag{35}$$

$$ \tag{36} $$

$$ \left.\begin{matrix}\sigma_r' \\ \sigma_\theta'\end{matrix}\right\} = \left\{\mp(p'-q')\left(\frac{b}{r}\right)^2 + p' - q'\,\frac{b^2}{a^2}\right\} \Big/ \left(\frac{b^2}{a^2}-1\right) \tag{37} $$

and

$$ \frac{U'}{r} = E^{-1}(1+\nu)\left[(p'-q')\left(\frac{b}{r}\right)^2 + (1-2\nu)\left(p'-q'\frac{b^2}{a^2}\right)\right] \Big/ \left(\frac{b^2}{a^2}-1\right) \tag{38} $$

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

$$ \sigma_\theta'' = \sigma_\theta + \sigma_\theta' \text{, etc.} \tag{39} $$

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

$$ \sigma_r'' - \sigma_\theta'' \le \sigma'' = \sigma_o[1 + m\xi/(1-m)] \tag{40} $$

The unloading solution considering reverse yielding, but neglecting the Bauschinger effect, was first obtained by Bland (ref 6). If we need to consider the Bauschinger effect during unloading, analytical solutions given in Reference 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 compound tube. The steel liner for the laboratory test specimens (ref 5) had an inner diameter of 4.5 inches and an outside diameter of 5.3 inches. A standard tensile test for the ASTM A723 steel was conducted to determine the 0.1 percent offset yield strength (155 Ksi) and the ultimate tensile strength (178 Ksi). The jacket consisted of SiC fibers wrapped directly on the liner in a circumferential layup, and 6061 aluminum alloy matrix was applied by plasma spray. The elastic material constants for the composite and the steel are given in Table I. The total thickness of the composite jacket is 0.2 inch and the steel liner is assumed to be linear-hardening with a = 2.25 inches, b = 2.85 inches, σ_o = 155 Ksi, and m = 0.02.

Table I. Elastic Constants of Composite Jacket and Steel Liner

Elastic Constants for SiC/Al, Hoop Layup		
E_r = 18.6 Mpsi	$\upsilon_{r\theta}$ = 0.138	$\upsilon_{\theta r}$ = 0.248
E_θ = 32.0 Mpsi	$\upsilon_{\theta z}$ = 0.248	$\upsilon_{z\theta}$ = 0.138
E_z = 18.6 Mpsi	υ_{zr} = 0.355	υ_{rz} = 0.355
Elastic Constants for Steel		
E = 30.0 Mpsi	υ = 0.3	

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 complete (including elastic, elastic-plastic, and fully-plastic) ranges of loadings have been considered. 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. These numerical results for the strains are presented here for future comparisons with experimental data. The results of hoop stresses at the bore (σ_θ/a) and interfaces (σ_θ/b- and σ_θ/b+) are shown in Figure 3 as functions of internal pressure. It should be noted that the hoop stresses at the interface are discontinuous with b- and b+ representing the location in the liner and jacket, respectively. Figure 3 shows very clearly that the results change drastically when yielding occurs. The relation changes from linear to nonlinear when yielding sets in, and a more significant change occurs when the fully-plastic state is reached. The distribution of hoop stresses in the liner and jacket can be obtained at any given value of internal pressure. In Figure 4 we present the stress distributions for four values of internal pressure, i.e., p = 29.268, 33.541, 36.069, and 37.885 Ksi. The first three values correspond to initial yielding, 50 percent yielding, and 100 percent yielding, respectively. The percent yielding in the elastic-plastic range is defined by (ρ-a)/(b-a) x 100 percent. After the fully-plastic state is reached, the stress distribution changes drastically as shown in the figure. The hoop stresses decrease slightly, but those in the jacket increase elastically as internal pressure is increased. If the pressure p is subsequently removed completely, the residual displacements, strains, and stresses can be obtained. In Figure 5, we show the distributions of residual hoop stresses in the liner and jacket corresponding to four values of internal pressure before unloading. Residual stress occurs only when the internal pressure p is larger than p^* (= 29.268 Ksi).

CONCLUSION

The stresses, strains, and displacements in a pressurized steel cylinder jacketed with metal matrix composite can be obtained analytically in the linear and nonlinear ranges of loadings. The plastic deformation in the liner has a significant effect on the overall performance of the composite structure.

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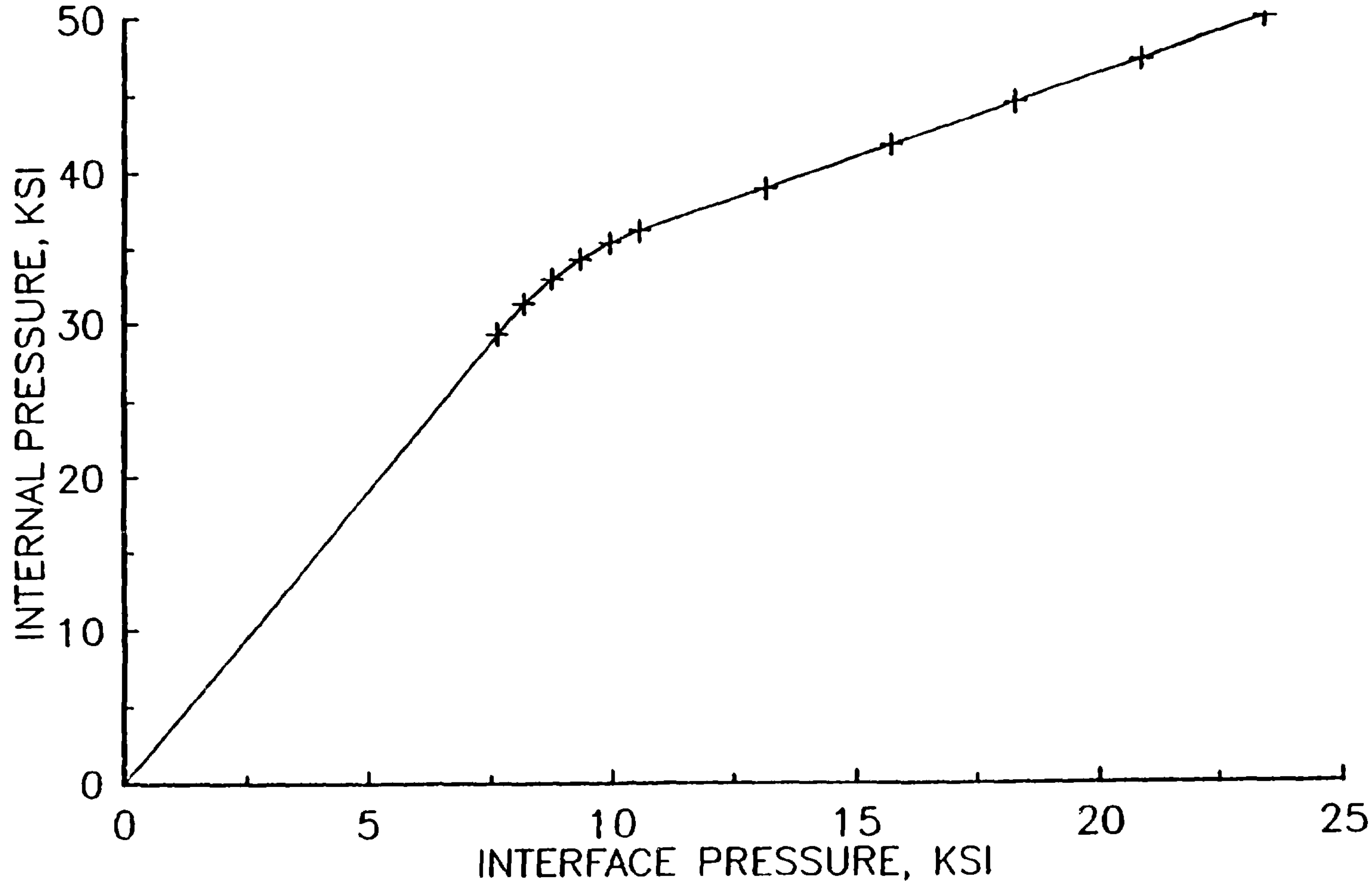

Figure 1. Interface pressure as a function of internal pressure.

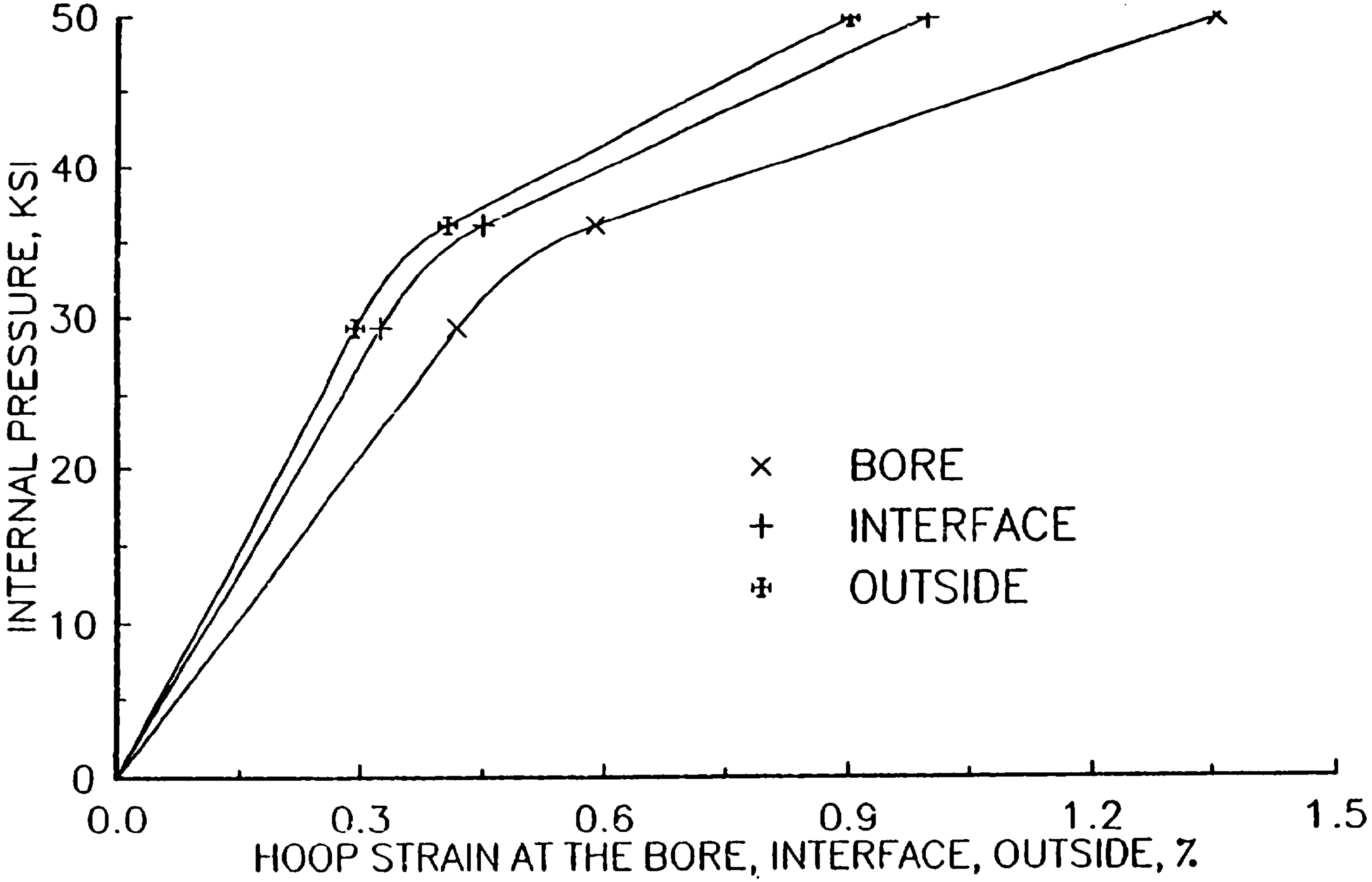

Figure 2. Hoop strains at the bore, interface, and outside surface as functions of internal pressure.

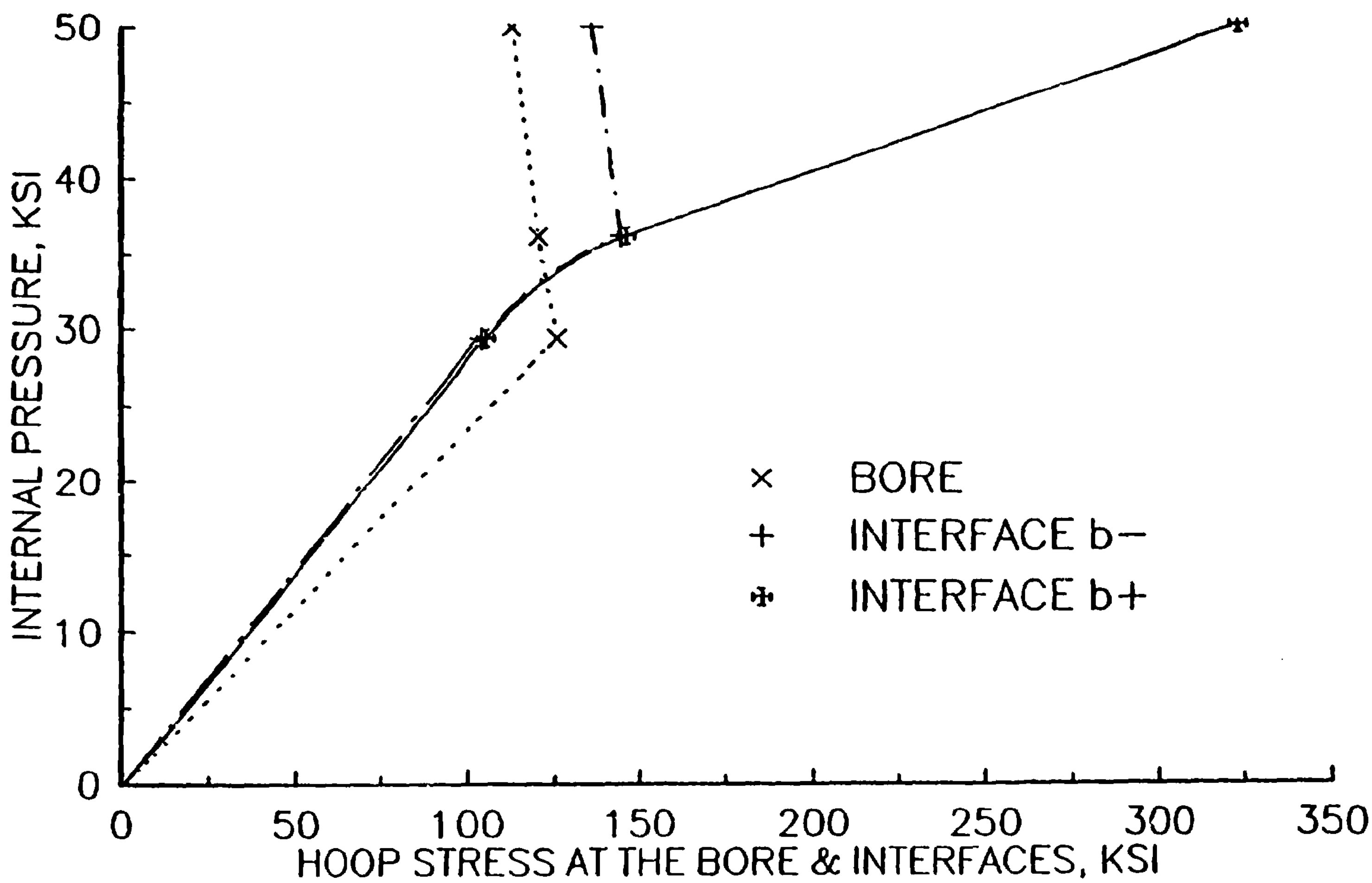

Figure 3. Hoop stresses at the bore and interfaces as functions of internal pressure.

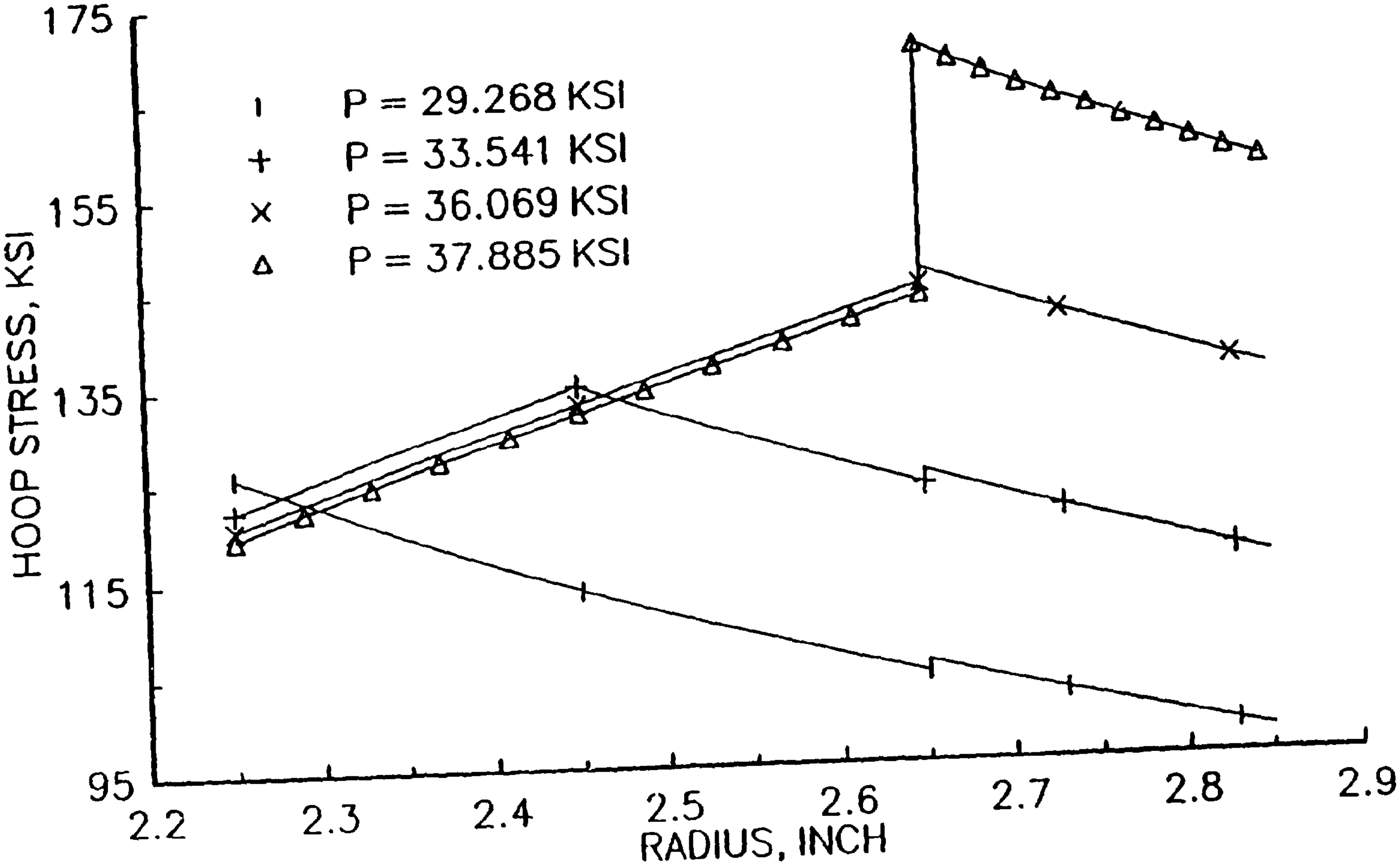

Figure 4. Distribution of hoop stresses in the liner and jacket.

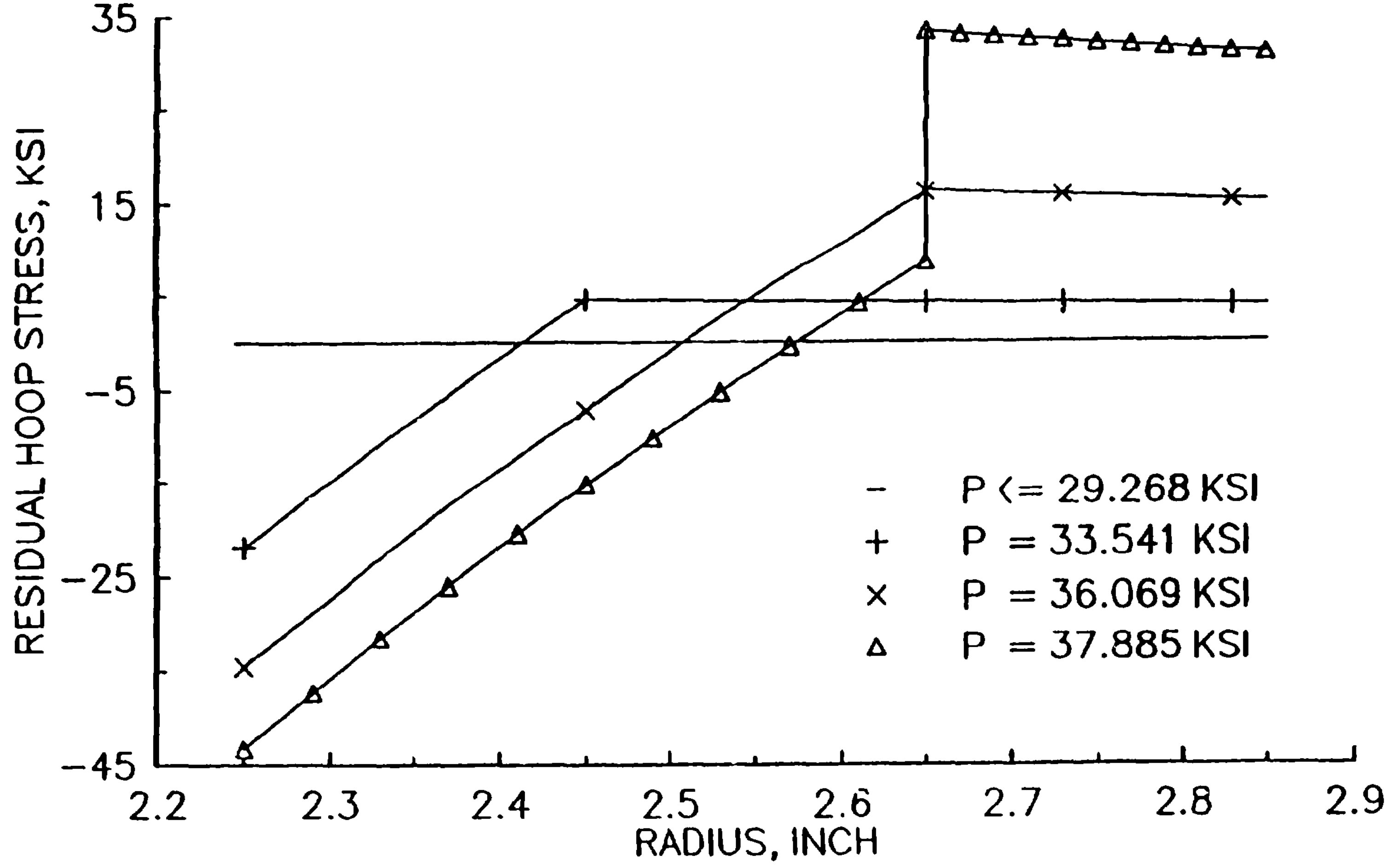

Figure 5. Distribution of residual hoop stresses in the liner and jacket.

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