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STRESS ANALYSIS OF A RUPTURE DISK

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STRESS ANALYSIS OF A RUPTURE DISK

R. W. Werne

ABSTRACT

The results of an elastic stress analysis of the rupture disk for an internal pressure of 45.5 MPa (6600 psi) indicate that the maximum von Mises stresses occur in the membrane and are on the order of 483 - 690 MPa (70,000 psi). This far exceeds the yield of the membrane material of 207 MPa (30,000 psi). These high stresses are expected since the membrane is designed to burst at that design pressure. The von Mises stresses in the rest of the body are less than 138 MPa (20,000 psi).

An elastic-plastic analysis of the membrane alone subjected to the 45.5 MPa (6600 psi) pressure indicates that it becomes plastically unstable, i.e., it continues to deform under constant load.

A second load case with a constant 6.9 MPa (1000 psi) pressure throughout the entire body (i.e., after release of pressure by burst the membrane) was analyzed. The results indicate that the elastic von Mises stresses are less than 26.7 MPa (3880 psi) throughout the body.

INTRODUCTION

The rupture disk is a pressure limiting device having a membrane which is designed to burst at a pressure of 45.5 MPa (6600 psi). It is a safety device which is used in gas handling systems in order to insure that the system pressure does not exceed some specific value. The entire unit is manufactured from 316 stainless steel. The detailed dimensions of the rupture disk are shown in Figure 1. In order to assess the structural integrity of the rupture disk body, a detailed stress analysis was performed. Of particular interest in the analysis is the area in which the membrane is joined to the main body. As can be seen in Figure 1, the lower and upper portions of the body as well as the membrane itself, are joined together by a single circumferential "groove weld." Thus, the nature of the stress distribution in and around this weld is a key factor in assessing the structural integrity of the unit as a whole.

Figure 1. Dimensions of the rupture disk. (Note: All dimensions are in mm with inches below in parenthesis.)

The analysis is performed in several steps in order to properly model the most realistic set of loading conditions. First, an elastic stress analysis was performed using the NAOS [1]* finite element code. The overall finite element model and the detail of the mesh in the vicinity of the groove weld are shown in Figure 2. Because of the way in which the membrane is joined to the body, there exists a contact surface between the membrane and the upper portion of the body. This surface is indicated in Figure 3(a). For the case in which the maximum pressure of 45.5 MPa (6600 psi) is acting on the membrane, but it has not burst, there will be normal and friction forces acting on the contact surface. These forces are shown in Figure 3(b). By assuming that the forces, or pressures in this case, are related by the

Figure 2. Finite element model of the rupture disk.

* Numbers in brackets refer to references at the end of the report.

* Note: P_T = Friction stress,
 P_N = Normal stress
 Dimensions are in mm (in.)

** A = curved sur-
 face
 B = flat sur-
 face

Figure 3. Detail of the membrane contact forces due to an internal pressure of 45.5 MPa (6600 psi) — Load Case I.

elementary friction law, $P_T = \mu P_N$, and that the contact surface is of known shape, then an elementary equilibrium analysis of an element of the membrane will yield expressions for P_T and P_N as a function of the contact angle, θ , and the internal pressure, P_0 . A detailed derivation of the equations are presented in Appendix A, but the expressions for the normal and tangential pressures are as follows:

$$P_N^* = P_0 \left[1 + \left(\frac{R_0 r_0}{2Rr} \right) \right] e^{-\mu\theta} \quad (1)$$

$$P_T = \mu P_0 \left[1 + \left(\frac{R_0 r_0}{2Rr} \right) \right] e^{-\mu\theta} \quad (2)$$

where the variables R_0 , r_0 , R , r , θ are as shown in Figure A-2. These expressions were used to calculate the pressures acting on the contact surface and were used as input data to the NAOS finite element code. A coefficient of friction of $\mu = 0.35$ was used as being indicative of friction between machined steel surfaces [3].

In Figure 2(b) it can be seen that the contact surface is represented by five zones. The contact pressures are assumed to be constant over these zones and had the magnitudes shown in Table I.

Table I.

	P_N - MPa (psi)		P_T - MPa (psi)		
Increasing, θ	282	(40,900)	99	(14,300)	Curved Surface
(see Fig. 3(b))	261	(37,900)	91	(13,300)	
↓	243	(35,000)	85	(12,300)	
	45.5	(6600)	15.9	(2310)	Flat Surface
	45.5	(6600)	15.9	(2310)	

As can be seen from Table I the contact pressures are significant. However, one might argue that the friction values will be reduced or eliminated

* $P_N = P_r$, $P_T = P_\theta$.

due to slip along the contact surface. Therefore in order to evaluate the effect of the friction pressures, two elastic calculations were performed for this loading case, one with, and one without, friction forces acting on the membrane and upper section of the body.

An additional elastic analysis was performed for a uniform pressure of 6.9 MPa (1000 psi) acting throughout the body in order to simulate the loading conditions which would exist after the membrane had burst. In this case the finite element model of the membrane remained intact and the pressure was simply applied to all interior surfaces of the body, including both sides of the membrane. No contact pressures were considered in this analysis.

In all of the elastic analysis the elastic modulus, E , and Poisson's ratio, ν were

$$E = 206,850 \text{ MPa } (30 \times 10^6 \text{ psi}) \quad (3)$$

$$\nu = 0.30$$

The elastic-plastic behavior of the membrane alone was studied using the HEMP code [2]. In this model only the membrane and the contact surface of the upper portion of the body were considered. The model used in the HEMP code is shown in Figure 10(b) and the pressure loading history is shown in Figure 10(a). A "slide-line" was used to model the contact surface between the membrane and upper surface of the body. This allowed the membrane to "wrap" around the upper surface. Because of a limitation within the HEMP code, the contacting surface was treated as frictionless.

The material model used in the HEMP code contained strain hardening and was a standard form utilized in a library of constitutive models within the code. In essence the code treats the material as elastic below the yield strength, σ_y . However, as the equivalent state of stress exceeds the initial uniaxial yield strength, σ_0 , the yield increases in accordance with the relation.

$$\sigma_y = \sigma_0(1 + \text{IPD}) \quad (4)$$

where IPD is a measure of the "Internal Plastic Deformation." This material model is very crude and results should therefore be considered as qualitative only.

For this portion of the analysis, the initial yield strength of the material was assumed to be $\sigma_0 = 207 \text{ MPa } (30,000 \text{ psi})$.

RESULTS

1. Elastic Analysis

The outline of the rupture disk body and the pressure distribution are shown in Figure 4(a) for Load Case I. As mentioned earlier the pressures along the contact surface between the membrane and upper portion of the body are shown in Figure 3(b). The resulting von Mises stress contours throughout the body are shown in Figure 4(b). These results include the effect of friction pressures. As can be seen from the figure, the stress contours are highly concentrated in the vicinity of the groove weld. Figure 5 shows the von Mises stress contours in the lower portion of the body. The highest von Mises stress in this region is approximately 84 MPa (12,200 psi). Detailed plots of the von Mises stress contours at the

Figure 4. Load Case I.

Figure 5. von Mises stress contours in the lower body at a pressure of 4.5 MPa (6600 psi) - Load Case I.

junction of the membrane and body are shown in Figures 6(a) and 6(b). The highest von Mises stress occurs in the membrane at Point A in Figure 6(b) and has a magnitude of 680 MPa (98,000 psi). The maximum von Mises stress at the centerline of the membrane is 607 MPa (88,000 psi), while the minimum stress at the centerline is 469 MPa (68,000 psi). This variation in stress throughout the thickness indicates that the membrane is not behaving as such from the structural point of view. In this case it is behaving more like a shell.

Figure 6(a) also shows that the magnitude of the von Mises stress contours diminishes very rapidly away from the end of the membrane.

The case in which friction pressures are absent along the contact surface is shown in Figures 7(a) and 7(b). Surprisingly, the distributions of the von Mises stress contours are virtually identical to the corresponding situation with friction. Careful comparison of Figures 6 and 7 supports

(a)

Stress - psi

- 1= 3.30E-01
- 2= 1.00E+04
- 3= 2.00E+04
- 4= 3.00E+04
- 5= 4.00E+04
- 6= 5.00E+04
- 7= 6.00E+04
- 8= 7.00E+04
- 9= 9.87E+04

Stress - Pa

- 1= 2.20E+03
- 2= 6.89E+07
- 3= 1.30E+08
- 4= 2.07E+08
- 5= 2.70E+08
- 6= 3.45E+08
- 7= 4.14E+08
- 8= 4.82E+08
- 9= 6.80E+08

(b)

Figure 6. von Mises stress contours in the membrane and body due to Load Case I with friction.

Stress - psi

- 1= 2.80E-01
- 2= 1.00E+04
- 3= 2.00E+04
- 4= 3.00E+04
- 5= 4.00E+04
- 6= 5.00E+04
- 7= 6.00E+04
- 8= 7.00E+04
- 9= 9.87E+04

Stress - Pa

- 1= 1.93E+03
- 2= 6.89E+07
- 3= 1.38E+08
- 4= 2.07E+08
- 5= 2.76E+08
- 6= 3.45E+08
- 7= 4.14E+08
- 8= 4.83E+08
- 9= 6.80E+08

Figure 7. von Mises stress contours in the membrane and body due to Load Case I without friction.

this conclusion. Therefore we must assume that the presence of the friction pressure has a negligible effect on the stress distribution in the membrane and body.

The second load case for the elastic analysis is shown in Figure 8(a). In this situation the membrane no longer acts as a barrier and the pressure is distributed uniformly throughout the body, including both sides of the membrane. The overall distribution of von Mises stress contours is shown in Figure 8(b) with additional plots for the lower, mid, and upper sections being shown in Figures 9(a), 9(b), and 9(c), respectively. The figures show that the stresses are fairly uniform throughout the body with no significant

(a) Uniform pressure distribution of 6.9 MPa (1000 psi).

(b) Distribution of von Mises stress contours due to a uniform internal pressure of 6.9 MPa (1000 psi).

Figure 8. Load Case II.

Stress - psi

- 1= 4.70E+01
- 2= 5.47E+02
- 3= 1.05E+03
- 4= 1.55E+03
- 5= 2.05E+03
- 6= 2.55E+03
- 7= 3.05E+03
- 8= 3.55E+03
- 9= 3.88E+03

Stress - Pa

- 1= 3.24E+05
- 2= 3.77E+06
- 3= 7.22E+06
- 4= 1.07E+07
- 5= 1.41E+07
- 6= 1.76E+07
- 7= 2.11E+07
- 8= 2.45E+07
- 9= 2.67E+07

Figure 9. von Mises stress contours at various areas of interest for a uniform internal pressure of 6.9 MPa (1000 psi) - Load Case II.

stress concentrations present for this load case. For the loading shown the maximum von Mises stress is 26.7 MPa (3880 psi) which occurs at Point B in Figure 8(b). However, in service that point will not be loaded by the internal pressures since it is in reality a threaded surface. The next highest stress is represented by contour No. 6 in Figures 8(b) and 9(c) and represents a magnitude of 17.6 MPa (2550 psi).

2. Elastic-Plastic Analysis

An analysis was performed on the membrane and the contact surface of the upper portion of the body assuming that the material was elastic-plastic. As discussed earlier, the material had strain hardening capabilities but only in a qualitative sense. No attempt was made to model the elastic-plastic behavior of the real material. Therefore these results must be viewed as qualitative.

The loading function and the HEMP model are shown in Figure 10(a) and 10(b), respectively. The cross-hatched boundaries shown in the Figures 10(b) through 10(f) indicate that they are rigid. As can be seen from the figure, the deformed shape of the membrane at various times is shown. It is interesting to note that the membrane continues to deform even after the pressure has reached a constant value. Note also that the membrane actually "wraps" around the interior surface of the body. Since the HEMP code does not have the capability of modeling fracture of the material, the deformation of the membrane (in the model at least) would continue indefinitely.

Figure 11 shows the time history plots of several variables at Point C in Figure 10(b). Shown in the figure are the x-coordinate, x-velocity, strains, ϵ_{xx} , and ϵ_{yy} ; Internal Plastic Deformation; IPD; and stress, σ_{yy} . The plot of IPD in Figure 11(e) controls the strain hardening model given by equation (4).

CONCLUSIONS

1. Elastic Analysis

The results of the elastic analysis for the load case in which the membrane serves as the pressure barrier (see Figure 4(a)) indicate that significant yielding will take place in the membrane as one would expect. This is based upon a minimum yield strength for 316 stainless steel of 207 MPa

(a)

(b) $t = 0.0 \mu$ s

(c) $t = 25.0 \mu$ s

(d) $t = 50 \mu$ s

(e) $t = 75 \mu$ s

(f) $t = 95 \mu$ s

Figure 10. Deformed membrane.

*Note: IPD = Internal Plastic Deformation

Figure 11. Time response for variables at the center of the membrane (Point A in Figure 10(b)).

(30,000 psi) [4]. The elastic von Mises stresses in the membrane are on the order of 483 - 690 MPa (70,000 - 100,000 psi) (see Figure 6). The elastic von Mises stresses in the lower section of the body are below 138 MPa (20,000 psi) which is well below the minimum yield of the material. For this loading case, that portion of the body in the vicinity of the membrane, does not seem to be a significant stress concentration as one might expect. The high stresses in this region are actually in the membrane rather than the valve body itself (see Figure 6).

For the load case modeling the post-burst condition in which a 6.9 MPa (1000 psi) pressure is uniformly distributed throughout the body (see Figure 8(a)), the maximum von Mises stress within the body itself is 17.6 MPa (2550 psi). This may be linearly extrapolated to any other pressure. In fact if we assume that the minimum yield of the material is 207 MPa (30,000 psi), then this corresponds to an internal pressure of 81.2 MPa (11,760 psi) at initial yield.

2. Elastic-Plastic Analysis

As shown in Figures 10 and 11 the membrane continues to deform plastically even after the applied pressure has reached a constant value. In fact the plot of the velocity near the centerline of the membrane shown in Figure 11(b) indicates that the membrane is actually accelerating. Likewise the other plots in Figure 11 show a similar behavior for the variables which they represent. The plot of the stress, σ_{yy} , in Figure 11(f) shows an initial transient dynamic elastic response, until yield occurs at between 25 - 30 microseconds. In this plot the apparent yield is slightly above the uniaxial yield of 207 MPa (30,000 psi) but it must be remembered that this is only one component of a three-dimensional state of stress.

The behavior of the membrane under this loading condition indicates that it has reached a state of plastic instability. Since the membrane material is incompressible, the total volume of material must remain constant during the deformation. Therefore as the membrane "stretches" it must be reduced in thickness in order to maintain its isochoric mode of deformation. A reduction in the thickness of the membrane requires an increase in the nominal membrane stress if equilibrium is to be reached. However, for the given amount of strain, the material does not strain harden

enough to produce the stress level necessary for equilibrium. Thus a state of instability results.

It is interesting to note that during the plastic deformation of the membrane, the stress distribution is essentially uniform through the thickness. The yielding has caused the stresses to redistribute, resulting in a true membrane behavior.

ACKNOWLEDGMENT

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APPENDIX A. Membrane Friction Analysis

Figure A-1. Equilibrium of a membrane element.

Equilibrium in the tangential direction (Figure A-1):

$$\Sigma F_\theta = 2\pi R N_\theta \cos \frac{d\theta}{2} - \left(N_\theta + \frac{\partial N_\theta}{\partial \theta} d\theta \right) 2\pi(R + dR) \cos \frac{d\theta}{2} - 2\pi \left(R + \frac{dR}{2} \right) P_\theta r d\theta = 0$$

Note: $\cos \frac{d\theta}{2} \approx 1$ for $d\theta \ll 1$

$$\Sigma F_\theta = RN_\theta - \left(N_\theta + \frac{\partial N_\theta}{\partial \theta} d\theta \right) (R + dR) - \left(R + \frac{dR}{2} \right) P_\theta r d\theta = 0$$

$$\Sigma F_\theta = RN_\theta - \left(N_\theta + \frac{\partial N_\theta}{\partial \theta} d\theta \right) (R + dR) - \left(R + \frac{dR}{2} \right) P_\theta r d\theta = 0$$

$$\Sigma F_\theta = \cancel{RN_\theta} - \cancel{N_\theta R} - N_\theta dR - \frac{\partial N_\theta}{\partial \theta} R d\theta - \frac{\partial N_\theta}{\partial \theta} dR d\theta - R P_\theta r d\theta - P_\theta r d\theta \frac{dR}{2} = 0$$

Neglect all products of differentials, i.e., $dRd\theta$,

$$\Sigma F_{\theta} = -N_{\theta} dR - \frac{\partial N_{\theta}}{\partial \theta} R d\theta - P_{\theta} R r d\theta = 0$$

Note: $\frac{\partial N_{\theta}}{\partial \theta} = \frac{dN_{\theta}}{d\theta}$ since N_{θ} is only a function of θ .

$$\Sigma F_{\theta} = -N_{\theta} \frac{dR}{d\theta} - R \frac{dN_{\theta}}{d\theta} - P_{\theta} R r = 0$$

Therefore,

$$\frac{dN_{\theta}}{d\theta} + N_{\theta} \frac{1}{R} \frac{dR}{d\theta} = -P_{\theta} r$$

Equilibrium in the normal direction (Figure A-1):

$$\begin{aligned} \Sigma F_r = & \cancel{2\pi} R N_{\theta} \sin \frac{d\theta}{2} + \cancel{2\pi} (R + dR) \left(N_{\theta} + \frac{\partial N_{\theta}}{\partial \theta} d\theta \right) \sin \frac{d\theta}{2} \\ & - \cancel{2\pi} \left(R + \frac{dR}{2} \right) P_r r d\theta = 0 \end{aligned}$$

Note: $\sin \frac{d\theta}{2} \approx \frac{d\theta}{2}$ for $d\theta \ll 1$

$$\Sigma F_r = N_{\theta} R \frac{d\theta}{2} + \left(N_{\theta} + \frac{\partial N_{\theta}}{\partial \theta} d\theta \right) (R + dR) \frac{d\theta}{2} - P_r \left(R + \frac{dR}{2} \right) r d\theta = 0$$

$$\begin{aligned} \Sigma F_r = & N_{\theta} R \frac{d\theta}{2} + N_{\theta} R \frac{d\theta}{2} + N_{\theta} dR \frac{d\theta}{2} + \frac{\partial N_{\theta}}{\partial \theta} d\theta R \frac{d\theta}{2} + \frac{\partial N_{\theta}}{\partial \theta} d\theta dR \frac{d\theta}{2} \\ & - P_r R r d\theta - P_r \frac{dR}{2} r d\theta = 0 \end{aligned}$$

Neglect all second and third order differentials,

$$\Sigma F_r = N_{\theta} R d\theta - P_r r R d\theta = 0$$

Therefore,

$$N_{\theta} = P_r r$$

The set of equilibrium equations are,

$$\frac{dN_{\theta}}{d\theta} + N_{\theta} \left(\frac{1}{R} \frac{dR}{d\theta} \right) = -P_{\theta} r \quad (1)$$

$$N_{\theta} = P_r \cdot r \quad (2)$$

$$P_{\theta} = \mu P_r \quad (\text{Friction equation}) \quad (3)$$

where μ = coefficient of friction

Sub. (2) into (3)

$$P_{\theta} = \mu \frac{N_{\theta}}{r} \quad (4)$$

Sub. (4) into (1)

$$\begin{aligned} \frac{dN_{\theta}}{d\theta} + N_{\theta} \left(\frac{1}{R} \frac{dR}{d\theta} \right) &= -\mu N_{\theta} \\ \frac{dN_{\theta}}{d\theta} + N_{\theta} \left(\frac{1}{R} \frac{dR}{d\theta} + \mu \right) &= 0 \end{aligned} \quad (5)$$

Let

$$\frac{1}{R} \frac{dR}{d\theta} + \mu = \alpha(\theta)$$

therefore (5) becomes

$$\begin{aligned} \frac{dN_{\theta}}{d\theta} + \alpha N_{\theta} &= 0 \\ \frac{dN_{\theta}}{N_{\theta}} &= -\alpha d\theta \end{aligned} \quad (6)$$

Integrating (6) we get

$$\ln N_{\theta} = -\int \alpha d\theta + A$$

where A is a constant of integration.

Therefore the solution to (6) becomes

$$N_{\theta} = Ae^{-\int \alpha d\theta} \quad (7)$$

where A must be evaluated from some boundary condition and

$$\alpha = \frac{1}{R} \frac{dR}{d\theta} + \mu$$

Figure A-2.

Consider the following integral,

$$-\int \alpha d\theta = -\int \left(\frac{1}{R} \frac{dR}{d\theta} + \mu \right) d\theta = -\int \frac{1}{R} \frac{dR}{d\theta} d\theta - \int \mu d\theta$$

$$-\int \alpha d\theta = -\int \frac{dR}{R} - \mu \int d\theta = -\ln R - \mu\theta$$

Therefore

$$N_{\theta} = Ae^{-(\ln R + \mu\theta)} = Ae^{-\ln R} e^{-\mu\theta}$$

Note that,

$$e^{-\ln R} = \frac{1}{e^{\ln R}}$$

and for any x,

$$x = \ln e^x$$

thus if

$$y = e^{\ln R}$$

$$\ln y = \ln R \quad \therefore \quad y = R \implies e^{-\ln R} = \frac{1}{R}$$

therefore (7) becomes,

$$\boxed{N_{\theta} = \frac{A}{R} e^{-\mu\theta}} \quad (8)$$

From Figure A-2 assuming that the portion a-b is a spherical membrane we have,

$$(a) \quad \theta = 0, \quad N_{\theta} = N_{\phi} = \frac{P_0 r_0}{2}, \quad R = R_0$$

$$\therefore \quad \frac{P_0 r_0}{2} = \frac{A}{R_0} \implies A = \frac{P_0 r_0 R_0}{2}$$

Thus (8) becomes

$$\boxed{N_{\theta} = \frac{P_0 r_0 R_0}{2R} e^{-\mu\theta}}$$

where $R = R_0 + r \sin \phi - r \sin (\phi - \theta)$ (see Figure A-2).

Recalling equation (2) and adding the normal pressure, P_0 , we get

$$P_r = \frac{N_{\theta}}{r} + P_0 = \frac{P_0 r_0 R_0}{2R} e^{-\mu\theta} + P_0$$

$$P_r = P_0 \left(\frac{R_0 r_0}{2Rr} \right) e^{-\mu\theta} + P_0$$

$$P_r = P_0 \left[1 + \left(\frac{R_0 r_0}{2Rr} \right) e^{-\mu\theta} \right]$$

and from (3) we get,

$$P_\theta = \mu P_0 \left[1 + \left(\frac{R_0 r_0}{2Rr} \right) e^{-\mu\theta} \right]$$

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