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Collapse Pressure of Oval Coiled Tubing

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Introduction

Coiled Tubing (CT) is sometimes used in applications where the pressure outside the CT may be higher than the pressure inside the CT. These applications include operations in high pressure wells[1] and reverse circulation operations where a fluid is pumped down the annulus and returns are taken up through the CT. If the difference between the internal and external pressures becomes too large, the CT will collapse. CT collapse could lead to serious well control problems.

During its life CT becomes oval due to bending around the reel and over the gooseneck. This ovality reduces the collapse pressure of the tubing. The pressure and tension limits for CT were analyzed in reference 2. The need for further work to understand the affect of ovality on the collapse pressure of CT was mentioned and is the purpose of this paper.

First an analysis was made to develop an analytical method for calculating the collapse pressure of an oval tube. Then testing was performed to validate this method.

Analytical Formulation

The axial stress, hoop stress and radial stress are the three principle stresses in the CT. These stresses are described and defined by equations in reference 2.

References and figures at end of paper.

Assumptions

This analysis assumes the CT is a straight oval tube. For the tube to become oval, it had to be plastically deformed. For it to collapse, it will obviously have to be plastically deformed further. Plastic hinges[3] at the major and minor axis of the oval are assumed to have stress distributions as shown in Figure 1 just before the tubing collapses. Through most of the wall thickness, the stress is assumed to be at the yield stress, either in compression or in tension (σ_{hc} and σ_{ht}). There will be an elastic transition area in the wall thickness where the stress is less than the yield stress. For this analysis the plastic hinge stress distribution was approximated as a square waveform, shown in Figure 2, which ignores this transition area. This approximation assumes rigid perfectly plastic material flow with all of the wall material at the yield stress.

For purposes of this analysis, ovality is defined as:

$$\begin{aligned}\%Ovality &= \left[\frac{MajorDiameter}{MinorDiameter} - 1\right]100 \\ &= \left[\frac{r_{oA}}{r_{oB}} - 1\right]100\end{aligned} \quad (1)$$

The ovality of the CT that is measured before the external pressure is applied is different from the ovality of the CT just before it will collapse. The external pressure will increase the ovality. This increase in ovality causes both the tensile and compressive strains at the plastic hinges, which in turn cause the stress distribution discussed above. This analysis ignores this change in ovality by assuming that the ovality measured before external pressure is applied is the same as the ovality just before collapse.

Both of these assumptions will tend to make the calculated collapse pressure higher than the actual collapse pressure. We would have preferred an analysis which would give a conservative collapse pressure, but this was not possible with these assumptions.

Hoop Yield Stresses

The yield stresses in the hoop direction depend on the radial and axial stresses. The axial stress equations are given in reference 2. The radial stress is the smallest of the three principle stresses and is often ignored. For simplicity, this analysis assumes:

$$\sigma_r = -P_i \tag{2}$$

The Von Mises Yield Criterion[4] given in equation 18 of reference 2 is:

$$2\sigma_y^2 = (\sigma_h - \sigma_r)^2 + (\sigma_h - \sigma_a)^2 + (\sigma_a - \sigma_r)^2 \tag{3}$$

Substituting equation 2 into equation 3 and solving for σ_h yields:

$$\sigma_h = \frac{\sigma_a - P_i}{2} \pm \sqrt{\sigma_y^2 - 0.75(\sigma_a - P_i)^2} \tag{4}$$

or:

$$\sigma_{hc} = \frac{\sigma_a - P_i}{2} - \sqrt{\sigma_y^2 - 0.75(\sigma_a - P_i)^2} \tag{5}$$

and:

$$\sigma_{ht} = \frac{\sigma_a - P_i}{2} + \sqrt{\sigma_y^2 - 0.75(\sigma_a - P_i)^2} \tag{6}$$

The difference between the tensile yield hoop stress (σ_{ht}) and the compressive yield hoop stress (σ_{hc}):

$$\Delta\sigma_h = \sigma_{ht} - \sigma_{hc} = 2\sqrt{\sigma_y^2 - 0.75(\sigma_a - P_i)^2} \tag{7}$$

Equilibrium Equations for Square Waveform

Summing forces in the A and B directions for Figure 2, and setting the summations equal to zero:

$$P_o r_{oA} - P_i r_{iA} + \sigma_{ht} X_A - \sigma_{hc}(X_A - t) = 0 \tag{8}$$

$$P_o r_{oB} - P_i r_{iB} + \sigma_{ht} X_B - \sigma_{hc}(X_B - t) = 0 \tag{9}$$

Solving these equations for X_A and X_B:

$$X_A = \frac{P_i r_{iA} - P_o r_{oA} - \sigma_{hc} t}{\Delta\sigma_h} \tag{10}$$

$$X_B = \frac{P_i r_{iB} - P_o r_{oB} - \sigma_{hc} t}{\Delta\sigma_h} \tag{11}$$

Summing the moments about the origin in Figure 2, and setting it equal to zero:

$$\begin{aligned} &P_o(r_{oB}^2 - r_{oA}^2) + P_i(r_{iA}^2 - r_{iB}^2) + \\ &2\sigma_{ht}\Gamma - 2\sigma_{hc}[\Gamma + t(r_{oA} - r_{oB})] = 0 \end{aligned} \tag{12}$$

$$\Gamma = \frac{X_A^2}{2} + \frac{X_B^2}{2} - X_A r_{oA} + X_B r_{iB} \tag{13}$$

Substituting equations 10 and 11 into 12:

$$\alpha P_o^2 + \beta P_o + \gamma = 0 \tag{14}$$

$$\alpha = \frac{r_{oA}^2 + r_{oB}^2}{\Delta\sigma_h} \tag{15}$$

$$\beta = r_{oA}^2 + r_{oB}^2 - \frac{2P_i}{\Delta\sigma_h}(r_{oA}r_{iA} + r_{oB}r_{iB}) - 2r_{oB}r_{iB} + \frac{2t\sigma_{hc}}{\Delta\sigma_h}(r_{oA} + r_{oB}) \tag{16}$$

$$\gamma = \frac{P_i^2}{\Delta\sigma_h}(r_{iA}^2 + r_{iB}^2) - \frac{2tp_i\sigma_{hc}}{\Delta\sigma_h}(r_{iA} + r_{iB}) + P_i(r_{iB}^2 - r_{iA}^2 - 2tr_{iA}) + 2t^2\sigma_{hc}\left[\frac{\sigma_{hc}}{\Delta\sigma_h} + 1\right] \tag{17}$$

Solving equation 14 for positive values of P_0 yields:

$$P_o = \frac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha} \tag{18}$$

P_0 is the external pressure at which the tube will collapse based on the square waveform assumptions.

Experimental Validation Testing

Test Procedure

Sample lengths of 1.5" diameter CT with a 0.10" wall thickness and 70,000 psi nominal yield material were used. These lengths were taken from new CT that had been spooled on a reel. They were straightened as much as possible and a 12" section of each sample was ovaled by squeezing it between two flat plates. In some cases the longitudinal seam weld was placed at a major axis hinge, and in other cases this weld was placed at the minor axis hinge. A pull test indicated that the yield stress in the axial direction was 75,000 psi. No test was performed to determine the actual yield stress in the hoop direction.

Each sample was tested by placing it in a fixture which is shown in Figure 3. Both ends of the sample were free to move through '0'-ring seals at either end of the test fixture. External pressure was applied to the CT by pumping water through the high pressure pump line. In two of the cases an axial tensile load of 20,000 lbf was applied to the CT by placing the CT and the test fixture in a tensile load cell. The external pressure was increased gradually until collapse occurred. The resulting collapse pressures are given in Table 1.

In each case there was minimal deformation of the sample before collapse, giving little or no warning that collapse was imminent. In most cases all four plastic hinges were formed so that the cross section of the collapsed section formed a shape similar to an 8. In the case with the least ovality (nearly round) only three of the hinges formed so that the cross section of the collapsed section formed a "canoe" like cross section.

Comparison of Results

Figure 4 shows the calculated results using equation 18 compared with the measured results from Table 1. Since the actual yield stress in the hoop direction is not known, the calculate results are shown for both 70,000 psi and 75,000 psi. As was expected due to the assumptions, the calculated collapse pressures were higher than the actual collapse pressures. Unexpectedly, in the two cases where 20,000 lbf axial tension was applied to the CT the calculated collapse pressure is significantly below the measured collapse pressure.

Conclusions

Ovality and axial tensile force significantly reduce the collapse pressure of CT. The ovality of the CT should be monitored and the CT should be replaced when an ovality limit is reached (5% is suggested).

A method of calculating the collapse pressure for oval CT has been presented which yields a collapse pressure which is typically higher than the actual collapse pressure. In practice this calculation should be used with the minimum yield stress and minimum possible wall thickness. The calculated collapse pressure should then be multiplied by a factor of safety (70% is suggested) to account for the assumptions built into the calculation and to allow a safety margin.

Nomenclature

P_i Pressure inside the tube
P_o Pressure outside the tube which causes collapse
r_{iA} Inside radius of the tube at the major axis
r_{iB} Inside radius of the tube at the minor axis
r_{oA} Outside radius of the tube at the major axis
r_{oB} Outside radius of the tube at the minor axis
t Wall thickness of the tube
X_A Width of section with positive stress at major axis
X_B Width of section with positive stress at minor axis
α Constant given in equation 15
β Constant given in equation 16
Γ Constant given in equation 13
γ Constant given in equation 17
$\Delta\sigma_h$ Difference between hoop yield stresses
σ_a Axial stress
σ_h Hoop stress
σ_{hc} Compressive yield stress in hoop direction
σ_{ht} Tensile yield stress in hoop direction
σ_r Radial stress
σ_y Yield stress of the tube material

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References

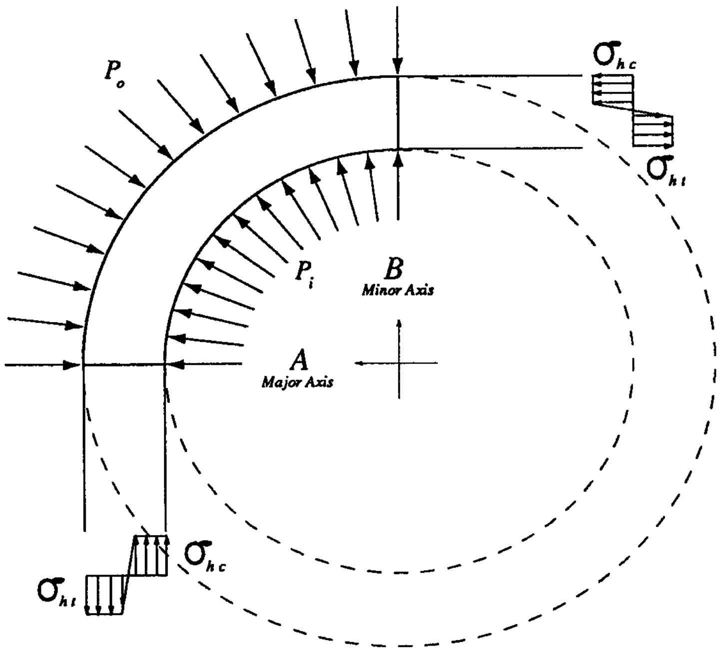
1) Newman, K.R., Allcorn, M.G.: "Coiled Tubing in High Pressure Wells," SPE paper 24793, SPE Annual Technical Conference, Washington D.C., October 1992.

2) Newman, K.R.: "Coiled-Tubing Pressure and Tension Limits," SPE paper 23131, Offshore Europe Conference, Aberdeen, September 1991.

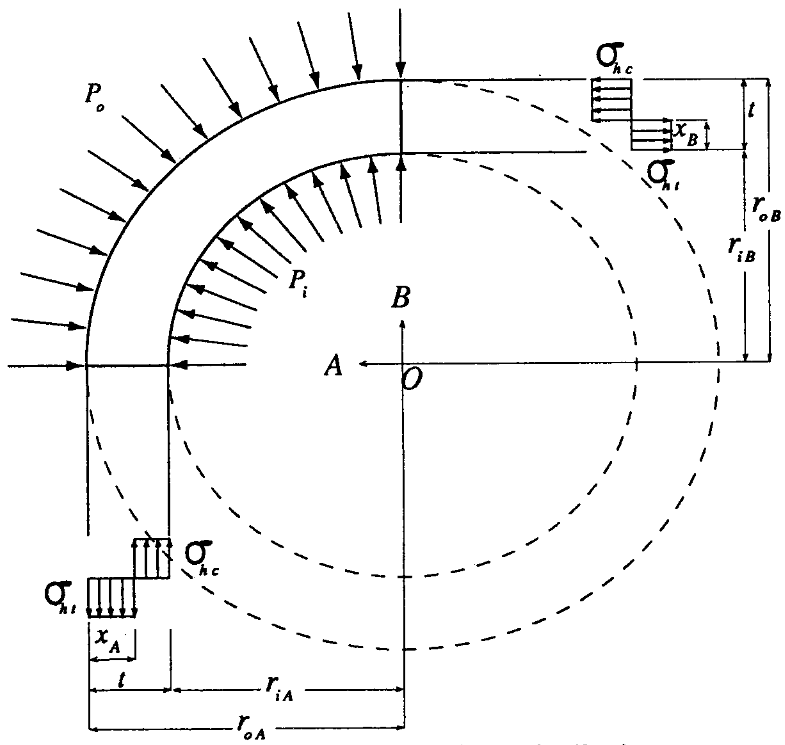
3) Hodge, P.G.: Plastic Analysis of Structures, McGraw-Hill, 1959.

Table 1
Comparison of Measured and Calculated Collapse Pressures

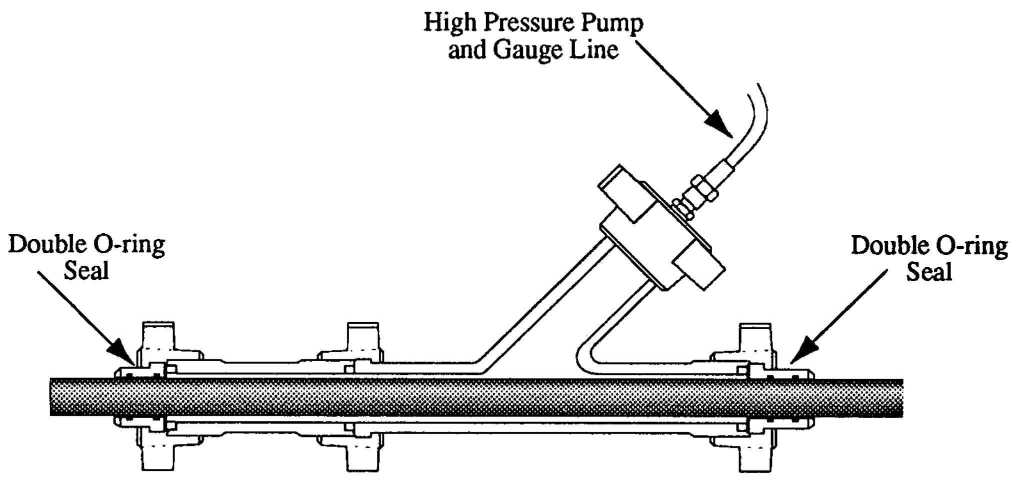
Ovality (%)	Axial Force (lbf)	Measured Collapse Pressure (psi)	Calculated Collapse Pressure [70,000 psi yield] (psi)	% Diff
0.4%	0	8,130	9,076	11.6%
2.7%	0	7,740	7,752	0.2%
2.7%	20,000	5,090	3,916	-23.1%
4.4%	0	6,690	6,931	3.6%
4.8%	0	6,310	6,757	7.1%
7.2%	0	5,760	5,831	1.2%
7.4%	20,000	4,180	2,998	-28.3%
9.3%	0	5,160	5,175	2.9%
9.9%	0	4,770	5,010	5.0%
12.9%	0	4,260	4,305	1.1%



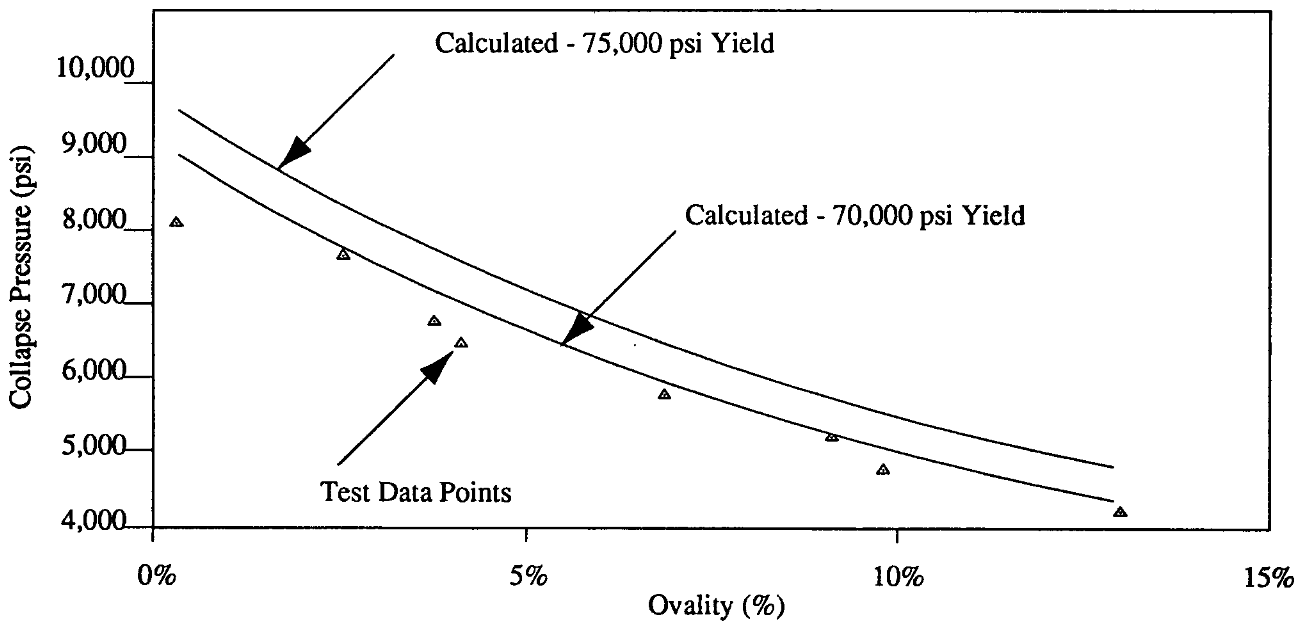
Assumed Plastic Hinge Stress Distribution
Figure 1



Square Waveform Plastic Hinge Distribution
Figure 2



Collapse Test Fixture
Figure 3



Collapse Pressure versus Ovality
Figure 4