A MACHINE TO STUDY FATIGUE CRACK GROWTH IN PVC PIPES

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ABSTRACT

A fatigue machine was designed to produce a sinusoidal load. The machine was used to study the fatigue crack propagation of poly vinyle chloride (PVC). The load is applied using Scotch Yoke and a spring . The spring stiffness is such that the accumulated deflection of the specimen is much small compared to the deflection of the spring . This insures that the load shape is approximately unchanged. The test specimens are chosen to be an arc segments of pipes. A fatigue test have been performed using different R - ratios (R = minimum load / maximum load). The fatigue data was analyzed in terms of Paris equation to calculate a crack growth kinetic parameters, A and m. The kinetic parameters were related to the R - ratios . The results were compared with similar tests carried out on standard MTS testing machine.

Keywords: Fatigue of polymers, Crack propagation, Fracture mechanics, Pressurised pipes.

INTRODUCTION

The objective of this work is to design a fatigue testing machine for the purpose of conducting tests on specimens of PVC pipes. The machine aimed to be "load control" , i.e. , the amplitude of the force applied and the mean load are completely controlled.

The second constraint imposed on the design is the possibility of studying the specimens in short term as well as long term fatigue according to the fracture mechanics approach. The simplicity and the low cost were also accounted for in the design approach. The load was applied mechanically for the last two reasons. The PVC pipe material was selected because of its high suspectibility to brittle failure (slow crack growth)

A theoretical model to predict the life time of unplasticized PVC (uPVC) pipes has been presented in [1] using Paris equation. The effect of mean stress in fatigue crack growth for uPVC was investigated using single edge notched specimens (SEN) [2]. The results obtained showed that, for a constant load ratio (minimum load/maximum load) and stress intensity factor range (ΔK), the mean stress has insignificant effect on the crack speed (da/dN). Also the kinetic parameters (A and m) of Paris equation have been obtained at different load ratios. The relation between da/dN and ΔK showed an almost constant slope (m) while A is increasing as the load ratio (R) increase (for $R=0.03$, $A=3.98*10^{-8}$ while for $R=0.47$, $A=7.59*10^{-8}$) [2].

The crack initiation and subsequent crack propagation have been studied for SEN PVC specimen using fatigue at 80 HZ [3]. The crack speed was related to the maximum stress intensity factor. An interrupted fatigue test at the region of constant crack growth rate showed that the fracture surface at this region is smooth and the crack tip is sharp.

The fatigue crack growth on a center-notched PVC plates was studied using a range of load, $\Delta K=0.95$ to 4.27 MPa $m^{1/2}$ and a frequency (0.2-20 HZ) [4]. It was found that the crack growth rate (da/dN) increased with increasing ΔK, but substantially decreased with increasing the frequency.

The fatigue behavior of pure PVC and compound PVC for pipe investigated in [5]. An S-N relation was developed for unnotched specimens. The S-N relation was found similar for pure PVC and for pipe compound PVC. The data trends, and the microscopic observation, indicates that the unnotched-specimen life-time in fatigue is dominated by the craze/crack initiation process.

The effect of a simulated notches similar to that occurred during installation on the fatigue lifetime was investigated in [6]. It was found that, there is a relationship between the depth of the notch and the cycles to failure. With damage less than 1.2 mm deep, cracks do not grow and the pipe lifetimes exceeding 100 years can be expected for pipes installed under such cyclic pressure conditions.

The fatigue failure of pressurized water pipe lines under service conditions was investigated in [7]. It was found that, fatigue cracks at service stress amplitude levels are concentrated in weld lines produced by the pipe die spider. An analysis for Linear Elastic Fracture Mechanics (LEFM) was developed.

In this work, fatigue as an accelerating agent was used to accelerate the crack propagation in PVC water pipes. The data was analyzed in terms of LEFM to calculate kinetic parameters valid for life time prediction.

DESIGN OF THE MACHINE

The machine, Figure (1), consists of a Scotch Yoke mechanism (12,13,14,15), with an adjustable stroke as shown in Figure (2), connected to a coil spring (19). The test specimen (25) is connected to the spring at one end while the other end is connected to a fixed support (29) through a load cell (28). The mean load of the spring is controlled by using an adjustable nut (30). The drive system consists of an electric motor (1), belt drive (4), speed reducer (5) and another belt drive (7). A limit switch (21) is used to stop the machine when the specimen breaks down. The speed of the Yoke can be adjusted by changing the pulleys diameter of the belt drives.

The force applied on the test specimen is given by:

$$F = k(\delta + C \sin(2\pi f) - \Delta) \tag{1}$$

where δ is the spring deflection when the yoke is in its mid position, C is the length of the yoke crank, k is the spring stiffness, f is the frequency of the variable load, and Δ is the deflection of the specimen.

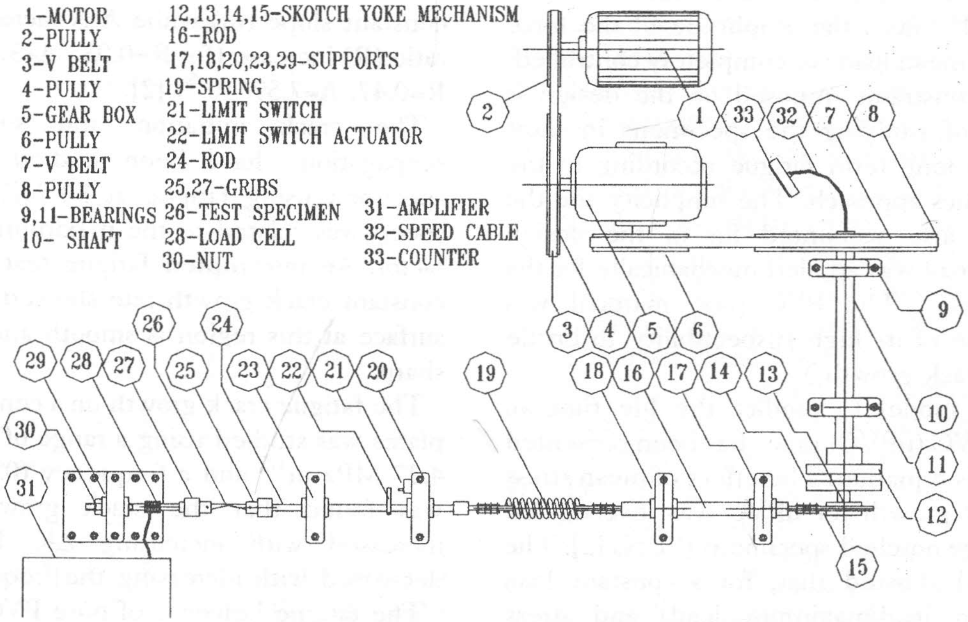

Figure 1. Fatigue testing machine.

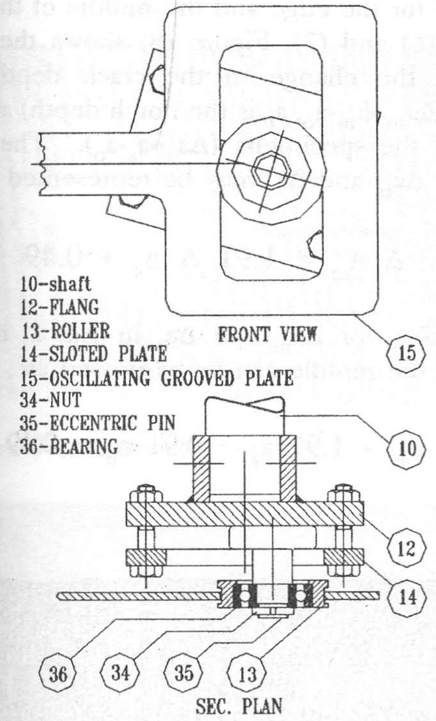

Figure 2. Scotch Yoke mechanism.

Figure (3) shows the specimen load F against the time.

The maximum deflection of the specimen is much smaller than the deflection in the spring and can be neglected for simplicity and the applied load is well approximated by sinusoidal wave. For this machine the frequency can be adjusted from 0.1 HZ to 10 HZ. The stroke can be adjusted from 0.0 to 100 mm. consequently the load level can be controlled by a combination from the stroke and the spring stiffness.

EXPERIMENTAL PROCEDURE

In order to study the actual performance of PVC pipes under fatigue cracking, the test specimens were taken as an arc segments from the pipes, Figure (4). The dimensions of the specimens comply with ASTM standard E399-81 [8]. Since the field failure occurs under plane strain, the width of each specimen is taken larger than that in the ASTM standard (the width is half the thickness) to increase the plane strain contribution. The specimens were prepared from PVC water pipes obtained from El-Sherif PVC piping factory, Cairo-Egypt. The pipes have 200 mm outer diameter and 9.6 mm wall thickness, extruded under a pressure of 400 bar and a temperature of 190 °C. The material density is 1.38-1.4 gm/cm^3. The yield stress is 51 MPa.

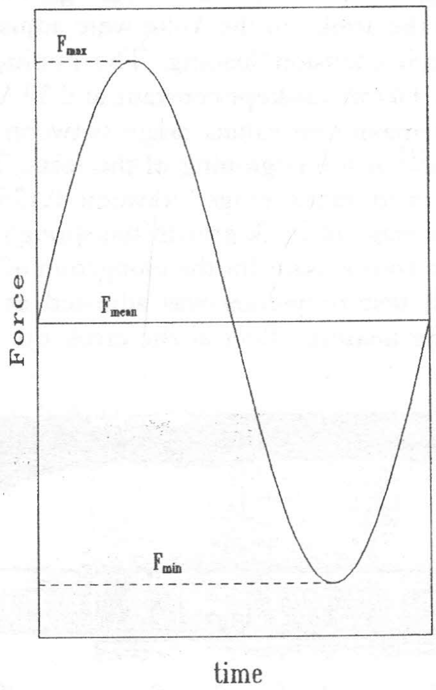

Figure 3. Load configuration (sinusoidal).

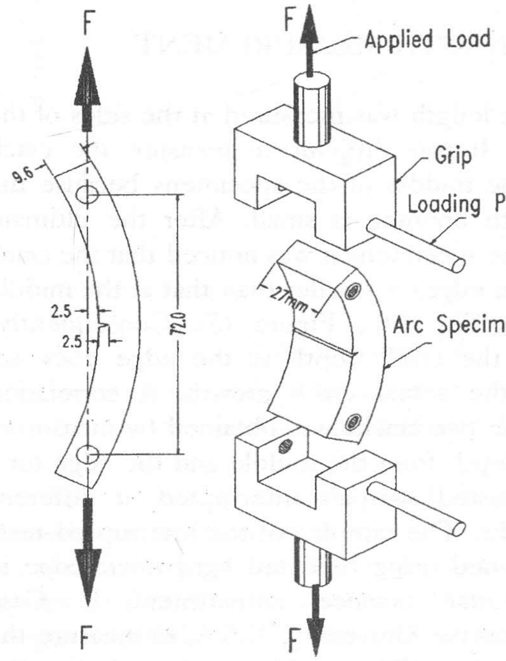

Figure 4. Test specimen geometry and its gripping fixtures.

Clamping holes were drilled at the edges of the specimens. Razor notch of 2.5 mm deep were made at the inner surface in the middle between the loading holes. The specimens were tested using the designed fatigue machine. The spring initial deflection and the stroke of the Yoke were adjusted to produce tension-tension loading. The minimum stress intensity factor was kept constant at 0.39 MPa $m^{1/2}$ while the maximum values range between 0.9 to 2.08 MPa $m^{1/2}$ at the beginning of the tests. The corresponding load ratios range between 0.175 to 0.43. At the last stage of crack growth the spring load was adjusted to compensate for the elongation of the specimen. The test frequency was adjusted at 0.6 HZ to avoid the heating effect at the crack tip.

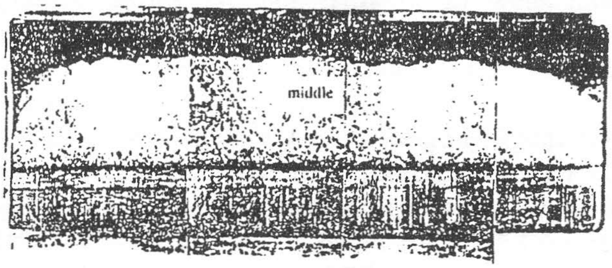

Figure 5. Micrograph for the fracture surface showing the difference between the edge and the middle cracks.

CRACK LENGTH MEASUREMENT

The crack length was measured at the sides of the specimens. It was difficult to measure the crack depth at the middle of the specimens because the crack mouth opening is small. After the ultimate failure of the specimens it was noticed that the crack depth at the edges is smaller than that at the middle (crack tunneling [9]), Figure (5). Consequently, measuring the crack depth at the edge does not represent the actual crack growth. A correlation between the two cracks was obtained by measuring the crack depth from the middle and the edge for a group of tested samples interrupted at different crack lengths. The samples of the interrupted tests were examined using reflected light microscope in Macromolecular Science Department in Case Western Reserve University, U.S.A, to measure the plastic zone size. The specimens were cut at the idle. A reflected light micrograph pictures were obtained for the edge and the middle of the cracks, Figures (6) and (7). Figure (8) shows the relation between the change in the crack depth at the middle ($\Delta a_m = a_m - a_o$, a_o is the notch depth) and at the edges of the specimens ($\Delta a_s = a_s - a_o$). The relation between Δa_m and Δa_s may be represented by

$$\Delta a_m = 1.91 \Delta a_s + 0.49 \quad (2)$$

Substituting for Δa_m and Δa_s in Eq. 2, the crack depth at the middle can be expressed as:

$$a_m = 1.91 a_s - 0.91 a_o + 0.49 \quad (3)$$

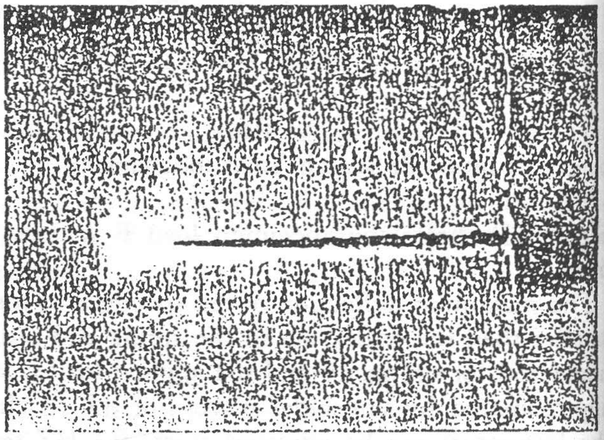

Figure 6-a. edge crack (a=2.5 mm).

Figure 6-b. middle crack (a=2.9 mm)

Figure 6. Comparison between the edge crack and the middle cracks.

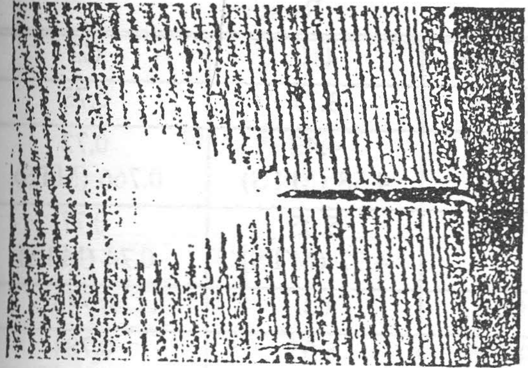

Figure 7-a. edge crack (a=4.5)

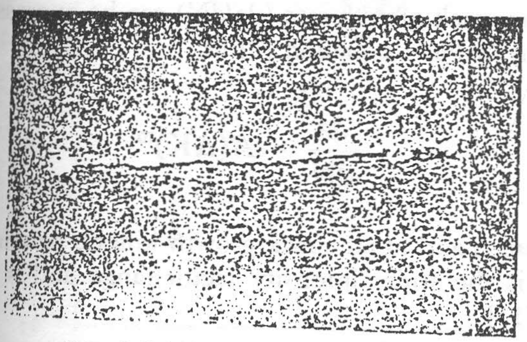

Figure 7-b. Middle crack (a=6.8)

Figure 7. Comparison between the edge crack and the middle cracks.

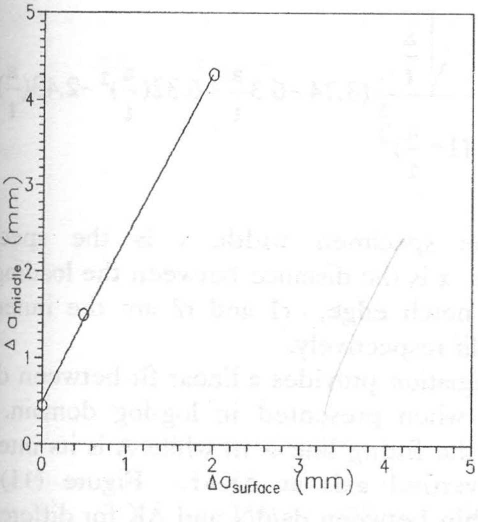

Figure 8. Relationship between the crack at the edge and the middle.

EXPERIMENTAL ANALYSIS

To validate the analysis with LEFM we have to establish the existence of both Small Scale Yielding (SSY) and plane strain [10] . The measured plastic zone in our experiments is very small compared to crack length which confirm the condition of SSY.

The plane strain criterion is also confirmed by using higher width to thickness ratio than that recommended by the ASTM standards

CRACK PROPAGATION KINETICS

The relation between the crack length and the number of cycles, for different R-ratios is shown in Figure (9). Each point in the plot is the average of three testes.

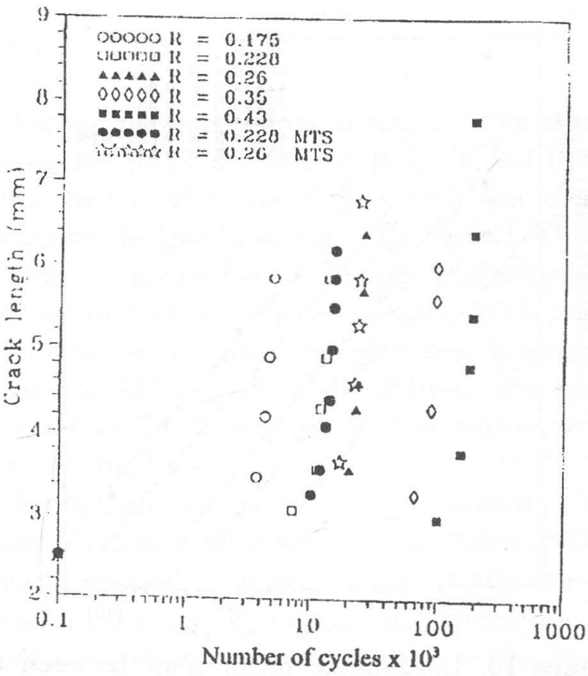

Figure 9. Relationship between the crack length and the number of cycles for different R-ratios.

It was suggested that the crack length is more suitable to be function of (N_f -N) [11]; N is the number of cycles and N_f is the total number of cycles to failure. The relation between the crack length and (N_f - N) for the data in figure 9 when plotted on semi log scale, Fig. 10 showed a series of straight lines. Hence this relation can be represented in the form

$$a = C1 - C2 \ln(N_f - N) \qquad (4)$$

where C1 is a constant depends on the load ratio, C2 is a constant independent of the load ratio, a in mm, N and N_f are in Kcycles.

The values of these constants are listed in table 1. The crack speed is obtained by differentiating Eq. (4) with respect to N. The crack speed is given by

$$\frac{da}{dN} = \frac{C2 * 10^{-6}}{e^{\frac{C1 - a}{C2}}} \qquad (5)$$

where da/dN is the crack growth rate in m/cycle.

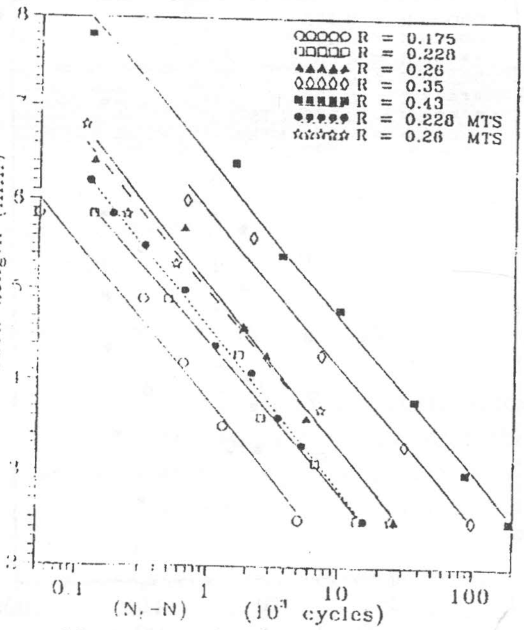

Figure 10. Logarithmic relationship between the crack length and (N_f-N).

To get confidence of the results of our machine, tests for R=0.228 and 0.26 were carried out for the same material using an MTS machine at the laboratory of CASE WESTERN RESERVE University ,USA for the purpose of comparison . The results of these tests are also presented in Table (1).

Table 1. The constants A and m for different R-ratios.

load ratio	C1	C2
0.175	3.77	0.75
0.228	4.42 4.58 (MTS)	0.72 0.766 (MTS)
0.26	5.05 4.97 (MTS)	0.77 0.74 (MTS)
0.36	6.0	0.745
0.446	6.55	0.784

The crack growth rate (da/dN) can be expressed in terms of Paris equation [2] as:

$$\frac{da}{dN} = A(\Delta K)^m \qquad (6)$$

where A and m are crack growth kinetic parameters. ΔK is the stress intensity factor range and is given by [11]

$$\Delta K = \frac{\Delta P}{B\sqrt{t}}\left[\frac{3x}{t} + 1.9 + 1.1\frac{a}{t}\right]\left[1 + 0.25\left(1 - \frac{a}{t}\right)^2\left(1 - \frac{r1}{r2}\right)\right] f\left(\frac{a}{t}\right) \qquad (7)$$

where

$$f\left(\frac{a}{t}\right) = \frac{\sqrt{\frac{a}{t}}}{\left(1 - \frac{a}{t}\right)^{\frac{3}{2}}}\left(3.74 - 6.3\frac{a}{t} + 6.32\left(\frac{a}{t}\right)^2 - 2.43\left(\frac{a}{t}\right)^3\right)$$

B is the specimen width, t is the specimen thickness, x is the distance between the loading axis and the notch edge, r1 and r2 are the inner and outer radii respectively.

This equation provides a linear fit between da/dN and ΔK when presented in log-log domain. The slope of the fitting line is m while A is its intercept with a vertical axis at ΔK=1. Figure (11) is a relationship between da/dN and ΔK for different R-ratios. The kinetic parameters A and m as functions of the R-ratio are shown in Figures (12) and (13) respectively. These relations were found to fit an exponential functions versus R as:

$$A = 3.32*10^{-9}e^{6.64R} \quad (8)$$

$$m = 4.63e^{-0.39R} \quad (9)$$

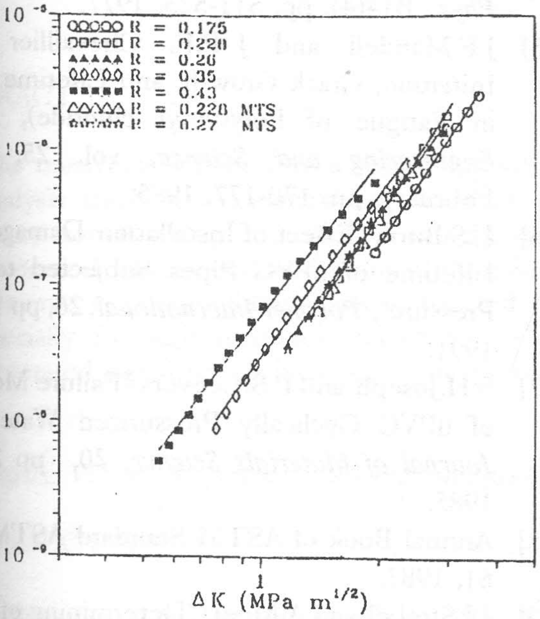

Figure 11. Crack kinetics in terms of Paris equation for different R-ratios.

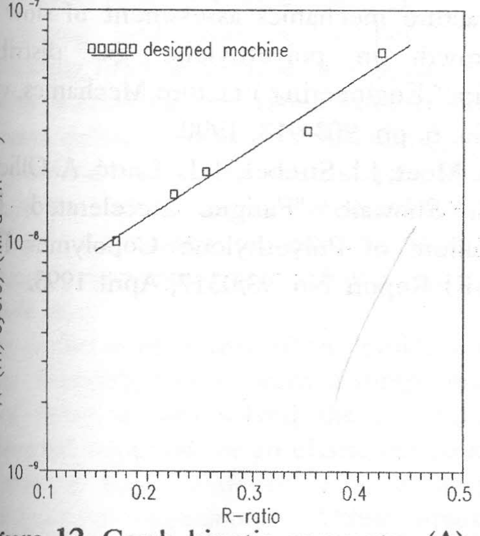

Figure 12. Crack kinetic parameter (A) versus the load ratio.

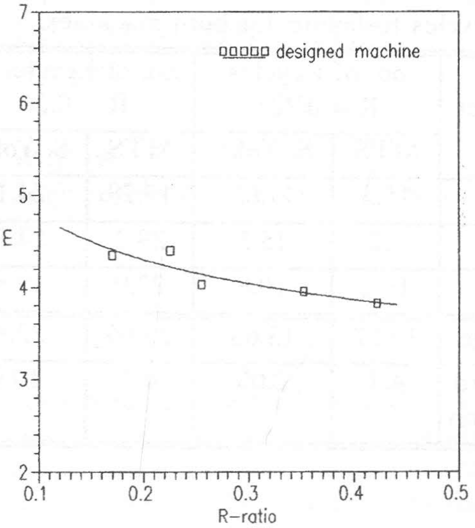

Figure 13. The slope "m" versus the load ratio (R).

DISCUSSION

For the purpose of comparison, the data obtained using the MTS machine at R=0.228 and 0.26 are presented in the same figures with that obtained using the designed machine, Figs. 9,10,11. This data shows that the performance of the designed machine is very well when compared with the MTS machine although the designed machine cost is much less than the MTS machine. In addition, the running cost of the MTS machine is more expensive than the designed one.

Brittle materials provide large scattering when they are tested for fatigue cracks. Since PVC is a brittle material, scattering in the data is expected. Table 2 presents a comparison between the total number of cycles to failure for both machines. This table shows that the scattering (standard deviation) of the designed machine is comparable to that of the MTS machine. This small scattering may be related to the simplicity of the load control for the designed machine.

Table 2. Comparison between the total number of cycles to-failure for both machines.

test number	no. of Kcycles R = 0.228		no. of Kcycles R = 0.26	
	MTS	S. Yoke	MTS	S. Yoke
1	15.3	14.65	19.78	24.1
2	9.2	15.5	29.2	24.5
3	19.2	10.8	27.9	19.8
average	14.57	13.65	25.66	22.8
standard deviation	4.1	2.05	4.2	2.13

CONCLUSIONS

1- The performance of the designed fatigue machine is similar to that for hydraulic servo machine (MTS) regardless their relative cost.

2- The crack growth kinetic parameters are obtained under LEFM conditions, so, they are transferable to predict the life time of the actual pipe in service.

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