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Tensile Stresses on the Surface of an Ellipsoidal Cavity in Compressive Loading Situations

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CONTENTS

ABSTRACT

The stresses on the walls of embedded cavities have been investigated, particularly for compressive loading situations corresponding to those for shells for deep submergence. The discrepancy between theoretical and measured compressive strength of brittle solids is one motivating factor for extending this investigation. The maximum tensile stress components are equal numerically to the applied compressive stress. The maximum tensile stresses depend on the shape of the cavity, Poisson's ratio, and the orientation of the cavity in the shell. It is recommended that the work continue with the aim of showing the effects of cavities on strength. One approach recommended is to calculate the effects of cracks in the walls of the cavities.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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TENSILE STRESSES ON THE SURFACE OF AN ELLIPSOIDAL CAVITY IN COMPRESSIVE LOADING SITUATIONS

INTRODUCTION

In pressure hulls for deep submergence the presence of cavities gives rise to tensile stresses on the walls of the cavities. Such cavities may be in the form of porosity in weld deposits, air bubbles in massive glass, or irregularly shaped pores in pressed and sintered materials. In the absence of adequate tests of compressive strength on full-scale objects the compressive strengths of those proposed objects are sometimes estimated on the basis of theoretical strengths of the materials. The effects of defects on compressive strength are not so well established as for tensile loading, where fracture mechanics has had considerable success, particularly in dealing with cracks. In this way the discrepancy between the theoretical tensile strengths and measured strengths has been explained.

At present the compressive strength of solids as measured do not match the theoretical strength. For example, J. Outwater (University of Vermont) has measured compressive strengths of about 200,000 psi in carefully prepared and loaded specimens of glass, and his data (unpublished) are given in Table 1. The specimens show evidence of internal failure initiation not influenced by the outer surface condition of the specimen.

The present report is an attempt to show in a limited number of examples the magnitude of tensile stresses that can be developed by internal cavities. This does not alone provide the answer to the discrepancy between theoretical and measured compressive strengths, but it does indicate that the compressive strength of a solid with cavities may be limited by the tensile strength of the material on the walls of the cavities. Although the calculated stress is independent of the size of the cavity, the fracture strength would depend on the cavity size. For the specimen the strength would be a function of the number and size of cavities and the statistical distribution of flaws which might give rise to tensile failure initiating on the wall of a cavity. At present only special cases of particular interest for submersible hulls are considered.

NOMENCLATURE

Only ellipsoidal cavities are considered, and calculations of stress are made by superposing partial solutions provided in Refs. 1-3. The symbols are as follows:

Subscript $_0$ refers to the surface of the cavity.

x, y, and z are Cartesian coordinates.

ν = Poisson's ratio.

α, β, and γ are orthogonal curvilinear coordinates.

$q = \cosh \alpha$.

$\bar{q} = \sinh \alpha$.

Table 1
Compressive Strength of Pyrex Glass
(Unpublished Data of J. Outwater)

Condition	Av. Dia.	No. of Samples	Stress (lb/in.^{2})	Std. Dev. (lb/in.^{2})
Marbles				
As received	0.576 in.	10	634,100	30,617
As received	0.711 in.	11	611,181	60,024
As received	0.865 in.	11	845,866	39,360
Etched 5% HF - 5 min	0.576 in.	10	690,400	52,582
Etched 5% HF - 5 min	0.698 in.	10	690,700	38,284
Etched 5% HF - 5 min	0.867 in.	10	679,200	60,895
Sandblasted	0.576 in.	9	725,111	29,766
Sandblasted	0.698 in.	11	688,363	48,585
Sandblasted	0.867 in.	9	832,000	41,280
Conditioned scratch	0.574 in.	10	666,700	29,786
Conditioned scratch	0.724 in.	12	619,250	39,975
Conditioned scratch	0.867 in.	10	657,800	39,698
Etched 11% HF - 1 hr	0.583 in.	10	656,900	35,158
Etched 11% HF - 1 hr	0.739 in.	12	618,417	45,920
Etched 11% HF - 1 hr	0.866 in.	10	642,800	54,428
Annealed 75 hr at 1060°F	0.570 in.	11	799,000	131,405
Annealed 75 hr at 1060°F	0.725 in.	10	745,500	54,325
Annealed 75 hr at 1060°F	0.872 in.	11	841,727	36,613
Crossed Rods				
Annealed 2 hr at 1060°F	5 mm	100	387,443	37,300
Annealed 2 hr at 1060°F	6 mm	100	434,668	33,800
Annealed 2 hr at 1060°F	7 mm	100	353,178	
Annealed 2 hr at 1060°F	8 mm	100	349,937	20,900
Annealed 2 hr at 1060°F	10 mm	100	456,924	30,800
Annealed 2 hr at 1060°F	12 mm	100	495,409	37,100
Three-Point Load-Bending Test (Tensile Failure)				
Annealed 2 hr at 1060°F	5 mm	75	15,244	2,322
Annealed 2 hr at 1060°F	6 mm	80	24,408	
Annealed 2 hr at 1060°F	7 mm	75	11,376	2,105
Annealed 2 hr at 1060°F	8 mm	75	13,760	3,271
Annealed 2 hr at 1060°F	10 mm	75	20,725	
Annealed 2 hr at 1060°F	12 mm	75	20,715	2,524
Axial Compression - Necked Down Rods				
Annealed 2 hr at 1060°F	6 mm	75	217,000	--
Annealed 2 hr at 1060°F	8 mm	67	207,000	--
Crossed Rods				
As received	5 mm	12	343,083	31,160
As received	8 mm	12	420,750	29,079
As received	10 mm	11	430,909	40,385
Sandblasted	5 mm	12	254,583	15,098
Sandblasted	8 mm	12	331,583	16,400
Sandblasted	10 mm	12	349,167	14,954

s = b/a = shape factor for an ellipsoid of revolution, where a is the semimajor axis and b is the semiminor axis.

$$q_0 = \frac{1}{\sqrt{1 - s^2}} \, . \qquad \bar{q}_0 = \frac{s}{\sqrt{1 - s^2}} \, .$$

$$d_1 = \frac{1}{q_0}\left[-1 + \nu - \bar{q}_0^2 - (2 - 2\nu + 3\bar{q}_0^2)\,\bar{q}_0^2\,Q_0 + (1+\nu)\,\bar{q}_0^4\,Q_0^2\right] .$$

$$d_2 = 6 + 3\bar{q}_0^2 + \left[(-12 + 24\nu)\,\bar{q}_0^2 + 9\bar{q}_0^4\right]Q_0 \, .$$

$$D = -2(\nu+1)\,Q_0^2 - 4(\nu - 1)\,\frac{Q_0}{\bar{q}_0^2} + 6Q_0 + \frac{2}{\bar{q}_0^2} + \frac{2(1-\nu)}{\bar{q}_0^4} \, .$$

$$Q_0 = 1 + \frac{q_0}{2}\log\left(\frac{q_0 - 1}{q_0 + 1}\right) .$$

The points A, B, and C (Fig. 1) on the ellipsoid are the only points for which stresses are computed. These include all of the worst cases regarding tensile stress magnitude; however, for calculations of statistical strengths expected, the stresses for all points on the ellipsoid would have to be included. This is left for the future.

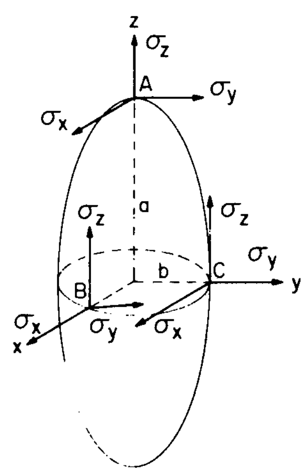

Fig. 1 - Ellipsoidal cavity of revolution prolate along the z axis. The orientation of the ellipsoid with respect to the Cartesian axes is kept constant in subsequent figures.

PARTIAL SOLUTIONS FOR UNIAXIAL APPLIED STRESS

Cases I, II, and III in this section are partial solutions which are combined in the next section in sample problems of special interest for hulls for deep submergence.

Case I - Uniaxial Stress P_x Applied in the x Direction

In Case I, stress $P_x \neq 0$ and $P_y = P_z = 0$.

Stresses at point A are:

$$\sigma_z = 0$$

$$\sigma_x = \frac{1}{2}\left[1 - \frac{(1+\nu)}{d_1\ q_0}\ (1 + \bar{q}_0^{\,2}\,Q_0)^2 + \frac{24\,(1-\nu)}{d_2}\right]$$

$$\sigma_y = \frac{1}{2}\left[1 - \frac{(1+\nu)}{d_1\ q_0}\ (1 + \bar{q}_0^{\,2}\,Q_0)^2 - \frac{24\,(1-\nu)}{d_2}\right].$$

Stresses at point B are:

$$\sigma_x = 0$$

$$\sigma_y = \frac{1}{2}\left\{1 - \frac{1}{d_1\ q_0}\left[1 - \nu + 2\,\bar{q}_0^{\,2}\,Q_0 + (1+\nu)\,\bar{q}_0^{\,4}\,Q_0^2\right] - \frac{24}{d_2}\right\}$$

$$\sigma_z = \frac{1}{2}\left\{\frac{-\bar{q}_0^{\,2}}{d_1\ q_0}\left[1 + (2 + 3\,\bar{q}_0^{\,2})\,Q_0\right] - \frac{24\ \nu}{d_2}\right\}.$$

Stresses at point C are:

$$\sigma_y = 0$$

$$\sigma_x = \frac{1}{2}\left\{1 - \frac{1}{d_1\ q_0}\left[1 - \nu + 2\,\bar{q}_0^{\,2}\,Q_0 + (1+\nu)\,\bar{q}_0^{\,4}\,Q_0^2\right] + \frac{24}{d_2}\right\}$$

$$\sigma_z = \frac{1}{2}\left\{\frac{-\bar{q}_0^{\,2}}{d_1\ q_0}\left[1 + (2 + 3\,\bar{q}_0^{\,2})\,Q_0\right] + \frac{24\ \nu}{d_2}\right\}.$$

Case II - Stress P_y Applied in the y Direction

In Case II, stress $P_y \neq 0$ and $P_x = P_z = 0$.

Stresses at point A are:

$$\sigma_z = 0$$

$$\sigma_x = \frac{1}{2}\left[1 - \frac{(1+\nu)}{d_1\ q_0}\ (1 + \bar{q}_0^{\,2}\,Q_0)^2 - \frac{24\,(1-\nu)}{d_2}\right]$$

$$\sigma_y = \frac{1}{2}\left[1 - \frac{(1+\nu)}{d_1\ q_0}\ (1 + \bar{q}_0^{\,2}\,Q_0)^2 + \frac{24\,(1-\nu)}{d_2}\right].$$

Stresses at point B are:

$$\sigma_x = 0$$

$$\sigma_y = \frac{1}{2}\left\{1 - \frac{1}{d_1\ q_0}\left[1 - \nu + 2\,\bar{q}_0^{\,2}\,Q_0 + (1+\nu)\,\bar{q}_0^{\,4}\,Q_0^2\right] + \frac{24}{d_2}\right\}$$

$$\sigma_z = \frac{1}{2}\left\{\frac{-\bar{q}_0^{\,2}}{d_1\ q_0}\left[1 + (2 + 3\,\bar{q}_0^{\,2})\,Q_0\right] + \frac{24\ \nu}{d_2}\right\}.$$

Stresses at point C are:

$$\sigma_y = 0$$

$$\sigma_x = \frac{1}{2}\left\{1 - \frac{1}{d_1\, q_0}\left[1 - \nu + 2\bar{q}_0^2\, Q_0 + (1+\nu)\,\bar{q}_0^4\, Q_0^2\right] - \frac{24}{d_2}\right\}$$

$$\sigma_z = \frac{1}{2}\left\{\frac{-\bar{q}_0^2}{d_1\, q_0}\left[1 + (2 + 3\bar{q}_0^2)\, Q_0\right] - \frac{24\,\nu}{d_2}\right\}.$$

Case III - Stress P_z Applied in the z Direction

In Case III, stress $P_z \neq 0$ and $P_x = P_y = 0$.

Stresses at point A are:

$$\sigma_z = 0$$

$$\sigma_x = \sigma_y = \frac{1}{\bar{q}_0^4\, D}\left[\bar{q}_0^2 - 2\nu + Q_0\, \bar{q}_0^2\,(2 - 2\nu + 3\bar{q}_0^2)\right].$$

Stresses at point B are:

$$\sigma_x = 0$$

$$\sigma_y = \frac{1}{D\,\bar{q}_0^2}\left[1 + Q_0\,(2 - 4\nu + 3\bar{q}_0^2)\right]$$

$$\sigma_z = 1 - \frac{1}{D\,\bar{q}_0^2}\left[1 + (4 - 2\nu + 3\bar{q}_0^2)\, Q_0 - 2Q_0^2\,\bar{q}_0^2\,(1+\nu)\right].$$

Stresses at point C are:

$$\sigma_y = 0$$

$$\sigma_x = \frac{1}{D\,\bar{q}_0^2}\left[1 + Q_0\,(2 - 4\nu + 3\bar{q}_0^2)\right]$$

$$\sigma_z = 1 - \frac{1}{D\,\bar{q}_0^2}\left[1 + (4 - 2\nu + 3\bar{q}_0^2)\, Q_0 - 2Q_0^2\,\bar{q}_0^2\,(1+\nu)\right].$$

SAMPLE PROBLEMS

For compressive applied stress, P_x, etc., is negative. The following are sample problems.

1. Let $s = 0.5 = b/a$ and $\nu = 0.3$. For uniaxial stress P_x, with $P_z = P_y = 0$, stresses at point A are

$$\sigma_z = 0 \qquad \frac{\sigma_y}{P_x} = 0.12 \qquad \frac{\sigma_x}{P_x} = 2.42\,,$$

stresses at point B are

$$\sigma_x = 0 \qquad \frac{\sigma_y}{P_x} = -0.806 \qquad \frac{\sigma_z}{P_x} = -0.661\,,$$

and stresses at point C are

$$\sigma_y = 0 \qquad \frac{\sigma_x}{P_x} = 2.48 \qquad \frac{\sigma_z}{P_x} = 0.325\,.$$

2. Let $s = 0.5$ and $\nu = 0.3$. For uniaxial stress P_y, with $P_x = P_z = 0$, stresses at point A are

$$\sigma_z = 0 \qquad \frac{\sigma_y}{P_y} = 2.42 \qquad \frac{\sigma_x}{P_y} = 0.12\,,$$

stresses at point B are

$$\sigma_x = 0 \qquad \frac{\sigma_y}{P_y} = 2.48 \qquad \frac{\sigma_z}{P_y} = 0.325\,,$$

and stresses at point C are

$$\sigma_y = 0 \qquad \frac{\sigma_x}{P_y} = -0.806 \qquad \frac{\sigma_z}{P_y} = -0.661.$$

3. Let $s = 0.5$ and $\nu = 0.3$. For uniaxial stress P_z, with $P_y = P_x = 0$, stresses at point A are

$$\sigma_z = 0 \qquad \frac{\sigma_y}{P_z} = -0.585 \qquad \frac{\sigma_x}{P_z} = -0.585,$$

stresses at point B are

$$\sigma_x = 0 \qquad \frac{\sigma_y}{P_z} = 0.02 \qquad \frac{\sigma_z}{P_z} = 1.43\,,$$

and stresses at point C are

$$\sigma_y = 0 \qquad \frac{\sigma_x}{P_z} = 0.02 \qquad \frac{\sigma_z}{P_z} = 1.43\,.$$

An extension of sample problem 3 for various values of $s = b/a$ and for $\nu = 0.25$, $\nu = 0.3$, and $\nu = 0.45$ is shown graphically in Fig. 2. The stresses are shown at only Point A because here the tensile stress is maximum. The greatest maximum tensile stress occurs for $b/a = 1$.

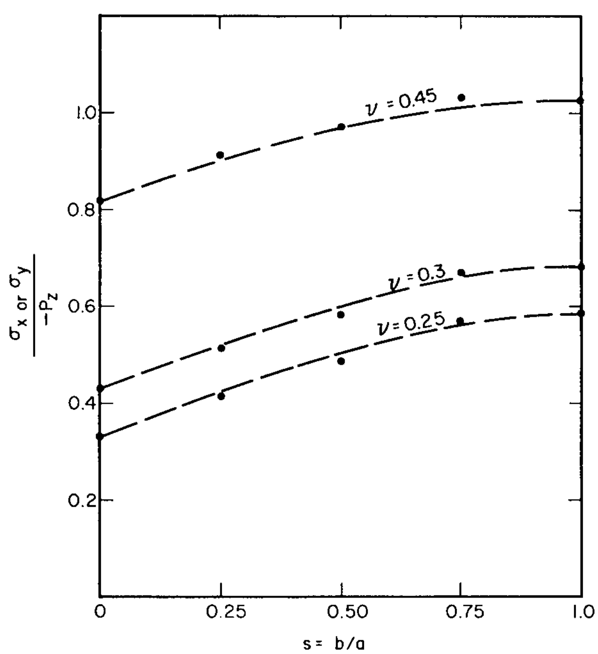

Fig. 2 - Extension of sample problem 3: effect of shape of cavity on the tensile stress at point A for $P_x = P_y = 0$. P_z is the applied compressive stress.

4. Combining sample problems 1, 2, and 3 by superposition of Cases I, II, and III, but again only for $b/a = 0.5$ and $\nu = 0.3$, stresses at point A are

$$\sigma_z = 0$$

$$\sigma_x = 2.42\ P_x + 0.12\ P_y - 0.585\ P_z$$

$$\sigma_y = 0.12\ P_x + 2.42\ P_y - 0.585\ P_z\ ,$$

stresses at point B are

$$\sigma_x = 0$$

$$\sigma_y = -0.806\ P_x + 2.48\ P_y + 0.02\ P_z$$

$$\sigma_z = -0.661\ P_x + 0.325\ P_y + 1.43\ P_z\ ,$$

and stresses at point C are

$$\sigma_y = 0$$

$$\sigma_x = 2.48\ P_x - 0.806\ P_y + 0.02\ P_z$$

$$\sigma_z = 0.325\ P_x - 0.661\ P_y + 1.43\ P_z\ .$$

5a. For a loading situation corresponding approximately to that in the wall of a cylindrical hull and with the prolate direction of the cavity assumed to be along the axis of the cylindrical shell, the stresses are as shown in Fig. 3. Only the tensile components are shown as functions of $s = b/a$ for $\nu = 0.25$, 0.30, and 0.45. The maximum tensile

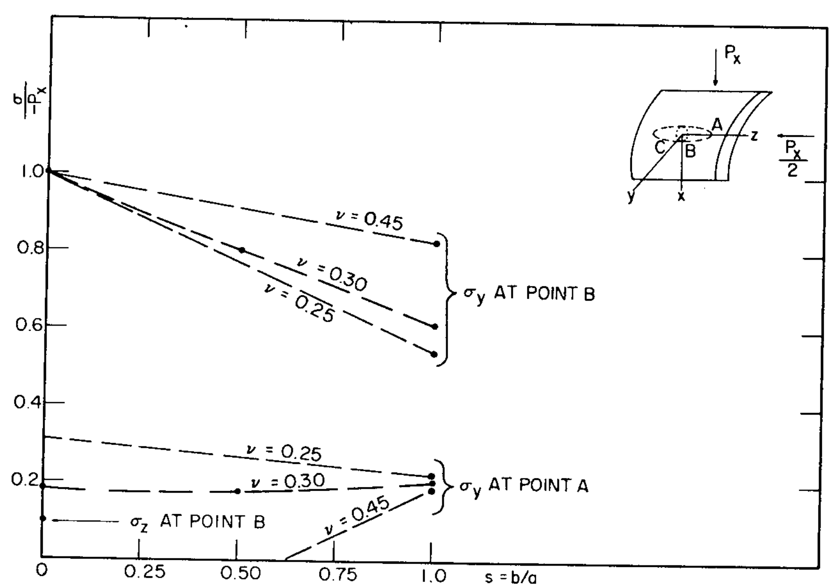

Fig. 3 - Sample problem 5a: tensile stress components which are typical for a cavity in a cylindrical shell. The ellipsoid is prolate in the cylindrical axis direction. The applied stresses are as follows: $P_z = P_x/2$, $P_y \approx 0$, and P_x is compressive.

stress component for this case is σ_y developed at point B on the ellipsoid. This is at most equal numerically to the applied hoop stress in the shell. A needle-shaped cavity with orientation as shown is the worst case.

5b. For a loading situation corresponding to that in the wall of a cylindrical hull and with the prolate direction in the hoop direction, the stresses are as shown in Fig. 4. Only the tensile components are shown as functions of the cavity shape $s = b/a$ for $\nu = 0.30$. Here the spherical shape represents the worst case, but the maximum value of the tensile stress is only about 0.6 times the applied hoop stress.

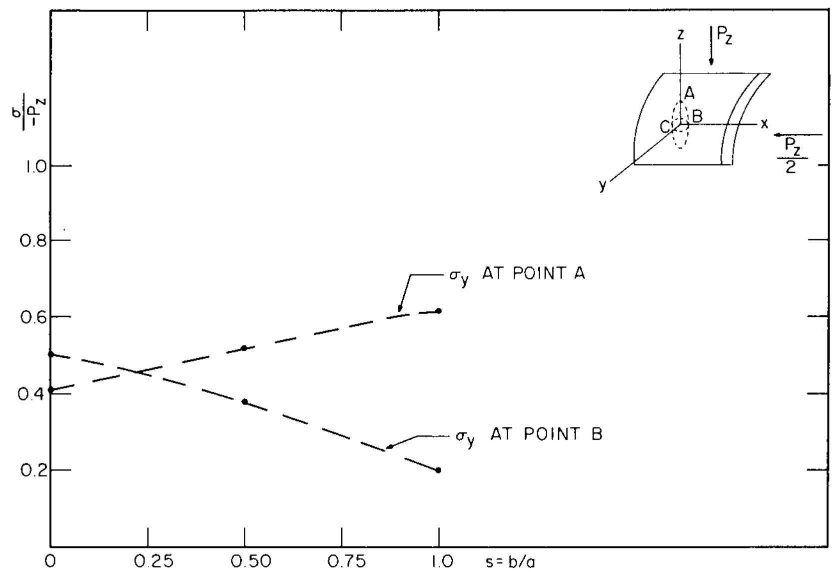

Fig. 4 - Sample problem 5b: tensile stress components which are typical for a cavity in a cylindrical shell. The ellipsoid is prolate in the hoop direction of the shell. The applied stresses are as follows: $P_x = P_z/2$, $P_y = 0$, and P_x is compressive.

5c. For a loading situation corresponding to that in the wall of a cylindrical hull and with the prolate direction of the cavity assumed to be in the z direction or through the thickness direction of the wall, the stresses are as shown in Fig. 5. As in examples 5a and 5b, only the tensile components are plotted as functions of the ellipsoidal shape factor $s = b/a$ for $\nu = 0.30$. The maximum value occurs at point B and is about 0.6 times the applied hoop stress.

6. For a loading situation corresponding approximately to that in the wall of a spherical shell the tensile components are as shown in Fig. 6 as functions of the ellipsoidal shape factor $s = b/a$ for $\nu = 0.30$. Here the maximum tensile stress is at point B and is numerically equal to the wall stress for a needle-shaped cavity. This is for the prolate direction in the plane of the wall. For the case where the prolate direction is in the through-the-wall-thickness direction the maximum tensile stress is at points B and C but is less than 0.6 times the wall stress.

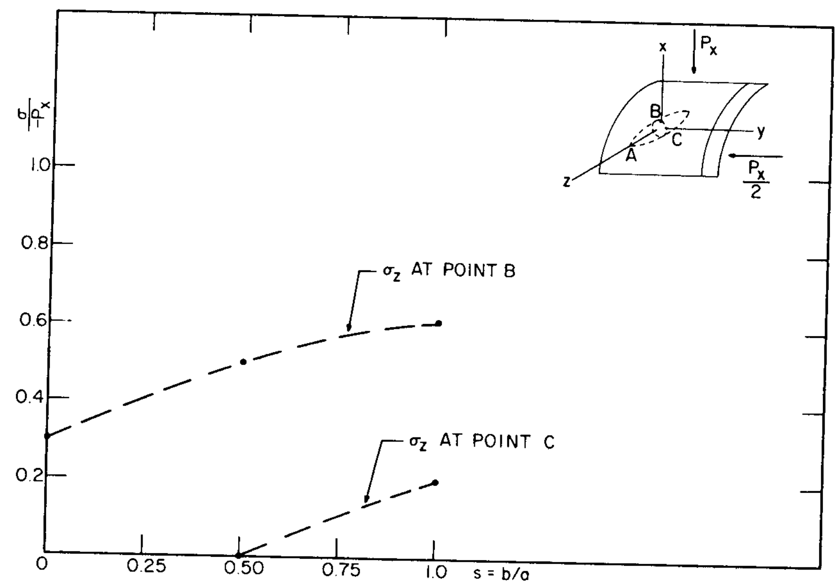

Fig. 5 - Sample problem 5c: tensile stress components which are typical for a cavity in a cylindrical shell. The prolate axis of the ellipsoid is in the through-the-thickness direction of the shell. The applied stresses are as follows: $P_y = P_x/2$, $P_z \approx 0$, and P_x is compressive.

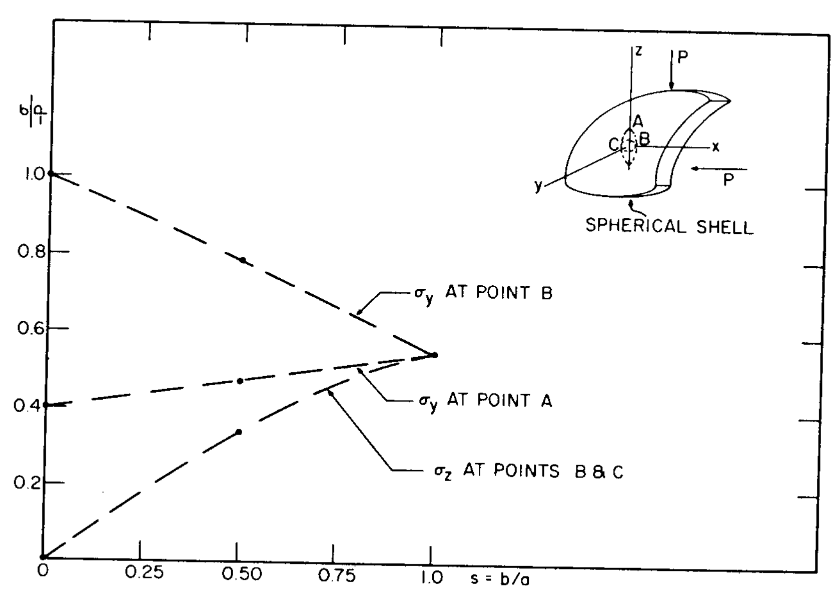

Fig. 6 - Sample problem 6: tensile stress components which are typical for a cavity in a spherical shell. The prolate axis of the cavity lying within the plane of the shell is represented in the two upper curves. The lowest curve represents a cavity with prolate axis in the through-the-thickness direction of the shell. For the upper two curves, $P_x = P_z$, $P_y \approx 0$, and P_x is compressive. For the lowest curve $P_x = P_y$, $P_z \approx 0$, and P_x is compressive.

SUMMARY AND RECOMMENDATIONS

The discrepancy between measured and theoretical compressive strengths of solids has not yet been explained to the same extent as for the case of tensile failures initiated by cracks. It is shown here that for engineering materials containing cavities, such as massive glass containing bubbles, tensile stresses are developed on the walls of the cavities numerically as high as the applied compressive stress. Their effect on the fracture strength of the specimen is not yet calculated. It would depend on the size and number of cavities and the statistical distribution of cracks in the cavity walls. The shape factor of the cavity is also important. Only prolate ellipsoidal cavities of various shape factors have been considered; oblate ellipsoidal cavities have been neglected because these produce less severe effects than those discussed. In this case the compressive stress concentration approaches infinity with the practical consideration of plastic yielding (4). Six sample problems have been solved showing special cases of interest for loading situations corresponding approximately to those in cylindrical and spherical shells for deep submergence. The cases considered here are cavities deeply embedded. Solutions for the stresses in cavities near a free surface are among future needs. At present, experiments on glass show that the compressive strength is not greatly affected by the condition of the outer surface of the specimen, and it is tentatively concluded that the fractures are internally initiated. For this reason it is recommended that further studies of the effects of internal cavities and other flaws on the strength of brittle materials be continued.

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The stresses on the walls of embedded cavities have been investigated, particularly for compressive loading situations corresponding to those for shells for deep submergence. The discrepancy between theoretical and measured compressive strength of brittle solids is one motivating factor for extending this investigation. The maximum tensile stress components are equal numerically to the applied compressive stress. The maximum tensile stresses depend on the shape of the cavity, Poisson's ratio, and the orientation of the cavity in the shell. It is recommended that the work continue with the aim of showing the effects of cavities on strength. One approach recommended is to calculate the effects of cracks in the walls of the cavities.

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