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Evaluation of Circumferential Flaw Limit Load Conditions: Kewaunee Feedwater Line

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A pin-hole indication has been found in one of the sockolet to feedwater line welds at Kewaunee, and the purpose of this note is to discuss the flaw tolerance of the weld region, in order to establish the margins of safety that exist in this region.

The calculations were carried out using established procedures to predict the ductile limit load of the region, as a function of flaw size. The feedwater line operates at a nominal temperature of 440F, so the mode of possible failure is clearly ductile. An enormous data base of flawed pipe experimental results exists to support this conclusion. Also, a calculation of the ASME Code screening criteria was made, and the value of K-R/S-R was found to be 0.195 for the actual flaw in the feedwater line, putting the failure mode as ductile limit load, since the value is below 0.2. The loads on the sockolet were too low to make a similar calculation for the actual flaw length. Additional calculations were done for continuous part-through circumferential flaws in both the feedwater line and the sockolet, and the values of the K-R/S-R ratio were found to be .18 and .184 respectively. These calculations used actual fracture toughness J-R curves for A106B feedwater piping of similar vintage, and were for flaw depths of 75 % of the wall thickness, showing that the failure mode will clearly be ductile.

Two fracture calculations were performed, one considering the flaw to be in the sockolet itself, and the second considering the flaw to be in the feedwater pipe. For each location, calculations were done considering the applied forces and moments from the stress analysis of record for the piping system. As will be seen, the results for all cases showed that a very large flaw would be necessary to cause a limit load failure. The methods used in these calculations are from reference 1, and the derivation of the limit moment expressions is shown in detail in Appendix A of this report.

Sockolet. The sockolet has an outside diameter of 1.75 inches, and the throat of the attachment weld was found to be no smaller than 0.56 inches, making this a very strong structure. The thickness of the sockolet itself is 0.25 inches, and this value was conservatively used. The sockolet is made of 106B carbon steel. Results of the evaluation showed that a through-wall circumferential flaw would be necessary to cause a limit load failure. The calculations show that if the pipe had a through-wall flaw as long as 70% of the circumference of the weld, the limit load pressure would still be 10,200 psi, a factor of safety of more than 8.5 over the maximum operating pressure of 1200 psi. A best estimate of the limit load pressure for the flaw as it exists is 17,200 psi, for a safety margin of nearly 14.

The detailed line loadings were obtained from the analysis of record for the sockolet line, and the results of the calculation of the limit load moment for this line is shown in figure 1. The results, as expected, show large moments are necessary to fail the line. The actual maximum load from the analysis of record was applied to the line, as seen in the figure. For a flaw which is not a through-wall flaw, a separate analysis was done, and the results for the same loading are shown in figure 2. Here we see that a flaw with a depth of 85 percent of the wall is needed for failure, assuming that the flaw extends all the way around the pipe.

Feedwater line. The feedwater line at this location has an outside diameter of 16 inches, and a wall thickness of 1.4 inches, and is made of 106B carbon steel. Results of the evaluation showed that the critical length for a through-wall circumferential flaw is 25 inches, or 50% of the pipe circumference. This corresponds to the maximum operating pressure of 1200 psi. The nominal operating pressure is 700 psi under normal conditions. A conservative estimate of the limit load pressure for the existing flaw is 9890 psi.

The complete piping analysis is also available for the feedwater line, and so a range of calculations were carried out for the three different loading cases considered in the original design (ANSI B31.1). These load cases are shown in Table 1, where it may be seen that there are no specific load criteria for level C conditions. We have considered each of the other conditions, and the results are given in the figures listed below:

Level A	P + DW + TH	Figure 3
Level B	P + DW + OBE	Figure 4
Level D	P + DW + DBE	Figure 5

The equivalent results for through-wall flaws are shown in figures 6,7,and 8, which are also attached.

Therefore it may be concluded that there is a very large margin against failure in this region, in general. Specific margins have been developed for both locations, and are shown below. Margins are provided on both flaw size and limit moment. These were calculated based on the conservative charcterization of the existing flaw as through wall with a length of 0.1 inches.

Condition	Margin on flaw size	Margin on limit moment
*********** Sockolet *********		
A		
B		
C		
D	30	43
*********** Feedwater Line ******		
A	249	27
B	232	13.0
C		
D	205	6.5

References

1. Bamford, W.H. and Begley, J.A., "Techniques for Evaluating the Flaw Tolerance of Reactor Coolant Piping". Presented at the 1976 PVP Conference, Paper 76-pvp-48.

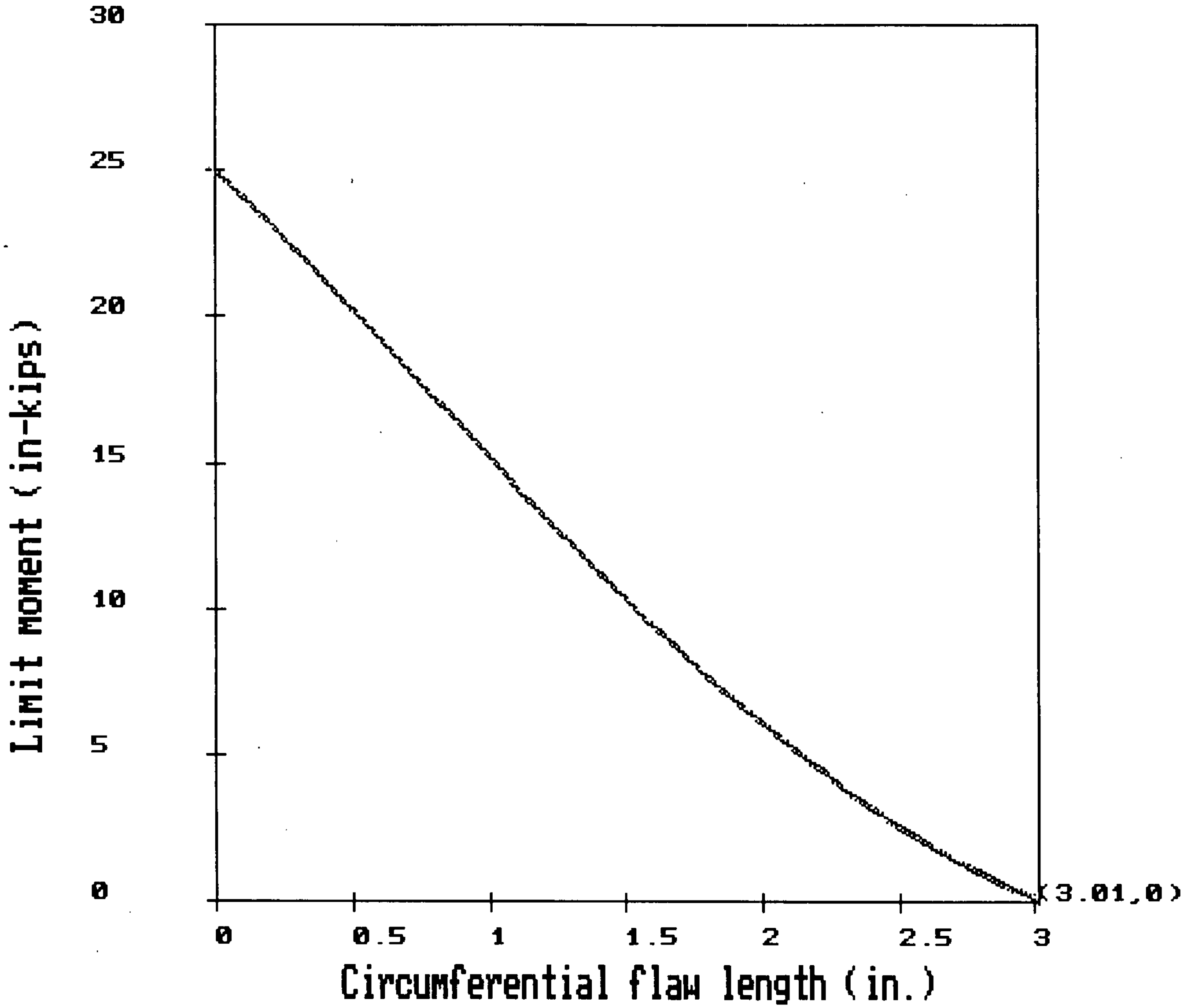
Revision 1

Revision 1 of this report was prepared to document several items which did not appear in the original report. The analysis of record was obtained for the sockolet line, and the results were included, as well as the calculation of the screening criterion for the ductile failure mode.

Also the flow properties of 106B piping were revised to use the lower bound properties of the ASME Code. Also, the thickness of the sockolet weld region was made smaller, set equal to the thickness of the sockolet itself(.25"), rather than the weld throat measurement(.625"). This also adds conservatism to the results.

Table 1 : ANSI B31.1 Stress Limits

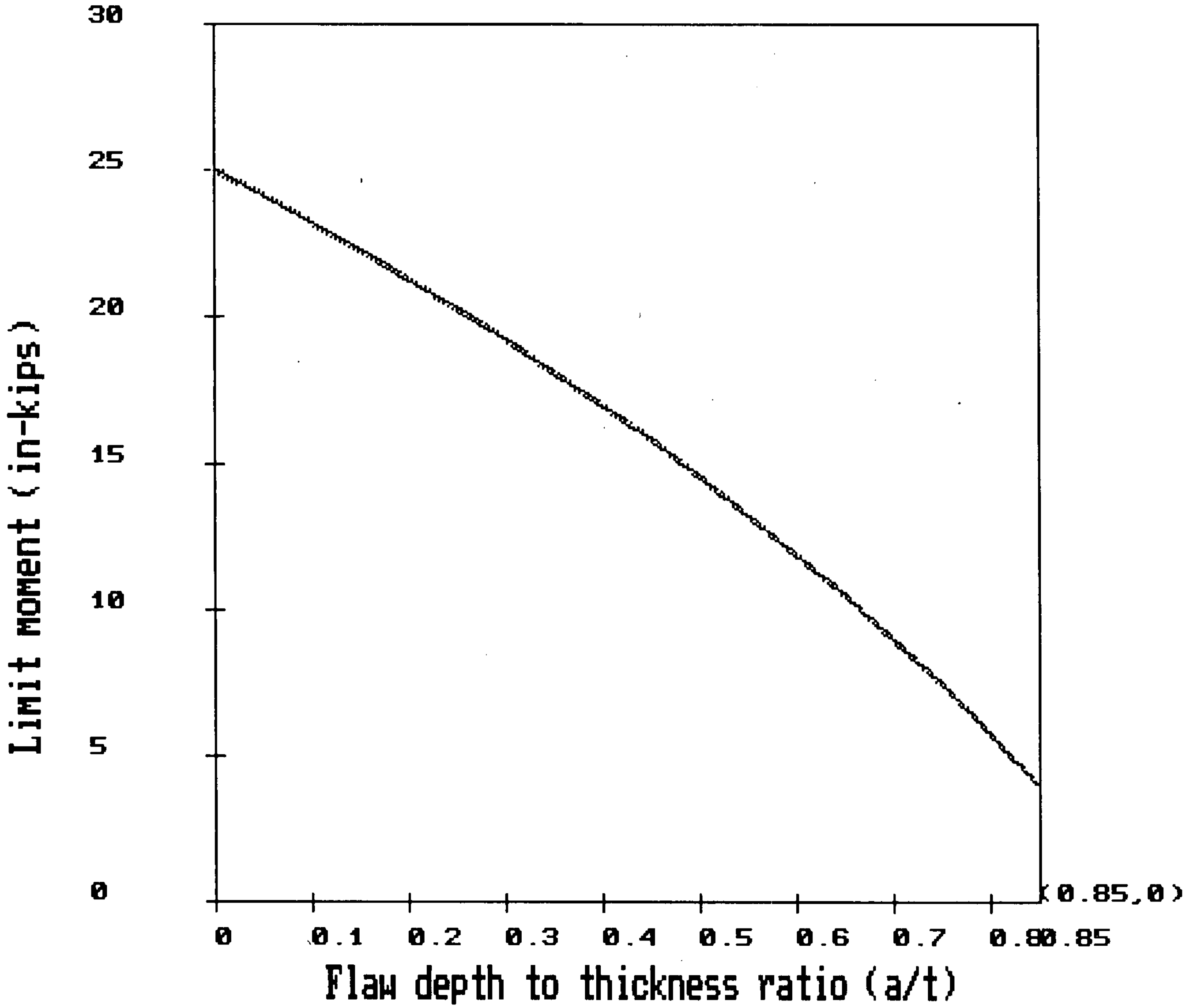
Service Level	ANSI B31.1 1973	Stress Category	Load Combination	Allowable stress	Carbon Steel A106B
Level A	102.3.2D 102.3.2C 102.3.2D	P_m+P_b P_b P_m+P_b	P+DW TH P+DW+TH	S_h S_A S_h+S_A	15.0 ksi 22.5 ksi 37.5 ksi
Level B	102.3.3A 102.3.2C 102.3.2D	P_m+P_b P_b P_m+P_b	P+DW+OBE TH P+DW+TH	$1.2S_h$ S_A S_h+S_A	18.0 ksi 22.5 ksi 37.5 ksi
Level C			N/A	$1.8S_h$	27.0 ksi
Level D		P_m+P_b	P+DW+DBE	$2.4S_h$	36.0 ksi



OD= 1.750 Thk=.250 P=1.20 F=.140E-01 Torque=.410E-01

WEP Sockolet -Dounding Loads

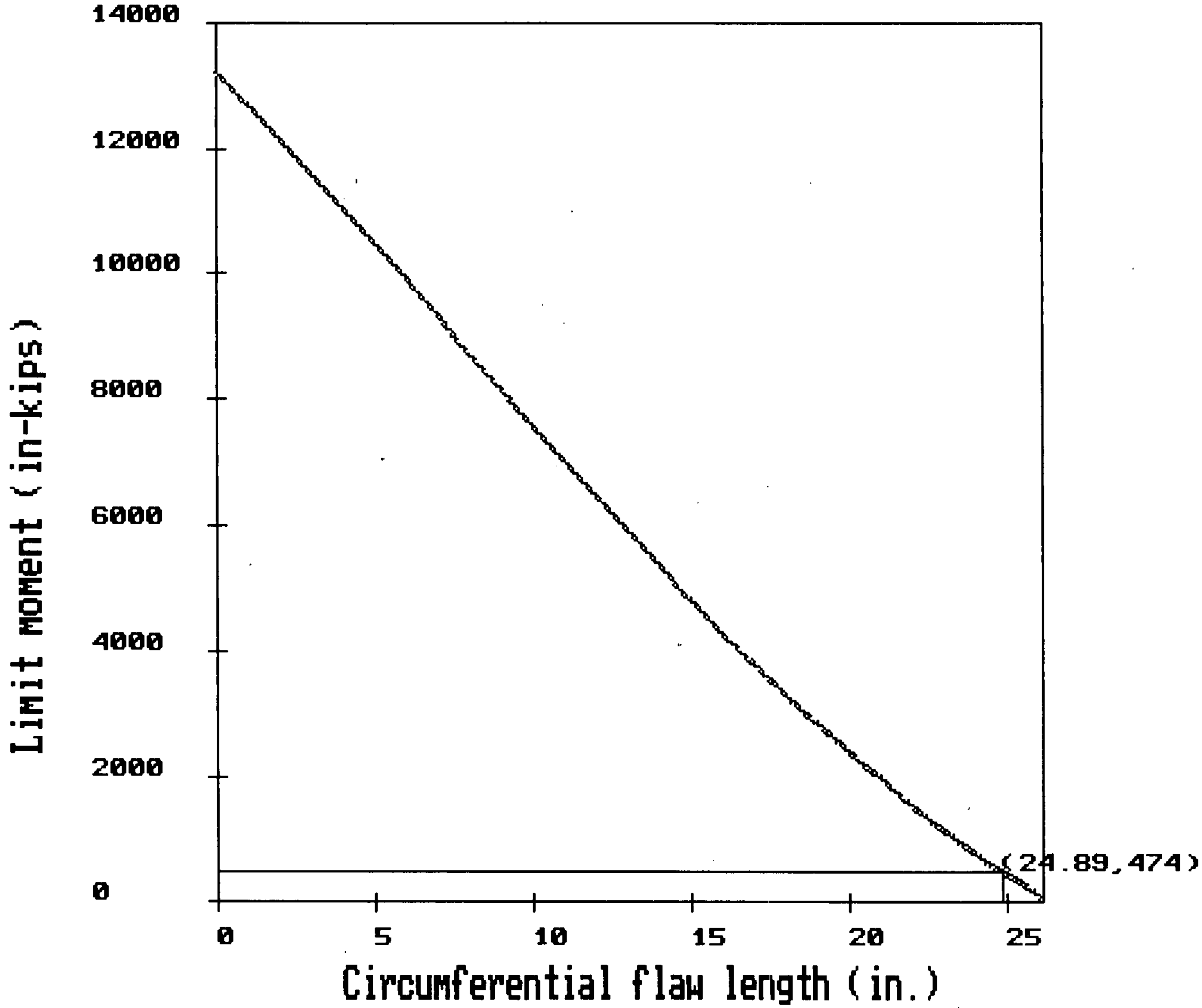
Figure 1



OD= 1.750 Thk=.250 P=1.20 F=.140E-01 Torque=.410E-01

WEP Sockolet -Bounding Loads

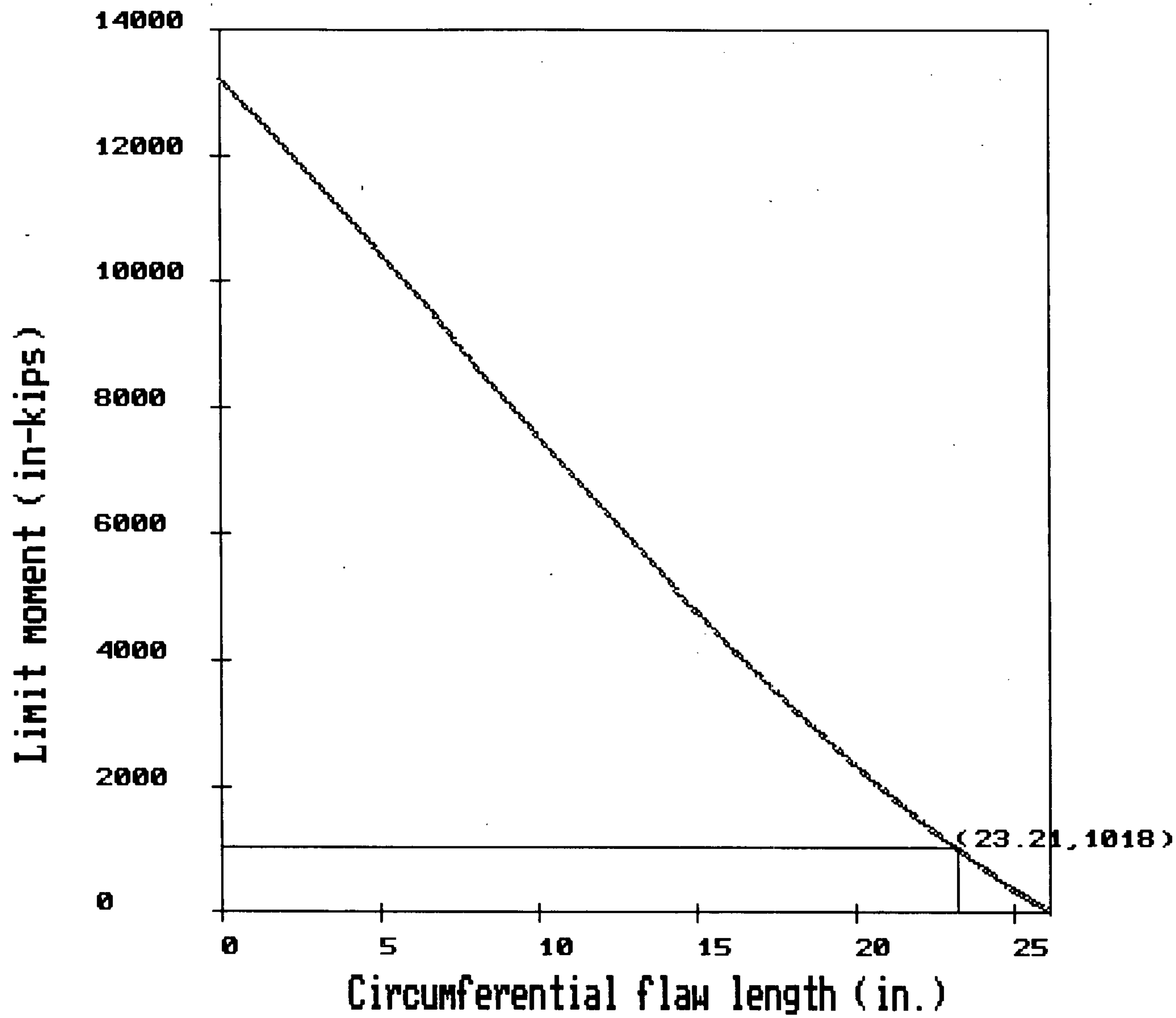
Figure 2



OD=16.000 Thk=1.40 P=1.20 F=1.40 Torque=53.0

WEP FW Line - Normal

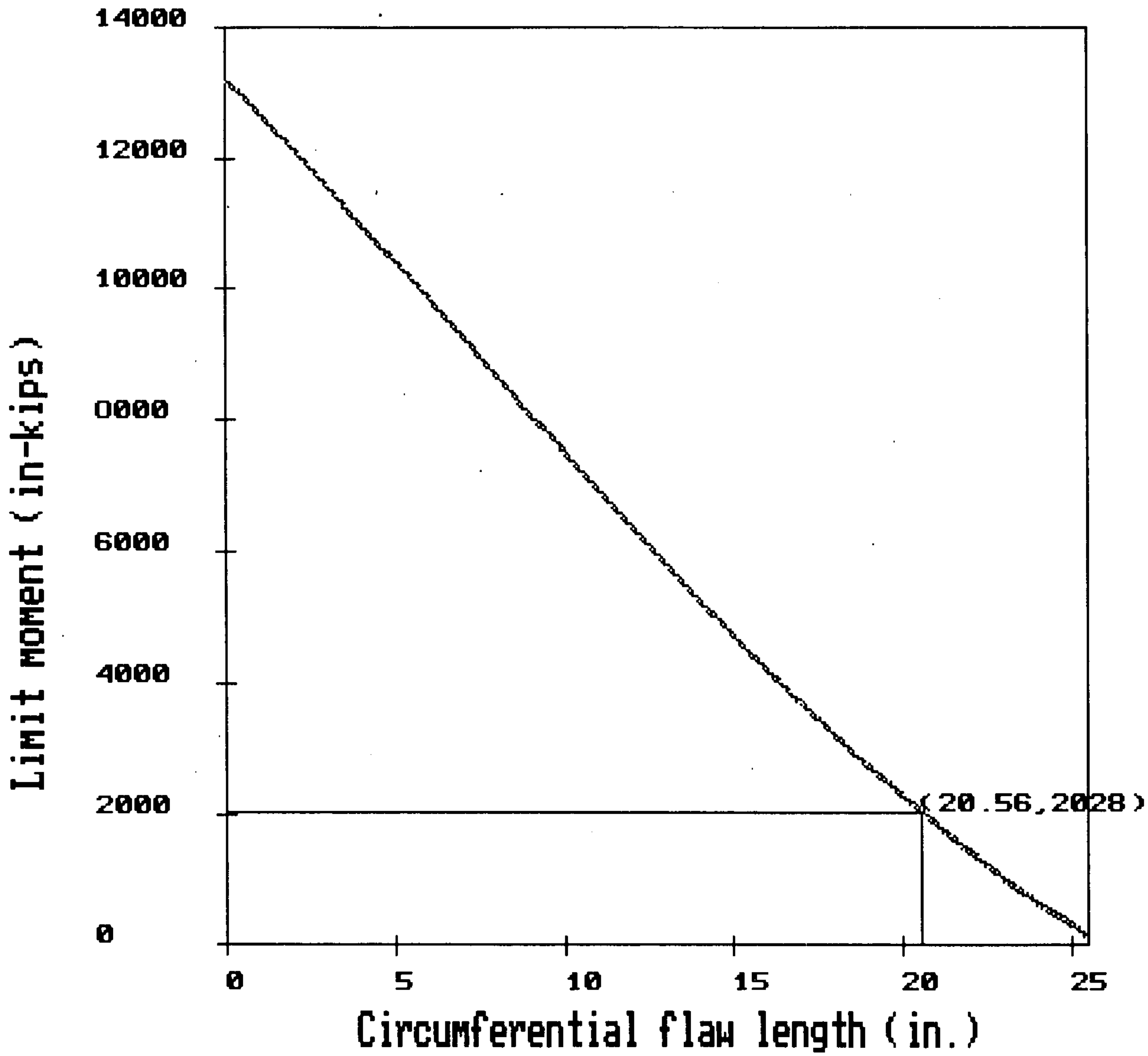
Figure 3



OD=16.000 Thk=1.40 P=1.20 F=10.8 Torque=98.2

WEP FW Line - DW + OBE

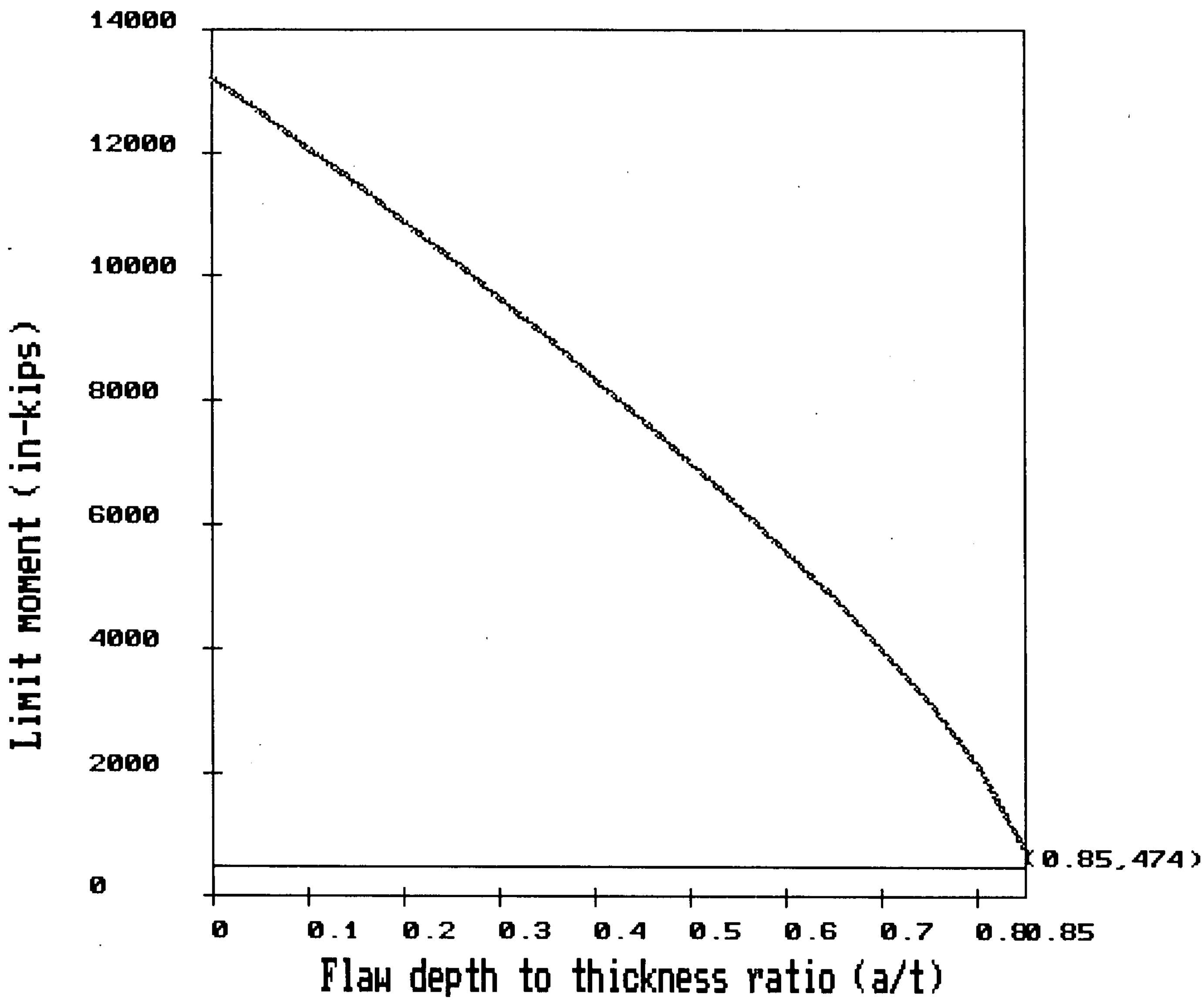
Figure 4.



OD=16.000 Thk=1.40 P=1.20 F=21.1 Torque=143.

WEP FW Line - DW + DDE

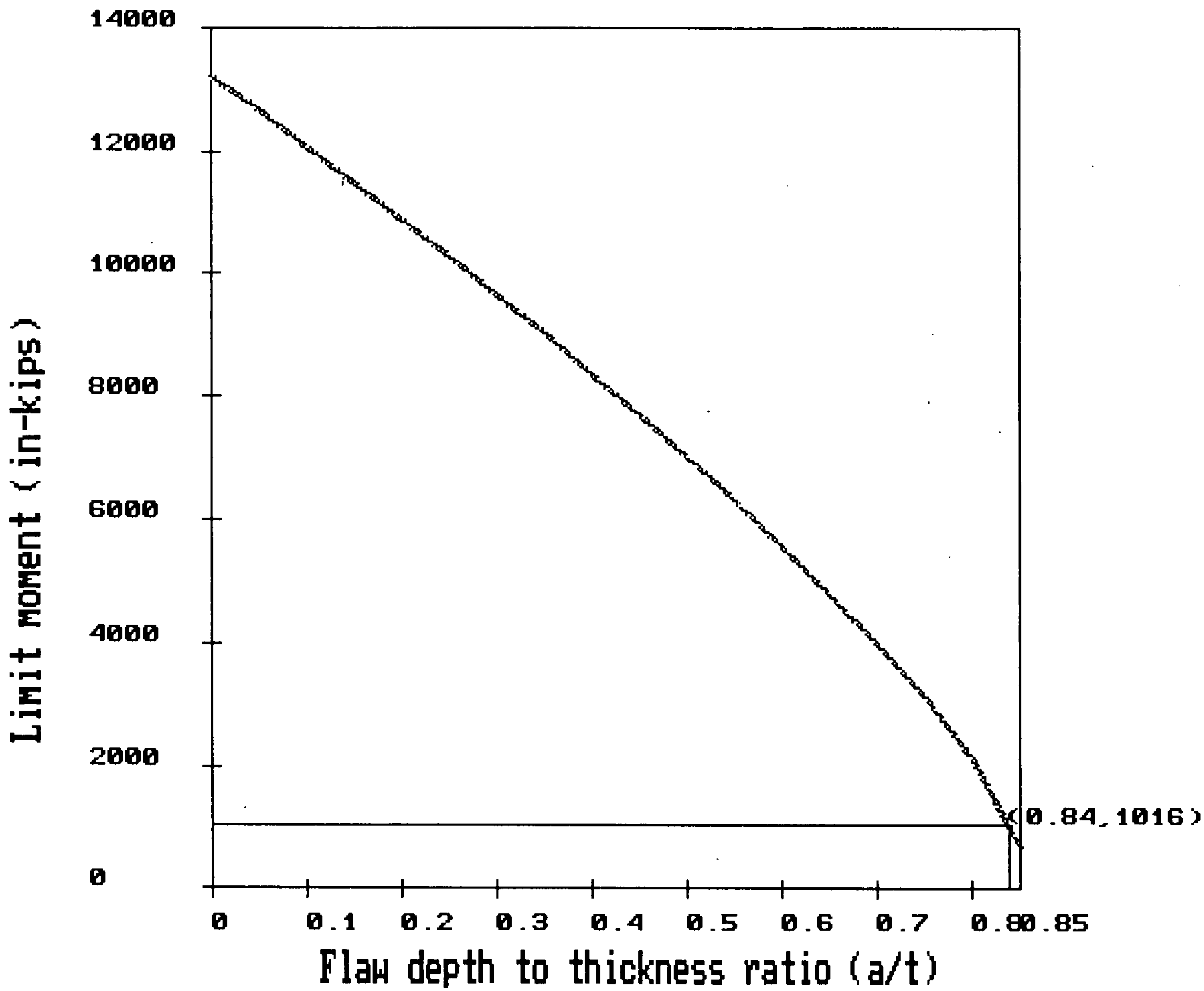
Figure 5



OD=16.000 Thk=1.40 P=1.20 F=1.40 Torque=53.0

WEP FW Line - Normal

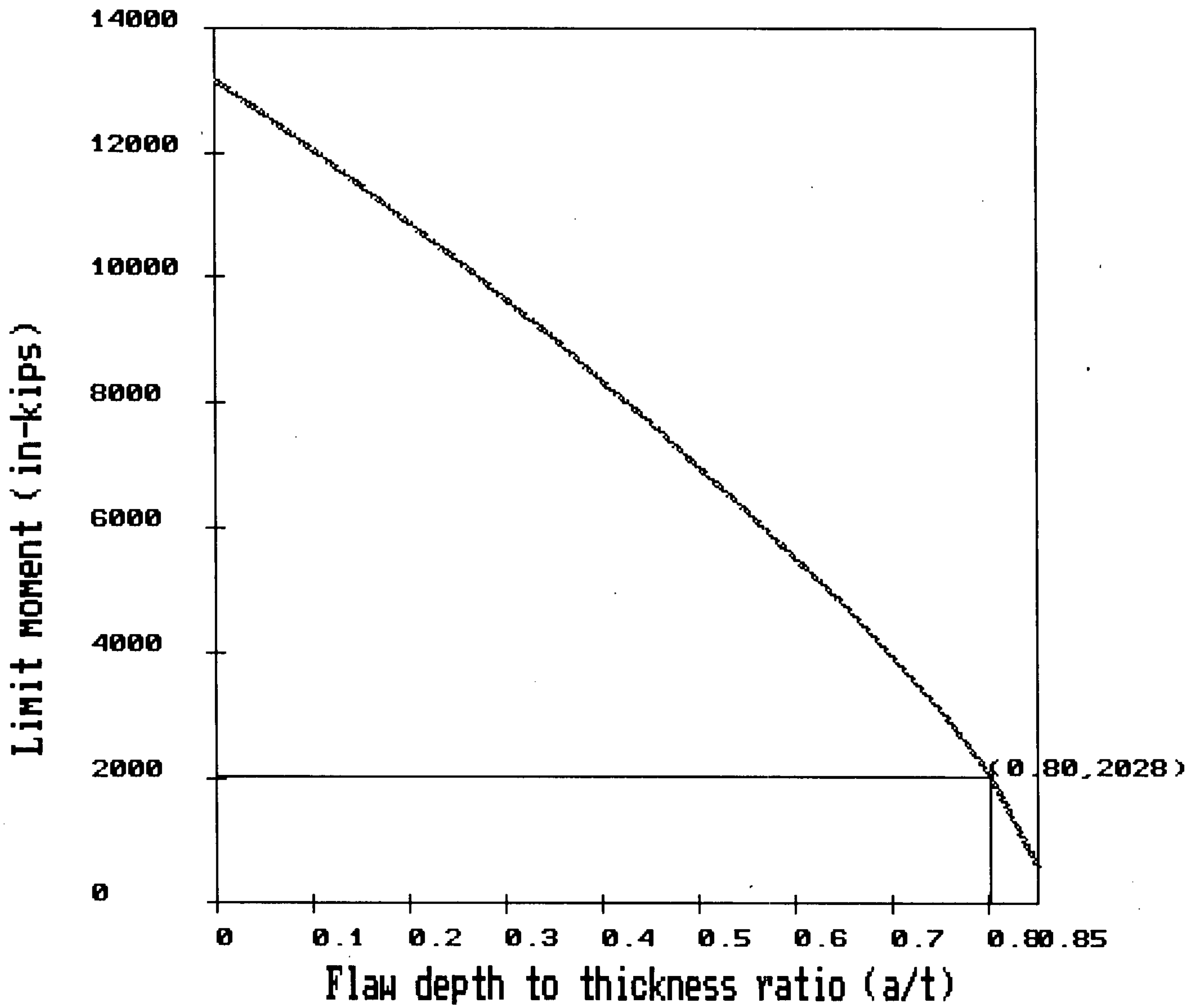
Figure 6



OD=16.000 Thk=1.40 P=1.20 F=10.6 Torque=98.2

WEP FW Line - DW + ODE

Figure 7



OD=16.000 Thk=1.40 P=1.20 F=21.1 Torque=143.

WEP FW Line - DW + DDE

Figure 8

APPENDIX A

LIMIT ANALYSIS OF A CIRCUMFERENTIAL THROUGH WALL CRACKED PIPE SUBJECT TO MULTIPLE LOADS

A-1 INTRODUCTION

Limit load solutions have been published for thin pipes containing through wall circumferential cracks. These solutions have been presented for various loading conditions. In this appendix the lower bound limit load solution will be presented for a combined loading condition consisting of a bending moment, an axial load, an internal pressure, and a torsional moment. The limit solution for all of these loading components acting simultaneously is not available in the literature. The solution is obtained following the approach that Larson et al.[1] used in the analysis of an uncracked pipe subject to the same multiple loading conditions.

A-2 SOLUTION

A thin walled pipe of mean radius R and wall thickness t, contains a through-wall circumferential crack of total angular length 2α (Figure A-1). The cracked cross-section of the pipe is subject to a bending moment M (about the y-axis), and axial load N, an internal pressure p, and a torsional moment T. The bending moment is assumed to be acting about the y-axis and the cross section is analytically divided into region 1 and 2 (Figure A-1). The stress state of the cracked cross-section consists of the hoop stress, axial stress, and shear stress. The hoop stress (σ_Θ) and shear stress ($\tau_{r\Theta}$) are constant on the uncracked portion of the circumference. The axial stress is uniform tension (σ_{zT}) in region 1 and uniform compression (σ_{zC}) in region 2. Region 1 is above the neutral axis (N.A.) of the cross section and region 2 is below the neutral axis. The position of the neutral axis is geometrically defined by the angle Θ_o.

Dimensionless load parameters to be used in the analysis are defined below:

$m = M/M_o$

$n_z = N/N_o$

$n_\Theta = p/p_o$

$q = T/T_o$

where $M_o = 4tR^2\sigma_{YS}$, $N_o = 2\pi tR\sigma_{YS}$, $p_o = t\sigma_{YS}/R$, $T_o = 2\pi R^2 t\sigma_{YS}/\sqrt{3}$, and σ_{YS} is the uniaxial yield stress. Each of the normalizing loads (M_o, N_o, p_o, T_o) are the respective limit loads when only the load component that is being normalized is operating on the uncracked pipe cross-section.

The dimensionless load parameters can be related to the stress components by integrating the stresses over the cross-section (Figure A-1).

$$m = [(\sigma_{zT} - \sigma_{zC}) \cos\Theta_o - \sigma_{zT} \sin \alpha]/(2\sigma_{YS}) \quad \text{(A-1)}$$

$$n_z = [(\pi + 2\Theta_o - 2\alpha)\, \sigma_{zT} + (\pi - 2\Theta_o)\, \sigma_{zC}]/(2\pi\, \sigma_{YS}) \quad \text{(A-2)}$$

$$n_\lambda = \sigma_\Theta/\sigma_{YS} \quad \text{(A-3)}$$

$$q = \sqrt{3}(\pi - \alpha)\, t\tau_{z\Theta}/(\pi\, \sigma_{YS}) \quad \text{(A-4)}$$

Assuming that the pipe material yields according to the von Mises yield criteria, the yield relationship between the tube stress components takes the form

$$\sigma_{YS} = [\sigma_z^2 + \sigma_\Theta^2 - \sigma_z\, \sigma_\Theta + 3t\tau_{z\Theta}^2]^{1/2} \quad \text{(A-5)}$$

where σ_z represents σ_{zT} in region 1 and σ_{zC} in region 2. For a given set of loading conditions there are three unspecified parameters (σ_{zT}, σ_{zC}, and Θ_o). By using equations (A-1) and (A-2), which are equilibrium relationships and equation (A-5), the yield criteria, these parameters can be determined and a lower bound on the yield locus can be obtained in terms of the normalized load parameters. First equation (A-5) is rewritten in quadratic form for σ_z.

$$\sigma_z^2 - \sigma_\Theta \sigma_z + (\sigma_\Theta^2 + 3t\tau_{z\Theta}^2 - \sigma_{YS}^2) = 0 \qquad \text{(A-6)}$$

This equation is solved for σ_z, taking the positive root for σ_{zT} and the negative root for σ_{zC}. Using the relationships of equations (A-3) and (A-4), the solutions to equation (A-6) are:

$$\frac{\sigma_{zT}}{\sigma_{YS}} = \frac{n_\Theta}{2} + [1 - \frac{3}{4} n_\Theta^2 - (\frac{\pi}{\pi - \alpha})^2 q^2]^{1/2} \qquad \text{(A-7)}$$

$$\frac{\sigma_{zC}}{\sigma_{YS}} = \frac{n_\Theta}{2} + [1 - \frac{3}{4} n_\Theta^2 - (\frac{\pi}{\pi - \alpha})^2 q^2]^{1/2} \qquad \text{(A-8)}$$

Substituting equations (A-7) and (A-8) into equations (A-1) and (A-2) leads directly to the lower bound yield locus.

$$\lambda m^2 + (\frac{1}{2} \lambda \sin \alpha) n_\theta m + (\frac{1}{16} \lambda \sin^2\alpha + \frac{3}{4}) n_\Theta^2 + (\frac{\pi}{\pi - \alpha})^2 q^2 = 1 \qquad \text{(A-9)}$$

where

$$\lambda = (\cos\Theta_o - \sin \alpha)^{-2} \qquad \text{(A-10)}$$

and

$$\Theta_o = \frac{\pi n_z + \alpha[\frac{n_\Theta}{2} + (1 - \frac{3}{4} n_\Theta^2 - (\frac{\pi}{\pi - \alpha})^2 q^2)^{1/2}] - \frac{\pi}{4} n_\Theta}{2\ [1 - \frac{3}{4} n_\Theta^2 - (\frac{\pi}{\pi - \alpha})^2 q^2]^{1/2}} \qquad \text{(A-11)}$$

Equation (A-9) defines a lower bound on the yield surface in a load space defined by the four dimensionless load parameters (m, n_z, n_λ, and q).

For specific values of three of the four load parameters, assuming they define a condition inside the limit surface, the magnitude of the fourth parameter which will put the load condition right on the limit surface can be obtained from equation (A-9). For example letting m be the fourth parameter leads to the equation

$$m=(-\frac{1}{4}\sin\alpha)\, n_\Theta + [1-\frac{3}{4}n_\Theta^2 - (\frac{\pi}{\pi-\alpha})^2 q^2]^{1/2} (\cos\Theta_o - \frac{1}{2}\sin\alpha) \qquad \text{(A-12)}$$

where Θ_o is obtained from equation (A-11).

REFERENCES (Appendix A)

1. L. D. Larson, W. F. Stokey, and J. E. Panarelli, "Limit Analysis of a Thin-Walled Tube Under Internal Pressure, Bending Moment, Axial Force, and Torsion," Journal of Applied Mechanics, pp. 831-832, September 1974.

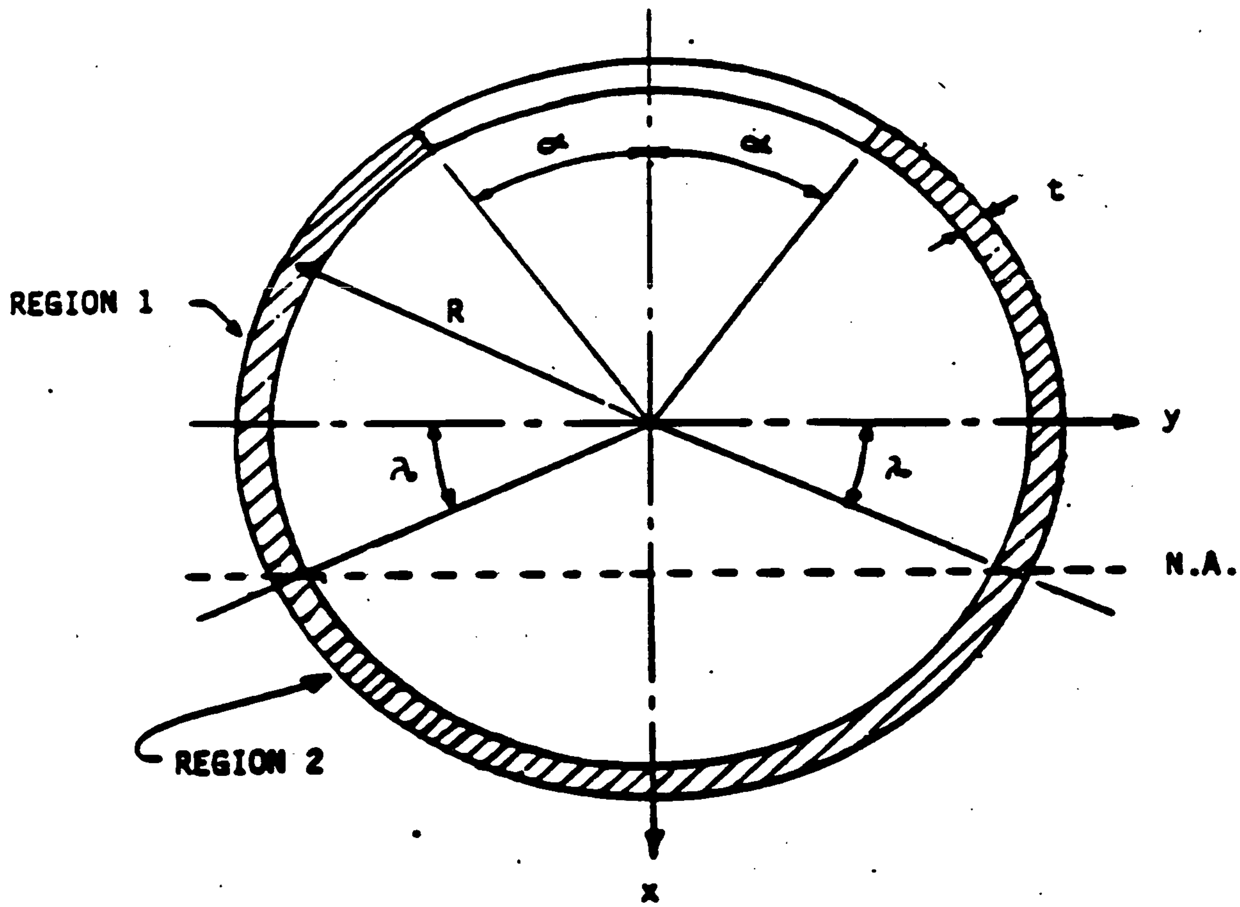


Figure A-1. Cross Section Of Pipe With A Through-Wall Circumferential Crack of Length 2α.