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TECHNICAL REPORT ARCCB-TR-95015

FATIGUE LIFE MEASUREMENTS AND ANALYSIS FOR OVERSTRAINED TUBES WITH EVACUATOR HOLES

JOHN H. UNDERWOOD
ANTHONY P. PARKER
DANIEL J. CORRIGAN
MICHAEL J. AUDINO

MARCH 1995

US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1995	Final

4. TITLE AND SUBTITLE
FATIGUE LIFE MEASUREMENTS AND ANALYSIS FOR OVERSTRAINED TUBES WITH EVACUATOR HOLES

5. FUNDING NUMBERS
AMCMS No. 6111.02.H611.1

6. AUTHOR(S)
John H. Underwood, Anthony P. Parker (University of Northumbria at Newcastle, UK), Daniel J. Corrigan, and Michael J. Audino

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-95015

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
To be presented at ASME Pressure Vessels and Piping Conference, Honolulu, Hawaii, 24-27 July 1995.
To be published in Proceedings of the Conference.

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

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Sections of cannon tubes with inner radius of 53, 60, and 78 mm were cycled from near zero to 100 to 300 MPa internal pressure until fatigue failure occurred. The failure locations were along 2-mm holes cut through the cannon wall at a 30° angle to the tube axis, for the purpose of evacuating combustion gases from the cannon after firing. The cannons had various amounts of autofrettage by overstraining, including 0, 30, 50, and 100 percent. The amount of overstrain affected both the initiation position of the fatigue crack along the evacuator hole and the measured fatigue life. Increasing the amount of overstrain moved the crack initiation from the tube inner radius toward a mid-wall position and significantly increased fatigue life.

Fracture mechanics and solid mechanics-based calculations of fatigue life were performed for comparison with the measured lives. The calculations gave a good description of the measured life, taking account of tube configuration, applied pressure, amount of overstrain, stress concentration of the hole, crack size and shape, material fatigue crack rate behavior and yield strength, and pressure in the hole and on the crack surfaces. As with measured fatigue life, the calculated life was significantly affected by the amount of autofrettage of the tube. The ratio of outer-to-inner radius of the tube and the presence of pressure in the evacuator hole also had substantial effects on the calculated fatigue life.

14. SUBJECT TERMS
Fatigue Life, Thick-Wall Cylinder, Residual Stress, Pressure Vessel, Stress Concentration

15. NUMBER OF PAGES
13

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

INTRODUCTION

Evacuator holes in a cannon tube are necessary but troublesome. They are required to expel combustion gases from the cannon tube, but their presence significantly reduces the fatigue life of the tube. The objective here is to compare measured and calculated fatigue lives for tubes with evacuator holes and thereby identify the configurational, material, and loading factors that most affect fatigue life. The measured fatigue lives were from sections of various cannon tubes tested to determine the safe fatigue life of the evacuator hole section of the tubes. These tests and results will be summarized first.

The calculations of fatigue life were based on recent stress and stress intensity analyses of pressurized autofrettaged tubes with evacuator holes (ref 1). The recent work included effects of partial or full autofrettage of the tube, pressure in the hole and on the crack faces, the stress ratio of the fatigue cycle, and calculated fatigue crack growth profiles for comparison with experimental results

Direct comparisons of measured and calculated fatigue crack growth behavior and lives are expected to give useful information for more efficient safe life testing and design of cannons.

FATIGUE LIFE TESTS

A sketch of an evacuator hole section of a cannon tube, Figure 1, shows the configuration of the tests, as well as a physical concept of the analysis and some of the nomenclature used. The location of the pressure seal of the hole is indicated near the tube outer radius. The sealing of the ends of the tube, not shown, is typically done using closure fixtures supported by a load frame so that the tube is pressurized in the open-end condition. An idealized crack is shown growing from a mid-wall position on the hole surface with length 2c and depth a. The actual cracks grew either near the mid-wall position or near the tube inner radius, as described in upcoming results.

A summary of the tests is shown in Table 1. Nine tubes were tested, made from forged ASTM A723 quenched and tempered steel with yield strengths in the vicinity of 1200 MPa, as shown in the table. Tube inner radii of 53, 60, and 78 mm correspond to various cannon sizes, with outer-to-inner radius ratio, r_2/r_1, of about 1.5 and hole radius-to-inner radius ratio, r_H/r_1, of about 0.03. The amount of autofrettage by overstrain, defined as the portion of the tube wall that has been plastically strained, varied from 0 to 100 percent, as listed in Table 1. The zero-to-peak pressure cycles were applied to the inner radii of tube and hole and to the surfaces of the cracks as they developed, using a synthetic hydraulic oil and the pressures listed in the table.

Table 1. **Specimen Material, Configuration, and Test Conditions**

Tube #	Yield Strength S_y MPa	Tube Size r_1 mm	 r_2 mm	Hole Size r_H mm	Amount of Overstrain %	Test Pressure p MPa
35A	1260	53	76	1.8	0	207
35B	1210	53	76	1.8	0	207
68A	1250	53	81	1.8	100	207
25A	1090	60	94	2.0	29	297
25B	1090	60	94	2.0	29	297
91A	1190	60	94	2.0	49	297
91B	1140	60	94	2.0	49	297
85A	1220	78	107	2.5	100	83
85B	1220	78	107	2.5	100	83

The monitoring of initiation and growth of cracks during the tests was difficult, given their secluded location. The most useful information was the post-test location and profile of the dominant crack at the evacuator hole and the resulting total fatigue life, typically defined as the point at which the crack is about to break through to one or both of the inner and outer surfaces of the tube. Severe leaks stopped the test at this point, which is believed to be very near the end of the useful fatigue life for the tube.

TEST RESULTS

As mentioned earlier, the growth of the dominant fatigue crack along the evacuator hole occurred in one of two locations, near the tube inner radius or at about the mid-wall position. Macrophotos of the fracture surface after the test show the location and profile of the dominant fatigue crack at failure, see Figure 2. Note that for Tube #35B with no overstrain, the crack is located near the tube inner surface, as would be expected due to the higher applied stresses at this location. For Tube #85B, with 100 percent overstrain, the crack is located near mid-wall where the combination of applied and residual stresses is a tensile maximum. The high compressive residual stress produced at the tube inner radius by overstraining has prevented cracking at this location, resulting in cracking at mid-wall where the compressive residual stress is near zero.

The measured fatigue life of each of the nine tubes is listed in Table 2. The significant difference in life between the group of tubes with a 3,000 to 10,000 cycle life and the two with a 40,000 to 43,000 cycle life can be explained from the overstrain and test pressure information in Table 1. The two high-life tubes had both the lowest test pressure and the highest amount of overstrain, 100 percent. Before discussing additional aspects of the fatigue test results, the fatigue life calculation methods and results will be described, so that appropriate comparisons of tests and calculations can be made.

Table 2. Measured and Calculated Lives

Tube #	Measured	Calculated Lives			Life Ratios	
	N_{MEAS} Cycles	x/t	$N_{1.0p}$ Cycles	$N_{0.2p}$ Cycles	$N_{1.0p}/N_{MEAS}$	$N_{0.2p}/N_{1.0p}$
35A	4,710	0.00	4,290	6,970	0.91	1.62
35B	5,770	0.00	4,290	6,970	0.74	1.62
68A	9,780	0.47	11,860	24,060	1.21	2.03
25A	4,780	0.24	3,500	6,860	0.73	1.96
25B	3,540	0.24	3,500	6,860	0.99	1.96
91A	3,520	0.36	4,110	8,400	1.17	2.04
91B	3,550	0.36	4,110	8,400	1.16	2.04
85A	43,340	0.48	80,880	139,200	1.87	1.72
85B	40,710	0.48	80,880	139,200	1.99	1.72
				Mean:	1.20	1.86

FATIGUE LIFE CALCULATIONS

The life calculations are based on the classic fracture mechanics approach involving the integration of the crack growth rate equation. The development of the equations is similar to that in prior work (ref 2). Starting with the experimentally determined relationship for the fatigue crack growth rate in terms of the stress intensity range, ΔK, we have

$$da/dN = 6.52 \times 10^{-12} \Delta K^3 \quad (1)$$

where 6.52×10^{-12} and the power 3 describe the growth rate for the A723 steel used and are appropriate for da/dN in m/cycle and ΔK in MPa $m^{1/2}$. The definition of ΔK is $\Delta K = K_{max} - K_{min}$ for $K_{min} > 0$ and $\Delta K = K_{max}$ for $K_{min} < 0$. The value of K for the tube configuration and loading is determined using the familiar expression for short cracks, as follows:

$$K = 1.12\ h\ S_{eff}\ (\pi\ a)^{1/2} \tag{2}$$

The use of a short-crack expression for K gives a good representation of the growth of the crack near the hole surface, which has most control over life, but does not account very well for growth away from the hole surface. In Eq. (2) a crack-shape factor, h, has a value of 0.64 (ref 3) for the semicircular shaped cracks believed to be of primary concern for growth near the hole surface. S_{eff} is a combined effective stress that includes the Lamé stresses in the tube wall, S_L, the residual stresses in the wall, S_R, and the direct effect of pressure on the crack faces, S_P, as follows:

$$S_{eff} = S_L + S_R + S_P \tag{3}$$

S_L is the circumferential Lamé stress in the wall, including the effects of the stress concentration factor of the hole, k_t, and the pressure in the hole, as follows:

$$S_L = -p\ k_t\ [r_1^2 (r_2^2 + r^2)]/[r^2 (r_2^2 - r_1^2)] - f\ p \tag{4}$$

where p is pressure (a negative quantity), k_t has a value of 3, and the second term in Eq. (4) accounts for any fraction, f, of the pressure being applied to the inner surface of the hole.

S_R is the concentrated circumferential residual stress in the wall due to overstrain, calculated as follows:

$$S_R = k_t\ [-p^* + S_Y\{1 + ln(r/r_1)\} - p^*\{r_1^2/(r_2^2 - r_1^2)\}\{1 + r_2^2/r^2\}]$$

$$p^* = S_Y\ ln(r_P/r_1) + S_Y\{(r_2^2 - r_P^2)/2r_2^2\}$$

$$\text{for } r < r_P \text{ and } S_R \leq S_Y \tag{5}$$

The expressions in Eq. (5) are, apart from k_t, the usual expressions for circumferential residual stress of an overstrained cylinder (ref 4), where p* is the autofrettage pressure. Including k_t in the expression for residual stress accounts for the effect of the hole. However, since the unconcentrated residual stress can approach the yield strength and k_t can be well above 1, the $S_R \leq S_Y$ requirement has been added. This limits S_R to the material yield strength, which is believed to occur in reality as a result of yielding at the hole. Equation (5) accounts for the effect of yielding on S_R, but does not account for any strain hardening that may occur.

S_P is the addition to the effective stress that accounts for the effect of pressure on the crack faces, written as follows:

$$S_P = -\ f\ p \tag{6}$$

Equation (6) is based on the fact that the K for a given crack configuration with a pressure applied to the crack faces is exactly equivalent to the K for the same crack with remotely applied tension of the same magnitude.

The expression for fatigue life, N, can thus be written by integrating Eq. (1) and combining the result with Eqs. (2) through (6) to give the following:

$$N = 2[1/\sqrt{a_i} - 1/\sqrt{a_f}]/6.52 \times 10^{-12}\,[1.12\,\sqrt{\pi}\,h\,S_{eff}]^3 \qquad (7)$$

The $2[1/\sqrt{a_i} - 1/\sqrt{a_f}]$ in Eq. (7), which includes the initial and final crack depths, a_i and a_f, is from integration. The other terms are from Eqs. (1) through (6). Equation (7) can be used to calculate fatigue life with account of the key material, configuration, and loading factors that control fatigue life in a pressurized, overstrained thick-wall cylinder with evacuator holes. Life calculations were made with Eq. (7) using just one arbitrarily selected input value, that of the initial crack depth, a_i. A single value of a_i, 0.01 mm, was used for all calculations, based on similar rationale as in prior work (ref 2). Relatively few cannon firings of the type expected to initiate heat-check type cracks had occurred with the tubes tested here, and the hole location was well removed from the hottest combustion gases, so this relatively small value of a_i was used. Comparison of the life calculations with experimental results is described next.

CALCULATED AND MEASURED LIVES

Referring again to Table 2, calculated and measured lives are compared for the conditions of the nine tubes tested. The calculated lives were obtained at the relative position through the wall, x/t, that gave the lowest life. For Tube #35A and Tube #35B the lowest calculated life was at the tube inner radius, x/t = 0. Recall from Figure 2(a) that tests indicated that the inner radius was the failure location. The calculations for the other seven tubes, which had partial or complete overstrain, had x/t values between 0.24 and 0.48, also in agreement with test results, such as in Figure 2(b). The ratio of calculated life with full pressure in the hole, $N_{1.0p}$, to measured life is listed in Table 2 for the nine tests. The overall agreement, indicated by the mean ratio of 1.20, is considered to be good, in light of the many factors which can affect both the calculation and the measurement of fatigue life.

One other comparison can be made from the results in Table 2, that being the difference in calculated lives with full or partial pressure applied to the evacuator holes. As has been mentioned, the tests were conducted with full pressure in the holes, whereas recent results by Carofano and Leach (ref 5) indicate that cannon firing involves less than full pressure in evacuator holes. Their results show various fractions of the nominal cannon firing pressure being present in a hole, depending on hole size, location in the hole, and other factors. As an admittedly simplistic representation of the Carofano and Leach results, the fraction, f, of the hole pressure relative to the cannon pressure was set at 0.2 in Eqs. (4) and (6). The resulting lives and life ratios are listed in Table 2. Note that the calculated mean life with f = 0.2, $N_{0.2p}$, is 1.86 times that with f = 1, $N_{1.0p}$.

A graphical comparison of calculated and measured lives for the conditions of the nine tests is shown in Figure 3. A plot of calculated life is shown for each of the five types of tube, using r values in Eqs. (4) and (5) appropriate to values of x/t. A minimum life is obtained as shown, either at $x/t = 0$ for the 0 percent overstrain case, or between $0.24 < x/t < 0.48$ for the overstrained tubes. The physical reason for the minimum life point is that it is the point at which the compressive residual stresses begin to counteract the tensile Lamé stresses in the tube wall. From this point inward, the favorable residual stresses delay fatigue cracking, and this results in the locations and values of calculated minimum life shown in the five plots. The measured lives (from Table 2) are plotted for comparison. Note that the x/t values used to plot the measured lives were the same as those for the calculated minimum lives. This correspondence between measured and calculated x/t was shown to be true for the two tests described in Figure 2, but this type of photographic comparison was not always possible.

Figures 4 and 5 show the effects of four important tube and hole conditions on the calculated fatigue life of a pressurized, overstrained tube with an evacuator hole. The variables are wall ratio, r_2/r_1, percent overstrain, pressure in the hole and crack, and position along the hole, x/t. The calculations are for typical values of these variables and for a material yield strength, S_Y, of 1200 MPa and a pressure, p, of 300 MPa. Figure 4 shows N versus x/t plots for $r_2/r_1 = 1.5$ and 2.0 and for 0, 50, and 100 percent overstrain. Note that the calculated minimum lives for 0 percent overstrain are at $x/t = 0$, which was also the measured failure location, as has been discussed. For 50 and 100 percent overstrain, the progressively higher compressive residual stresses cause an increase in both the minimum fatigue life and the x/t value at which it occurs. In general, the $r_2/r_1 = 2.0$ lives are about twice those for $r_2/r_1 = 1.5$. Comparing Figures 4 and 5 shows that eliminating the pressure in the hole (and in the crack emanating from the hole) results in lives about thrice those with pressure in the hole.

One other feature of the results in Figure 4 is worthy of discussion, that being the maximum in some of the calculated life plots. This is a consequence of limiting the compressive residual stress to the material yield strength, as indicated in Eq. (5). For the 100 percent overstrain, 2.0 wall ratio calculations plotted in Figure 4, for example, the compressive residual stress yield was limited to -1200 MPa for $0 < x/t < 0.3$. This caused the maximum in the plot.

The final presentations of calculated fatigue life, Figures 6 through 8, are intended to provide information that may be useful in design of overstrained tubes with holes or in planning and interpreting fatigue life tests of such tubes. Figure 6 summarizes several series of calculations of minimum fatigue life, for $r_1/r_2 = 1.5$ and 2.0, full pressure and no pressure in the hole, and 0 to 100 percent overstrain. Other inputs to the calculations are as in prior calculations, as indicated on the figure. These results are the minimum lives, which should give some guidance as to the life that would be obtained in a fatigue life test or service loading of a tube with a hole. Note that wall ratio has the most significant effect on life, with as much as a ninefold increase in life. Excluding pressure from the hole or adding 100 percent overstrain has a lesser but still significant effect on life, with as much as a fourfold increase in life.

Calculations were performed to assess the effect of material yield strength on fatigue life of an overstrained tube with a hole, with a surprising result. Very little effect was noted, as summarized in Figures 7 and 8. Note in Figure 7 that if a fatigue failure could somehow be forced to occur at or near the $x/t = 0$ position in an overstrained tube, there would be a significant effect of yield strength on life. The higher strength material would support a higher compressive residual stress and cause an increase in life. However, the minimum fatigue life occurs at an $x/t \approx 0.4$ where the residual stress is near zero, so there is little or no effect on fatigue life. Figure 8 summarizes a series of calculations of the type shown in Figure 7, for 0 to 100 percent overstrain and 1000 to 1400 MPa yield strength. The only effect noted was for 25 percent overstrain, where a 40 percent increase in strength resulted in only a 2 percent increase in life. Therefore, although overstrain results in a significant increase in life, the material strength has little effect on life, for a tube with a hole. This is quite contrary to the effects that would be expected in an overstrained tube with no hole, where both overstrain and increases in material strength would result in significant increases in fatigue life.

SUMMARY

Fracture mechanics-based calculations of fatigue life were shown to agree well with measured fatigue life from sections of cannon tubes with evacuator holes, over a wide range of test conditions, including tube, hole, and crack configuration; tube overstrain and material yield strength; and the pressure applied to the tube, hole, and crack.

The ratio of outer-to-inner radius of the tube had the most significant effect on calculated fatigue life; increasing the radius ratio from 1.5 to 2.0 produced up to a ninefold increase in life. Overstrain also had a significant effect on calculated life; a change from 0 to 100 percent overstrain produced up to a fourfold increase in life, and moved the calculated location of fatigue crack initiation along the hole from a position adjacent to the tube inner radius to a mid-wall position, in agreement with the experimentally observed locations of crack initiation.

No significant effect of material yield strength on calculated fatigue life was noted for any amount of overstrain of tubes with holes. This is contrary to fatigue life results for overstrained tubes without holes, where an increase in yield strength is known to significantly increase fatigue life.

REFERENCES

1. A.P. Parker and J.H. Underwood, "Stress Concentration, Stress Intensity, and Fatigue Crack Growth Along Evacuators of Pressurized, Autofrettaged Tubes," submitted to *Proceedings of 1995 ASME Pressure Vessels and Piping Conference.*

2. J.H. Underwood and A.P. Parker, "Fatigue Life Analysis and Tests for Thick-wall Cylinders Including Effects of Overstrain and Axial Grooves," *Proceedings of 1994 ASME Pressure Vessels and Piping Conference, PVP Vol. 280*, American Society of Mechanical Engineers, New York, 1994, pp. 303-311.

3. J.C. Newman and I.S. Raju, "An Empirical Stress Intensity Factor Equation for the Surface Crack," *Engineering Fracture Mechanics*, Vol. 15, 1981, pp. 185-192.

4. R. Hill, *The Mathematical Theory of Plasticity*, Oxford University Press, 1967.

5. G.C. Carofano and M.R. Leach, "A Stress Factor Method for Perforated Muzzle Brake Design," *Proceedings of 1994 ASME Pressure Vessels and Piping Conference, PVP Vol. 281*, American Society of Mechanical Engineers, New York, 1994, pp. 81-93.

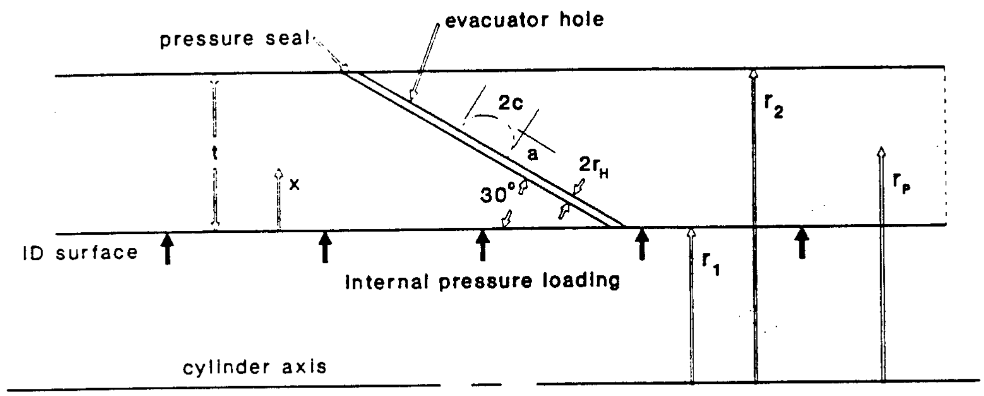

FIGURE 1 - CONFIGURATION AND NOMENCLATUE
FOR OVERSTRAINED CYLINDER WITH EVACUATOR

ID surface

[a] Tube #35B; 0% overstrain

ID surface

[b] Tube #85B; 100% overstrain

FIGURE 2 - FRACTURE SURFACES FROM
FATIGUE TESTS; 1.1 MAGNIFICATION

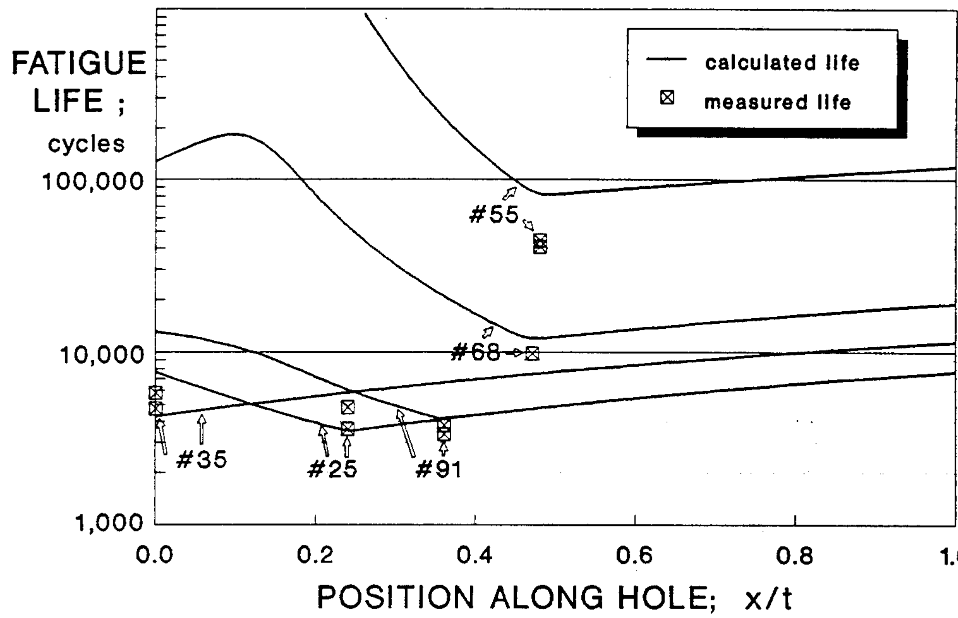

FIGURE 3 - CALCULATED AND MEASURED FATIGUE LIFE AT EVACUATOR HOLES

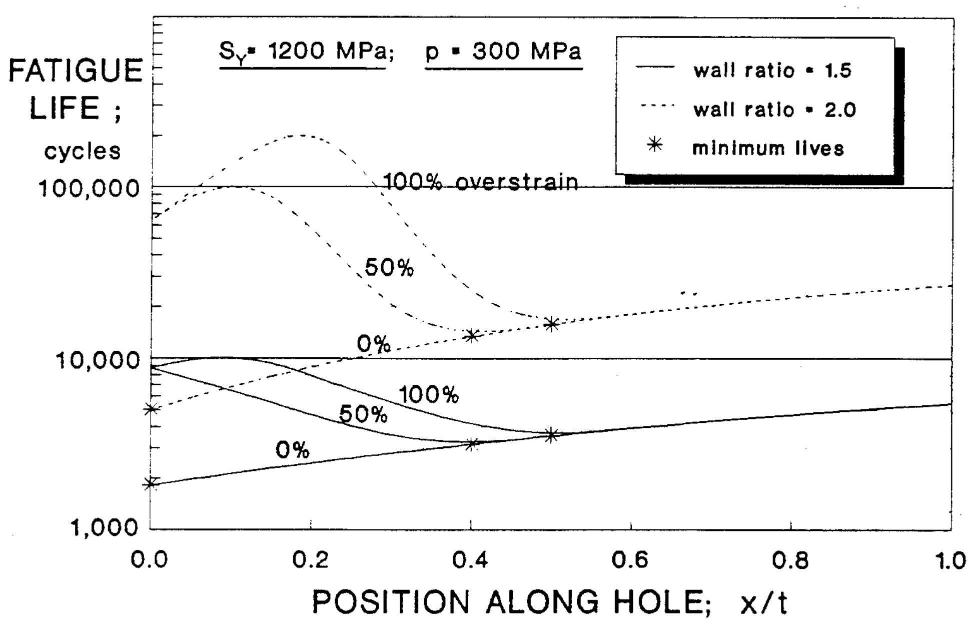

FIGURE 4 - WALL RATIO AND OVERSTRAIN EFFECTS ON LIFE; PRESSURE IN HOLE

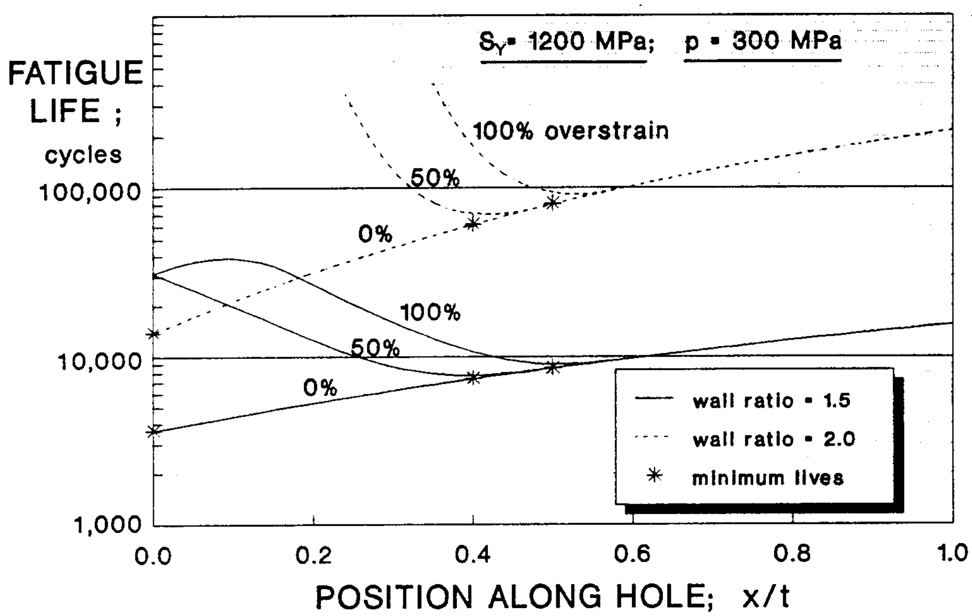

FIGURE 5 - WALL RATIO AND OVERSTRAIN EFFECTS ON LIFE; NO PRESSURE IN HOLE

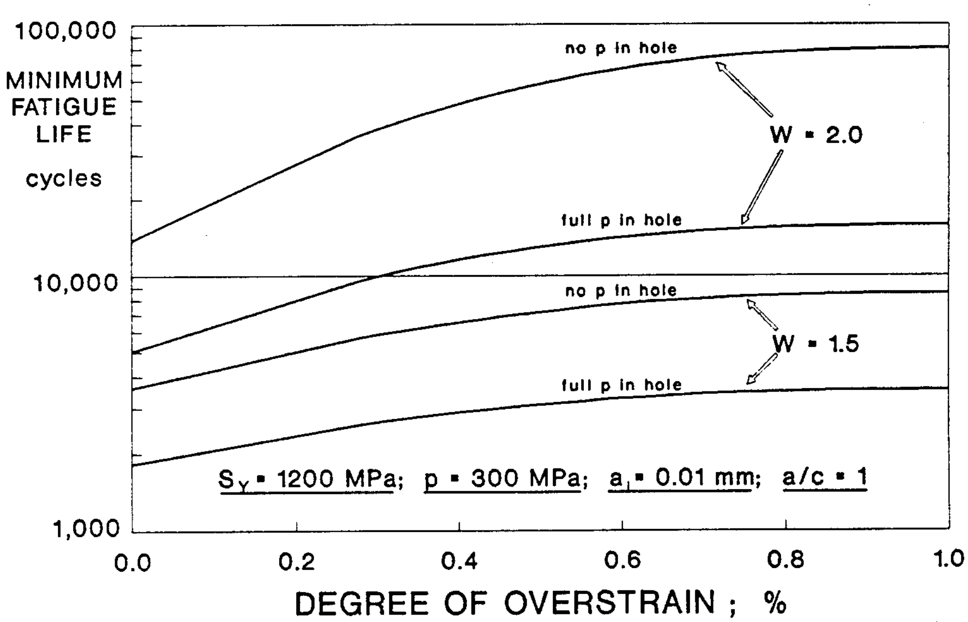

FIGURE 6 - MINIMUM LIFE AS A FUNCTION OF OVERSTRAIN, WALL RATIO AND HOLE PRESSURE

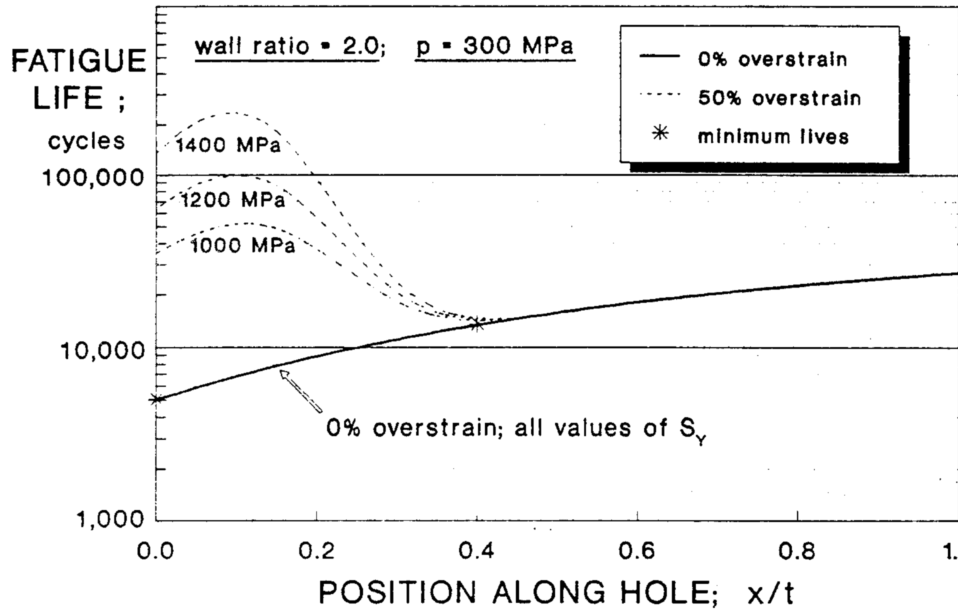

FIGURE 7 - STRENGTH EFFECTS ON LIFE;
0% AND 50% OVERSTRAIN; PRESSURE IN HOLE

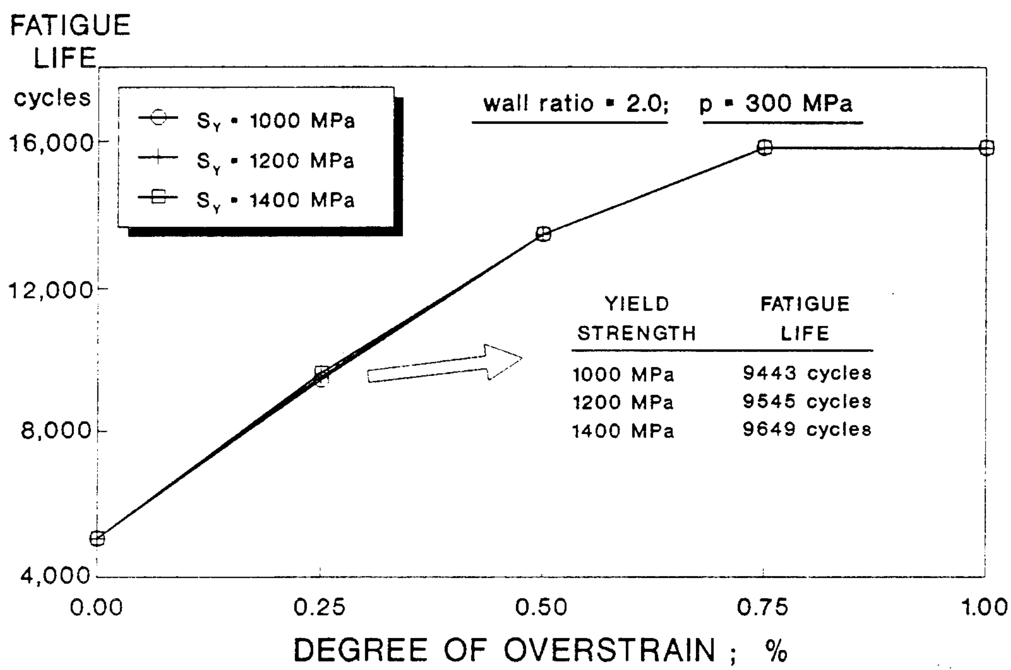

FIGURE 8 - FATIGUE LIFE AS A FUNCTION
OF YIELD STRENGTH

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