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MODELING OF TOTAL STRAIN RANGE-LOW CYCLE FATIGUE FOR AUSTENITIC STAINLESS STEEL

صياغة لمدى الانفعال الكلى لإطاقة الكلل للصلب الأوستنيتي

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خلاصة :

يرتكز اتجاه هذا البحث إلى دراسة مقدار الانفعال الكلى لإطاقة الكلل للصلب الأوستنيتي 316 عند درجات الحرارة المتسبة وذلك بالحصول على ماهو متوافر من بيانات تجريبية ثم تحليل هذه البيانات تحليلا منطقيا باستخدام تطبيقات علم ميكانيكا الكسور واستنتاج مجموعة منحنيات تجريبية تمثل سلوك الكلل في نطاق عدد مقدر من الترددات يتراوح مابين 10 إلى 10^6 تردد تمثل العمر الافتراضي المقدر للمكون المعدني تحت تأثير درجات الحرارة مابين درجة حرارة الغرفة ودرجة حرارة 766 درجة مئوية والتي تمثل حوالي 50% من درجة حرارة انصهار الصلب الأوستنيتي المعنى في هذه الدراسة.

ولإتمام هذا العمل تمت مراجعة الصياغات التجريبية المتاحة في الأبحاث المنشورة لدراسة مقدار الانفعال الكلى لإطاقة الكلل عند تعرض المعدن لدرجات الحرارة المرتفعة. وأكدت المقارنة بين نتائج الصياغات المتاحة إلى الحاجة إلى صياغة جديدة يمكن معها تمثيل العلاقة تمثيلا منطقيا دقيقا وهو ماتم تقديمه في هذا البحث. وقد تم اختبار هذه الصياغة التجريبية المقترحة باستخدامها في استنتاج مجموعة منحنيات تمثل العلاقة بين مقدار تغير إطاقة الكلل منسوبا إلى مقدار الانفعال الكلى تحت تأثير درجات الحرارة المختلفة.

وتشير المقارنة إلى تميز النتائج المستنتجة باستخدام الصياغة المقترحة والمقدمة في هذا البحث مقارنة بالنتائج المستخلصة من استخدام الصياغات التي أمكن حصرها في الأبحاث العلمية المنشورة.

ABSTRACT

Homologous temperature low cycle fatigue data on type 316 austenitic stainless steel have been collected and analyzed using fracture mechanics approach. Average fatigue curves between 10 and 10^6 cycles have been produced over the temperature rang Room Temperature to 766°C (following homologous temperature range of 0.0165, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0,45 and 0.50).

A modified approach for deriving predicted fatigue life curves has been developed in the present work. The developed approach successfully modeled the fatigue endurance in terms of total strain range and a family of temperature dependent fatigue curves has been derived. The data curves have been translated into design curves. Furthermore, the derived fatigue curves are then compared with the available fatigue curves.

KEY WORDS

Homologous temperatures; low cycle fatigue; fatigue curves; design curves; total strain range; fatigue number of cycles; fatigue endurance.

INTRODUCTION

Low cycle fatigue curves in addition to design curves are currently available in published research work and standard international codes such as ASME code [1-7]. These curves are believed not very well based, particularly in relation to the effect of temperature. The fatigue and design curves between 427° C and 538° C were interpolated by linear scaling on the log-log scale since there were no data in between [2-4]. Fatigue data on austenitic stainless steel were collected and re-analyzed, however more consistent set of fatigue curves were produced using a multiple linear regression statistical analysis method [5-7]. Since that time, many more fatigue data on type 316 steel have become available [8-16]. However, it was considered that an

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adequate database could now be compiled which could be treated statistically to give an acceptable set of fatigue curves.

In this work a relevant fatigue data on type 316 austenitic stainless steel have been statistically analyzed and a set of temperature dependent fatigue curves are produced. The fatigue curves then derived are compared with the available fatigue curves.

OUTLINE OF THE GENERAL APPROACH

The material and test conditions used for data selection were such that they should be approximately similar to those relating to ASME Code, [i.e. temperature 24-700° C, strain rate 1 x 10^{-3}/sec]. Data were compiled over temperature range room temperature (RT) to 766° C and strain rate range 1 x 10^{-3}- 1 x 10^{-4}/sec. All the relevant data meeting these conditions, which were available through experimental work [5-8], were collected and included in the analysis. Large number of continuous cycling fatigue results have been collected and analyzed on type 316 steel over the temperature range following homologous temperature range: 0.0165-0.50 (corresponding to RT-766 °C) while endurance values ranged from 10 t0 10^6.

The available approaches that could be founded yet in this interest are summarized in the following.

1-Langer Formula

In this method data at a particular temperature or over a temperature range are analyzed according to the expression [2]·

$$\varepsilon_T = A_1 N_f^{B1} + C_1 \qquad (1)$$

Where ε_T is the total strain range (%), N_f is the number of cycles to failure, and A_1, B_1 and C_1 are constants.

To apply this method, data were grouped into the following temperature ranges: RT, 350-427 ° C, 450-500 °C, 538-570 °C, 593-600 °C, 625 °C and 650 °C. In order to use Langer equation the constant C_1, which is in effect the fatigue limit, has to be pre-selected. A value of 0 31 was generally used.

The fatigue curves derived using this approach are given in Fig. 1.

The Langer approach was discarded because of the subjectivity associated with the pre-selection of the value of the constant C_1

2-Basquin Formula

In this method the elastic and plastic strain components are analyzed separately and then added together to arrive at the total strain range relationships [3-5]. Thus

$$\varepsilon_e = A_2 N_f^{a2} \qquad (2)$$

where ε_e is the elastic strain range (%), N_f is the number of cycles to failure, A_2, and a_2 are constants.

$$\varepsilon_p = B_2 N_f^{b2} \qquad (3)$$

where ε_p is the plastic strain range (%), N_f is the number of cycles to failure, B_2, and b_2 are constants.

$$\varepsilon_T = \varepsilon_e + \varepsilon_p$$

$$\varepsilon_T = A_2 N_f^{a2} + B_2 N_f^{b2} \qquad (4)$$

Thus, this approach utilizes four constants compared with the Langer approach, which only requires three. As in the Langer approach the data need to be grouped into different temperature ranges and the same seven ranges were adopted as those used in method 1. The fatigue curves derived using this method are shown in Fig. 2 in terms of total strain range. The curves obtained are very similar to those given in Fig. 1 using the Langer approach.

3-Multiple Regression Formula

Recent research work [6,7] was carried out using multiple regression analysis on fatigue data on type 316 steel. The cyclic life N_f was selected as the dependent variable and the independent variables chosen were total strain range ε_T in %, and test temperature T_c in °C. The following transformations on the independent variables was employed:

$$S = \log_{10}(\varepsilon_T / 100)$$

$$T = T_c / 100$$

By using the terms S and T, all the transformed variables had absolute values between 0 and 10, and this result in a more set of values for regression coefficients obtained. In addition, they found that the most consistent results were obtained by using the following transformations for N_f.

$$N = (\log_{10} N_f)^{-1/2}$$

The regression equation used was:

$$N = A + BS + CS^2 + DS^3 + ES^4 + FT + GT^2 + HT^3 + JT^4 + KTS + LTS^2 + MTS^3 + PTS^4 \quad (5)$$

A special computer program has been developed, however was employed in conjunction with an Apple Macintosh Computer to evaluate the constants [7]. The fatigue curves obtained using this method of analysis are shown in Fig. 3.

4-Modified Formula

In this stage, data collected at a particular homologous temperature over a temperature range of room temperature (RT) to 766° C were analyzed according to the proposed expression:

$$\varepsilon_T = 10^2\,[1-(t/t_m)].\,N_f^{-q} + [1-(t/tm)]^{t/tm} \qquad (6)$$

where $q = [1-(t/tm)]^{t/tm-1}$

To perform a satisfactory analysis using this approach it is necessary to have a reasonable number of data points at each temperature. However to allow this, the data were grouped into the following homologous temperature range: 0.0165, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0,45 and 0.50. Each set of collected data was treated statistically using a linear regression analysis. Thereupon, the best-fit values of temperature dependent fatigue curves were produced. These curves represent the best fit to the results at a certain temperature ratio. The best-fit fatigue life curves predicted in this analysis are as shown in Figs 4._ More details are summarised in Appendix-A.

The total strain range values that correspond with the number of cycles for different homologous temperature ratio are then calculated as shown in Table 1 given in appendix-B. The modified equation (6) successfully modeled the fatigue endurance in terms of total strain range and a family of temperature dependent fatigue curves has been produced as shown in Fig 5

DISCUSSION

The fatigue curves derived using Langer approach are given in Fig. 1. Although the shapes of the individual curves obtained are reasonable, and in general, the lowest temperature curves as expected gave higher endurance than the higher temperature curves, a completely logical series of curves was not obtained.

The Langer approach was rejected because of the subjectivity associated with the constant C_1 that has a pre-selected value of 0.31 for all sets of data, since it is not logically satisfactory

The fatigue curves derived using Basquin method are shown in Fig. 2 in terms of total strain range. The curves obtained are very similar to those given in Fig. 1 using the Langer approach. The shapes of the curves using this approach are less concave than when using the Langer approach. Furthermore, in this method it is necessary to know the elastic and plastic strain ranges: it was not possible to use all the test results due to the deficiency of plastic strain range data in some cases

As before, although the curves are generally in the correct positions with regard to temperature, some crossovers do occur and hence a completely logical series of curves is not obtained.

The fatigue curves shown in Fig 3 derived using the multiple regression method of analysis; it is believed that the fatigue curves derived using this method of analysis can form the basis of an acceptable set of curves. The curves were generally found to be consistent in relation to temperature, i.e. the higher the temperature the lower the endurance, except for some of the lower temperature curves around 10^5 cycles.

The comparisons of the data sets with the predicted fatigue curves from equ (6) are given in Figs 4, which show good correlation between the predicted curves and the data. It may be seen from these figures that the predicted fatigue lives is generally in good agreement with test results

Inevitably, scatter in the data was found at each temperature range. However, it may due to material variability, i.e. cast to cast effects, or to differences in testing conditions. This latter factor may include specimen shape and size, method of strain control, degree of axiality and temperature distribution. Surface finish is also likely to be important, particularly in test strain range. The curves were generally found to be consistent in relation to temperature, i.e. the higher the temperature the lower the endurance.

Observation of the family of curves given in Fig. 5, indicate that the shapes of the curves obtained are reasonable. Moreover the lowest temperature curves, as expected gave higher endurance than the higher temperature curves, and completely logical series of curves was obtained. In addition, a good correlation between predicted and actual N values is observed by using this method of analysis.

Comparison of the resulted set of curves given in Fig. 6 using the multiple regression and the proposed approach indicated that, the curves obtained by using multiple regression are similar to those given by using the present approach. Nevertheless, the shapes of the curves using multiple regression are less concave than when proposed approach. Moreover, in multiple regression approach it is necessary to utilize thirteen constants compared with the proposed approach, this only requires three. Besides, it is necessary to use an established program that was employed in conjunction with an Apple Macintosh Computer to evaluate the constants.

From the foregoing, it is believed that the fatigue curves derived using proposed approach method of analysis can form the basis of an acceptable set of curves

FATIGUE DESIGN CURVES

The fatigue design curves in ASME Code [1], are given in terms of equivalent strain, and have been derived by factoring the data curves by two on strain range or by 20 0n cycles.

In accordance with ASME code, curves of effective strain range versus cycles to failure were drawn which were factored by two on strain range and 20 on cycles. The effective strain range versus allowable number of cycles relationship thus derived for temperatures of RT, 400°C, 475°C, 550°C, 600°C, 625°C and 650°C (approximatcly corresponding to the temperature intervals quoted in ASME code).

The fatigue design curves derived by the present approach are compared with the fatigue design curves resulted by using multiple regression approach as shown in Fig. 7.

Figure 7 shows that the design curves are virtually similar in shape. There is not much difference in the positions of the curves at low strain ranges, whereas at high strain ranges. However, derived curves by using present approach would permit a higher number of allowable cycles than the curves based on the multiple analysis. Taking a practical strain range level, the number of allowable cycles permitted by the design curves derived in this work would permit 10^5 cycles.

It should be noted incidentally that at RT, 400°C, 475°C and 550°C beyond ~10^4 cycles, the total strain ranges resulted by using the present and multiple approaches are different.

CONCLUSIONS

1-A large number of low cycle fatigue data on type 316 austenitic stainless steel have been collected and analyzed over the temperature range following homologous temperature range· 0.0165-0.50% (corresponding to RT-766 °C).

2-A modified approach for deriving the predicted fatigue life curves has been developed in the present work.

3-Applying the modified model presented in this work, fatigue curves between 10 and 10^6 cycles have been derived over the temperature rang RT-766° C.

4-Four approaches were adopted; namely, Langer model, the Basquin model, multiple linear regression model and the present proposed model. The latter successfully modeled the fatigue endurance in addition to design curves in terms of strain range following the temperature ranges of RT, 400°C, 475°C, 550°C, 600°C, 625°C and 650°C.

5-The present analysis however has shown a significant effect of temperature in the ranges of RT, 400°C, 475°C, 550°C, 600°C, 625°C and 650°C as well as at following homologous temperature range: 0.0165, 0 05, 0.1, 0.15, 0 2, 0.25, 0.3, 0.35, 0.4, 0,45 and 0.50 (corresponding to RT, 77 °C, 153 °C, 230 °C, 306 °C, 383 °C, 460 °C, 536 °C, 613 °C, 690 °C and 766 °C).

6-It is believed that the fatigue curves derived in this work are more soundly based than those given in other adopted approaches are. Since they relate to a much larger, data bank and their constants have been determined by a more complicated procedure.

REFERENCES

1-ASME "Criteria for the design of elevated temperature class I components" Section III, Division I, ASME, New York, USA, (1976)

2-LANGER, B. F., " Design of pressure vessels for low cycle fatigue" J. Basic Engng, p84-107 (1962).

3-COFFIN, L. F., "A study of cyclic thermal stresses on a ductile material" Trans. ASME, 76 (1954).

4-BASQUIN, O. H., "The exponential law of endurance tests" Pro. ASTM. 10 (1910).

5-MANSON, S. S., "Behavior of materials under conditions of thermal stresses" NACA, U.S.A, NACA-TN-2933, (1953).

6-DIERCKS, D. R. and RASKE, D. T., "Elevated temperature strain controlled fatigue data on type 304 steel" a compilation multiple linear regression model and statistical analysis. ALR. ANL. P76-95, (1976).

7-WOOD, D.S. WYNN, J, and WILLIAMSON, K., "Derivation of design curves for the elevated temperature of fatigue endurance of type 316 stainless steel" Int. J. Pres. Ves. and Piping p171-188 (1989).

8-WEBSRER, G. A. "Lifetime estimates of cracked high temperature components" Int. J. Pres. Ves. And Piping, p133-145 (1992).

9-FUJIWARA, M.: ENDO, T. and KANASAKI, H. "Strain rate effects on the low cycle fatigue strength of 304 stainless steel in high temperature water environment" (ASM) Fatigue Life: Analysis and Prediction, Proc. of the international Conference on Fatigue, Corrosion Cracking, Fracture Mechanics and Failure Analysis, Salt Lake City, USA, p309-314 (1985)

10-POLLOCK, T M. and DONER, M. "Modeling of strain ratio effects on low cycle fatigue life" (ASM) Fatigue Life: Analysis and Prediction, Proc. of the international Conference on Fatigue, Corrosion Cracking, Fracture Mechanics and Failure Analysis, Salt Lake City, USA, p341-348 (1985).

11-BERKOVITS, A.: NADIV, S> and SHAIEV, G. "Estimation of high temperature low cycle fatigue on the basis of inelastic strain and strain rate" (ASM) Fatigue Life: Analysis and Prediction, Proc. of the international Conference on Fatigue, Corrosion Cracking, Fracture Mechanics and Failure Analysis, Salt Lake City, USA, p399-404 (1985).

12-NOVAK, V.; SESTAK, B. and KADECKOVA, S. "Strain localization during low-cycle fatigue of Iron and Iron-Silicon alloys single crystals" Proc. of ICF-6, Advances in Fracture Research, p2091-2098 (1984).

13-HAYHURST, D. R. and LECKIE, F. "Behavior of materials at high temperatures" Proc. of the fourth international Conf. on Mechanical Behavior of Materials, STOCKHOLM, SWEDEN, p1195-1212 (1983).

14-LEE, O. S.; PARK, C. and HAN, M. K. "Fatigue life prediction by statistical approach under constant amplitude loading" Proc. of Ninth International Conf. on Fracture, SYDNEY, AUSTRALIA, p1329-1336 (1997).

15-DUPRAT, D. BOUDET, R. and DAVY, A. "A simple model to predict fatigue strength with out-of-phase tension-bending and torsion stress condition" Proc. of Conf. on fatigue, AUSTRALIA, p1379-1386 (1997).

16-SHINGAI, K. "Cyclic elastic-plastic behavior of notches under cyclic tensile load and fatigue life" Proc. of Conf on fatigue, AUSTRALIA, p1421-1428 (1997).

APPENDIX-A

FORMULATION OF THE PROPOSED EQUATION

The main objective of the present work is to develop an empirical formula describing the variation of N_f with two variables: total strain range and homologous temperature ranging .0.0165 to 0.50 % (RT to 766°C).

At this stage, many trials of selecting a mathematical function have been attempted to formulate an empirical equation that may satisfy the required condition.

Since the strain value decreases with increasing the homologous temperature, thus the reasonable representative function for this relation is the monotonic function given as the following:

$$\delta f = f'(\chi_o)\,\delta\chi + \varepsilon\delta\chi.$$

Let $y = f(\chi)$ is a continuos value in the range of $a \leq \chi \leq b$,. The curve sketching of this function is shown in Fig, a.

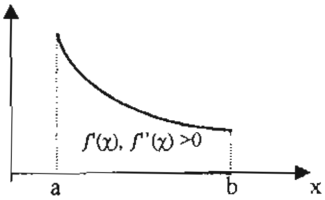


Fig. a

However, the relationship between the total strain values corresponds with number of cycles and homologous temperature range values may be represented by applying the developed formula given as the following:

$$\varepsilon_T = 10^2\,[1-(t/t_m)].\,N_f^{-([1-(t/tm)]\,(t/tm)-1)} + [1-(t/tm)]^{t/tm} \qquad \text{(ia)}$$

A large number of low cycle fatigue data resulted from fatigue tests have been collected and analyzed by using the developed approach.

For the sake of comparison, the present analysis utilized the same collected fatigue data transformations for statistical evaluation using the available method of analysis.

APPENDIX-B

TOTAL STRAIN VALUES CORRESPONDS WITH NUMBER OF CYCLES AT HOMOLOGOUS TEMPERATURE

TABLE 1. Relationships between number of cycles to failure and uniaxial strain range.

N_f Cycles to failure	Uniaxial strain range (%)										
	Homologous Temperature range										
	t/tm= 0.0165	t/tm= 0.05	t/tm= 0.01	t/tm= 0.15	t/tm= 0.2	t/tm= 0.25	t/tm= 0.3	t/tm= 0.35	t/tm= 0.40	t/tm= 0.45	t/tm= 0.50
10	45.95	43.68	40.55	37.36	33.99	31.37	28.56	25.76	23.09	20.53	18.02
100	10.93	10.24	9.33	8.4	7.41	6.74	6.0	5.28	4.62	3.99	3.41
1000	2.81	2.61	2.35	2.09	1.82	1.65	1.46	1.27	1.1	0.95	0.81
10000	0.93	0.87	0.8	0.72	0.64	0.59	0.54	0.48	0.44	0.39	0.35
100000	0.5	0.475	0.45	0.42	0.39	0.37	0.35	0.33	0.309	0.29	0.27
1000000	0.4	0.385	0.37	0.356	0.34	0.33	0.315	0.3	0.285	0.27	0.25

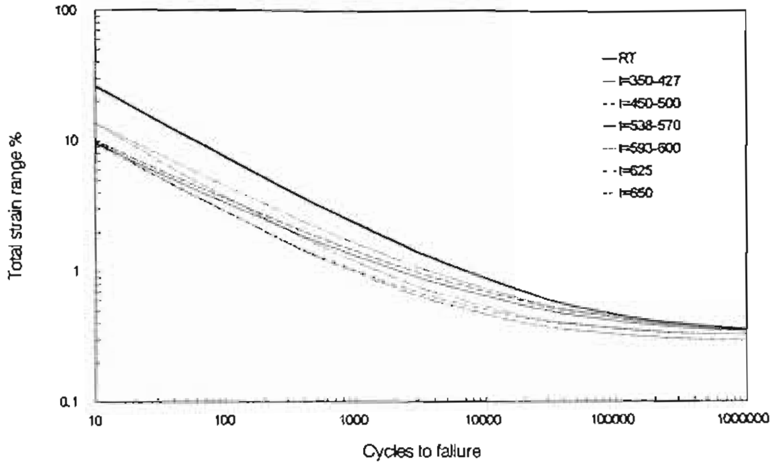


Fig. 1. Best fit curves from Langer equation.

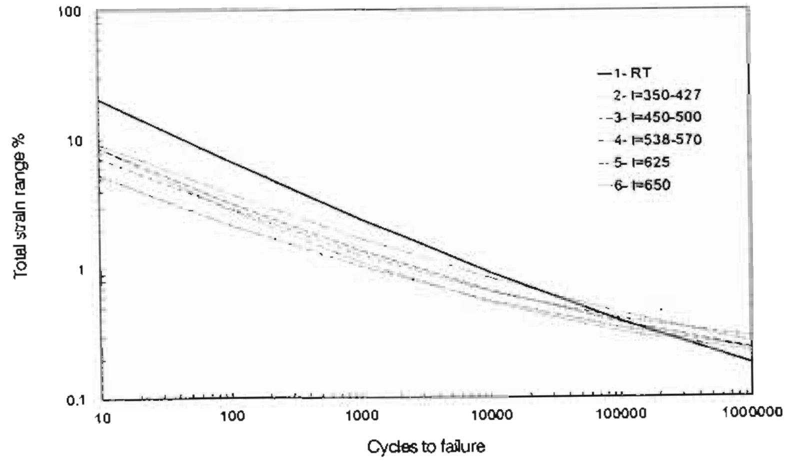


Fig.2. Best fit curves from Basquin equation.

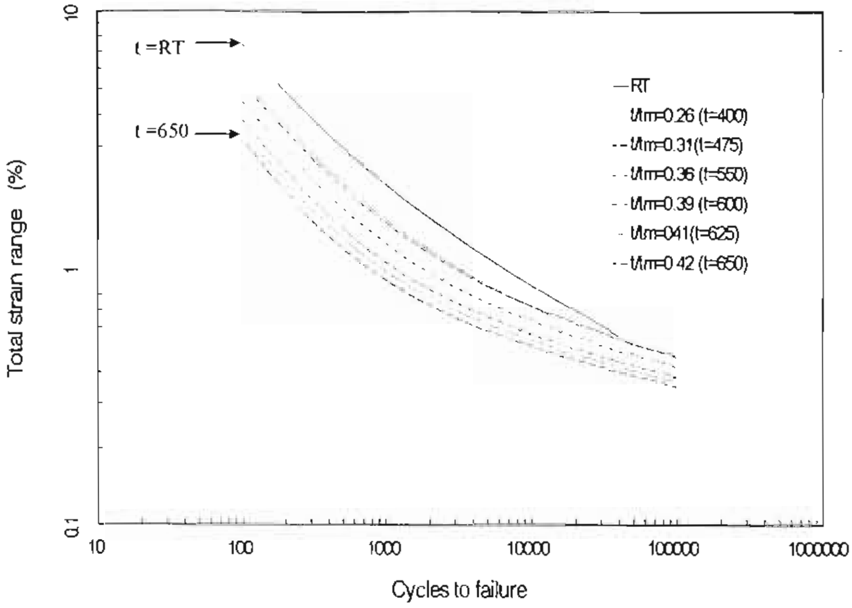
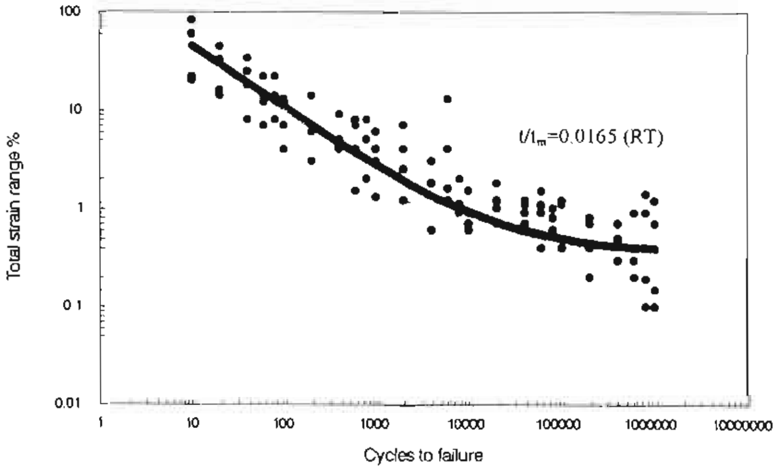
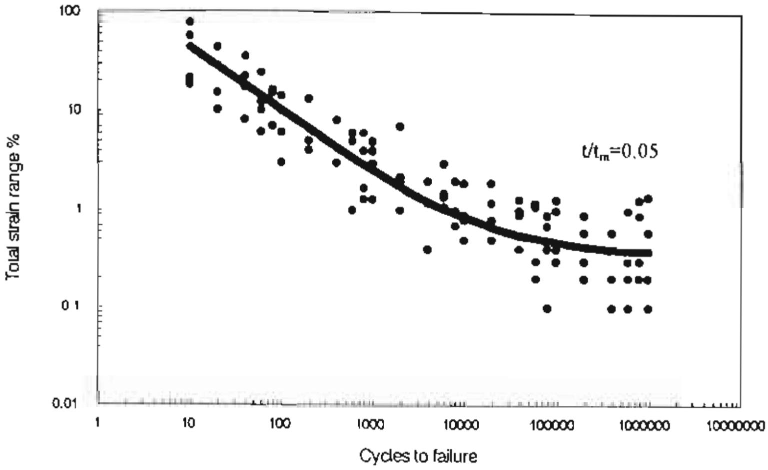
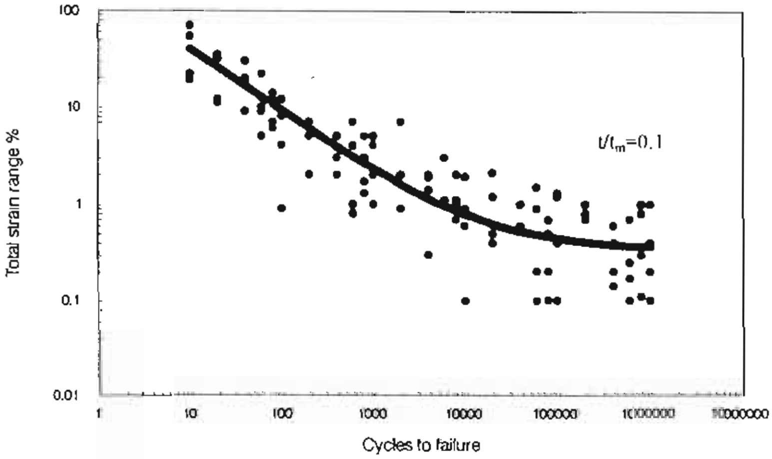


Fig 3 Best fit curves from multiple technique




100
10
1
0.1
0.01
Total strain range %
t/t_m=0.05
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure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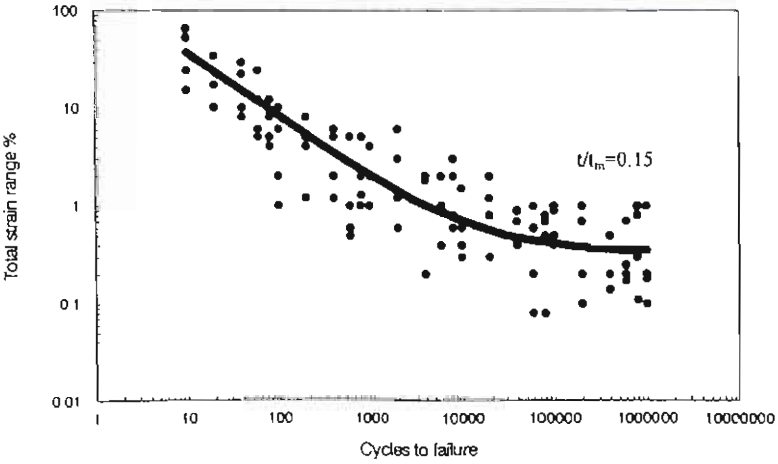
10
1
0.1
0.01
Total strain range %
t/t_m=0.1
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure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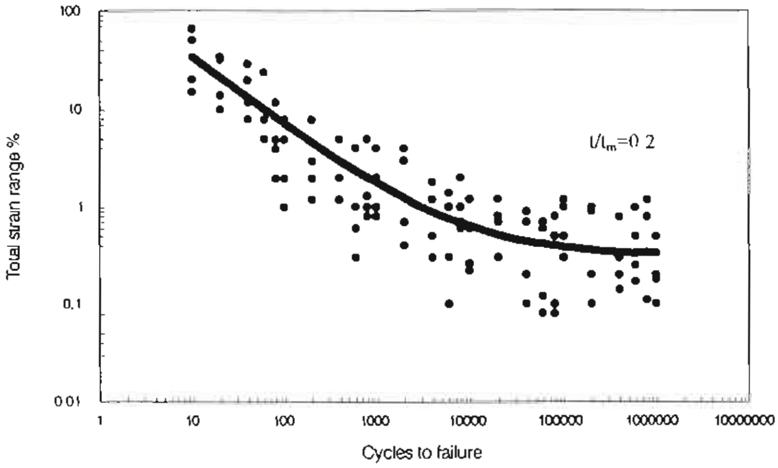
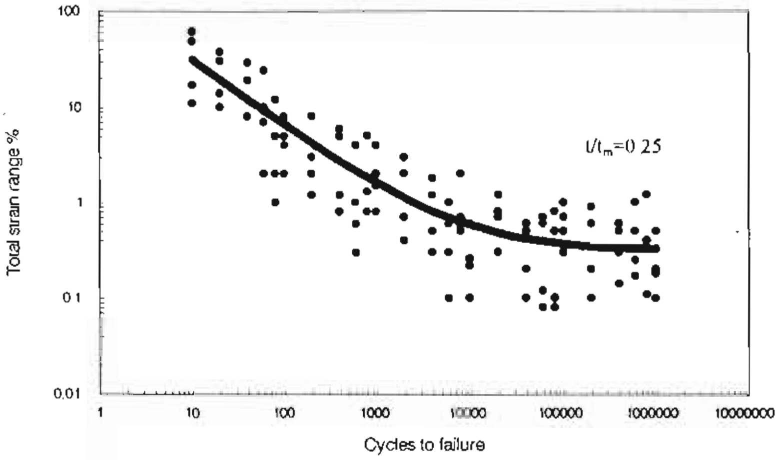
10
1
0.1
0.01
Total strain range %
t/t_m=0.15
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure


100
10
1
0.1
0.01
Total strain range %
t/t$_m$=0.2
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure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1
0.1
0.01
Total strain range %
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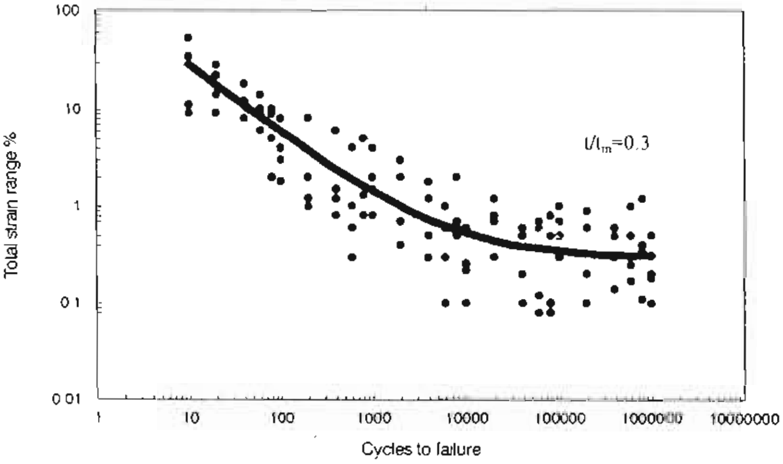
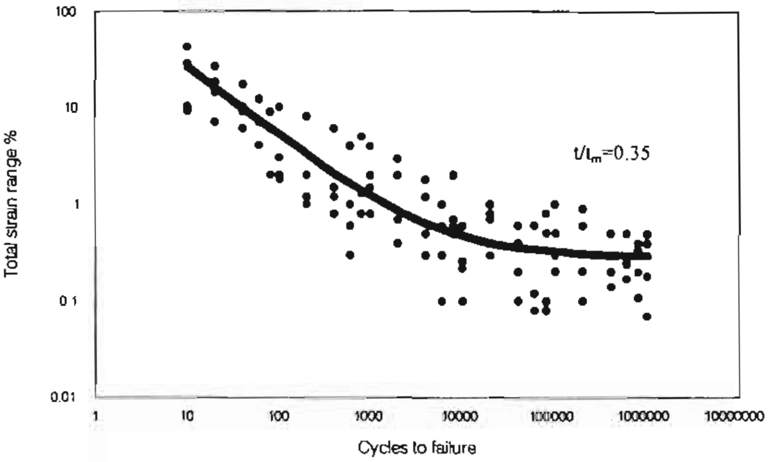
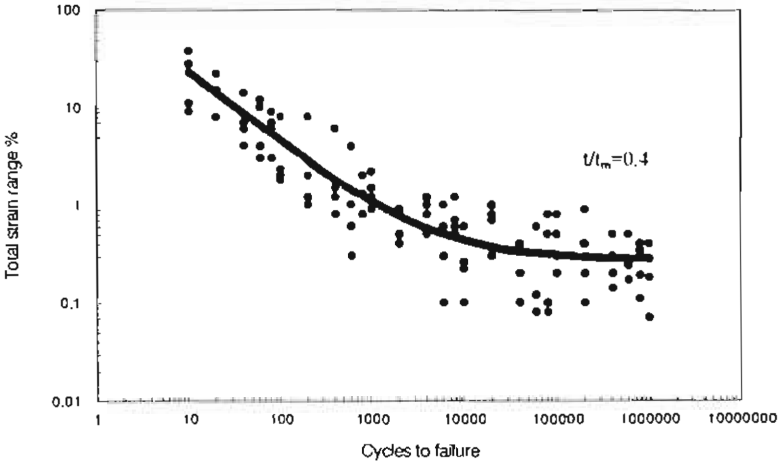
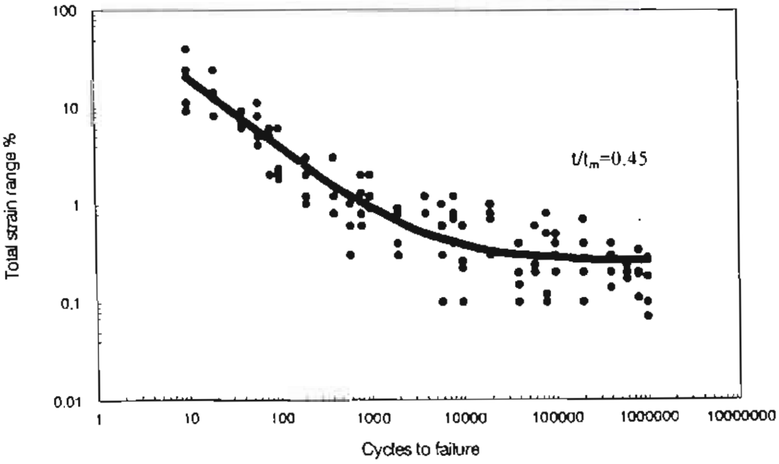
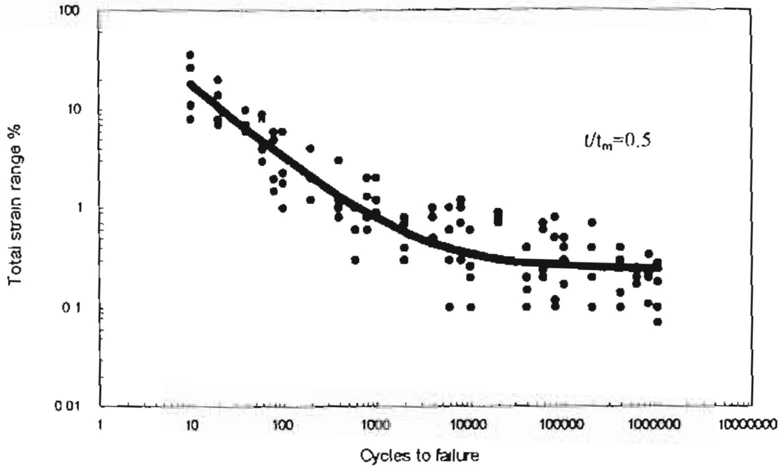
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure


100
10
1
0.1
0.01
Total strain range %
t/t$_m$=0.3
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure


100
10
1
0.1
0.01
Total strain range %
t/t_m=0.35
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure


100
10
1
0.1
0.01
Total strain range %
t/t_m=0.4
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure


100
10
1
0.1
0.01
Total strain range %
t/t_m=0.45
1
10
100
1000
10000
100000
1000000
10000000
Cycles to failure



Figs 4. Best fit curves at t/t_m =0.0165 (RT), 0.05, 0 1, 0.15, 0 2, 0.25, 0.30, 0 35, 0 40, 0 45and 0 50 respectively derived from proposed equation.

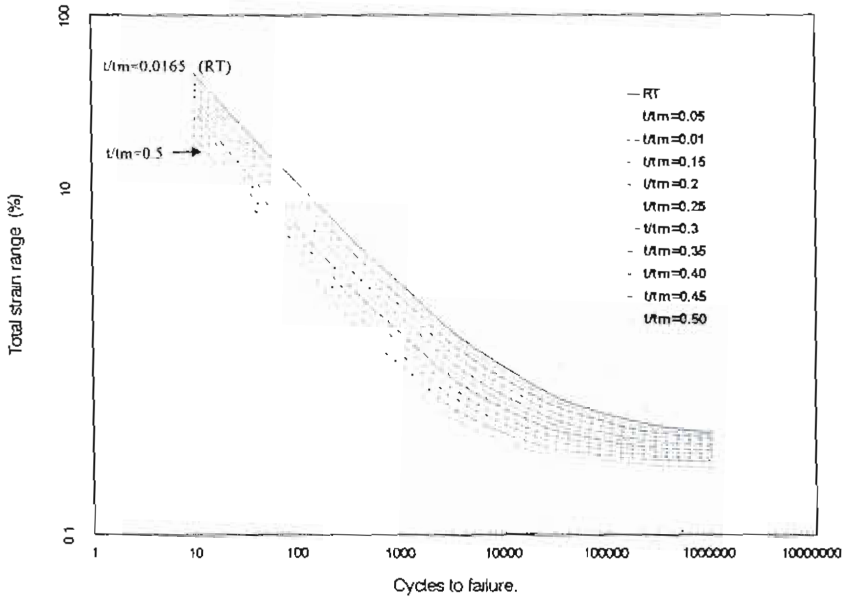


Fig.5 Best fit curves from proposed equation

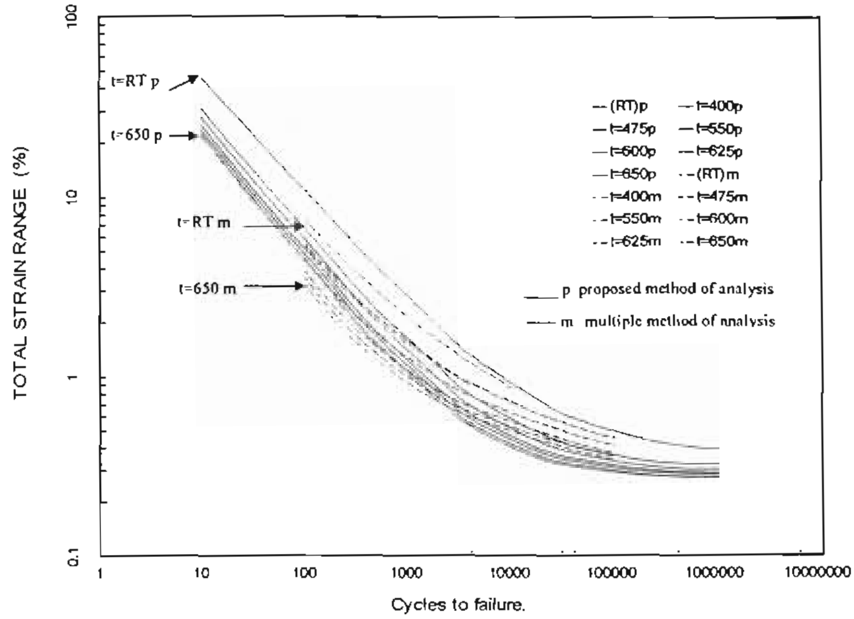


Fig.6 Comparison of fatigue curves obtained using (p) proposed equation and (m) multiple regression.

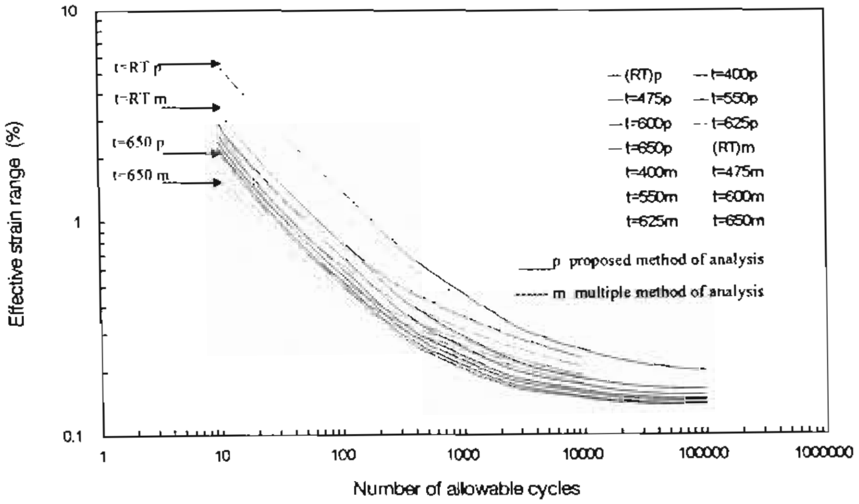


Fig. 7. Comparison of fatigue design curves using (p) proposed equation and (m) multiple regression equation.