Fatigue Life Assessment of SAE 1045 Carbon Steel under Strain Events using the Weibull Distribution

Mazian Mohammad, Shahrum Abdullah, Nordin Jamaludin, Othman Innayatullah*

M.Mohammad
Dept. of Engineering, Fac. of Engineering& Life Sciences,
Universiti Selangor (Unisel), Bestari Jaya Campus,
45600 Bestari Jaya, Selangor, Malaysia

S.Abdullah, N.Jamaludin
Dept of Mechanical and Materials Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia (UKM),
43600 Bangi, Selangor, Malaysia

O.Innayatullah
School of Engineering and Technology
University College of Technology Sarawak
868 Persiaran Brooke, 96000 Sibu, Sarawak, Malaysia

**mazian@unisel.edu.my*

ABSTRACT

The Weibull distribution has been widely used in predicting fatigue life of various materials. In this paper, the Weibull distribution plot is proposed in predicting fatigue life of carbon steel. The specimens made of SAE 1045 steel have been exposed to the cyclic test with five different loadings. The strain gauge has been attached on the specimen to collect the strain events. The cyclic tests were carried out at condition of R=-1 and at frequency of 8 Hz. The collected signals were then analysed based on the strain life model of Coffin-Manson, Smith-Watson-Topper and Morrow. These models provide the basis in predicting the fatigue life of SAE 1045 carbon steel. Statistical analysis was carried out to determine the strain range, root means square (r.m.s) and kurtosis value. From the Weibull distribution probability plots, fatigue lives

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was predicted for SAE 1045 carbon steel based on the given parameters. All plots fitted very well within the 95% confidence interval of the Weibull distribution. Hence, Weibull distribution was suggested to be used as one of assessment tool for fatigue life prediction.

Keywords: *carbon steel, fatigue life, strain, statistical analysis, Weibull distribution*

Introduction

Fatigue failure is known as the biggest contributor to damage or failed mechanical component and structures. Without any warning, fatigue failure will occur when the component or structures experiences cyclic loading for a long time. The failure will force sudden breakdown of a system and even creates the catastrophic damage that can lead to losses of life. Various research and studies in order to detect, locate, monitor as well as predict the fatigue damage of component [1]. Nowadays, the fatigue life problems having such a great attention from the researchers as many techniques and methods were introduced to cater various fatigue problems on different materials and applications. The proposed key part life method was proposed to predict the fatigue life of motor –generator rotor in a pumped-storage plant [2].

There are so many techniques and methods in assessing and analysing fatigue data in order to obtain meaningful results or outcomes. Finite element method has been used excessively used in fatigue life prediction to minimize the production cost and time [3]. Likewise, non-destructive testing (NDT), x-ray and microscopic observation also has been used depending of what type of research that has been carried out [4]. The usage of strain signal collected via strain gauge and other transducers also has been used in assessing fatigue failure. A group of researcher used the strain signals to estimate the fatigue life of an offshore truss structure as well as detecting the damage of a bridge structures [5].

There are many approach to manipulate the data gathered either in digital or analogue form, image as well as signals collected using a transducer. Signal processing and statistical approach has been using widely in analysing the data gathered in fatigue problems. Fast Fourier Transform (FFT), Short time Fourier transform (STFT), power spectral density (PSD) and wavelet are the common selected tool to analyse and display the final result of a fatigue failure cases [6]. The global statistical approach and correlation analysis also has been used in fatigue analysis [7]. The probability distribution such as Weibull distribution shows a number of previous researches with regards to fatigue problem. Previous research showed that Weibull distribution has been used to assess the fatigue life of friction spot welded of aluminium alloy and bearing [8].

The fatigue life prediction has drawn an important direction in fatigue research area. Although, a lot of researchers have conducted numerous techniques in assessing the fatigue life, studies to estimate the fatigue strain life of components is often overlooked. Therefore, It is inspired the authors to conduct a study on analysing the strain events collected from carbon steel specimens that are usually used in oil and gas industries. The aim of this paper is to predict the strain life using the probability technique. The Weibull distribution plots successfully predicted the fatigue life of the material using the experiment and strain model cycle to failure as well as statistic parameter such as strain range, r.m.s and kurtosis of the signals. The results obtain may use as a tool in assessing the remaining life of the material.

Theoretical Background

Fatigue Life based on Strain-Life Approach

The strain-based model of fatigue life usually practised for small component that is influence by the crack initiation. It is related to the plastic deformation that occurs at a localized region, where the crack begins to initiate. Usually, this model uses ductile material with short fatigue lives and it normally associated with the Palmgren-Miner linear. There are three strain-life fatigue models that are normally used in this approach [9]. The first model that neglected the mean stress effect is called Coffin-Manson model as shows in Equation 1:

$$\varepsilon_a = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \tag{1}$$

where ε_a is the true strain amplitude, σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, E is the modulus of elasticity, and N_f is the number of cycles to failure for a particular stress range. Other models are dealing with the mean stress effect are Morrow and Smith-Watson-Topper (SWT) model as shown in Equation 2 and 3, respectively.

$$\varepsilon_a = \frac{\sigma_f'}{E}\left(1 - \frac{\sigma_m}{\sigma_f'}\right)\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \tag{2}$$

$$\sigma_{max^{\varepsilon_a}} = \frac{\left(\sigma_f'\right)^2}{E}\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c} \tag{3}$$

Where σ_m is the mean stress, and σ_{max} is the maximum stress for the particular cycle.

Signal Analysis

In this study, the strain range has been extracted from the strain events. The strain range is determined using the peak and valley (PV) analysis. The mathematical expression to calculate the strain range is shown in Equation 4.

$$\text{Strain range, } \Delta\varepsilon = \text{Peak} - \text{Valley} \tag{4}$$

Beside strain range, the r.m.s and kurtosis also has been used in this study. It is known that both parameters are usually used in damage detecting for major engineering problems. The r.m.s is the 2nd statistical moment that has been used to quantify the overall energy content of the signal. For discrete data sets, the r.m.s value is defined in Equation 5.

$$r.m.s = \left\{ \frac{1}{n} \sum_{j=1}^{n} x_j{}^2 \right\}^{1/2} \tag{5}$$

The kurtosis which is highly sensitive to the spikiness of the data is the 4th statistical moment. The formula to determine kurtosis value is shown in Equation 6.

$$K = \frac{1}{n(r.m.s)^4} \sum_{j-1}^{n} \left(x_j - \bar{x}\right)^4 \tag{6}$$

Weibull Distribution

Weibull distribution is one of the probability methods that usually used in fatigue problems. The versatility in adapting the data makes it a wise solution in estimating crack size and sample data as well as distribution of life of components that experience fatigue loading [10]. The Weibull distribution function is shown in Equation 7, where β is the shape parameter, η is scalar parameter and t is the variable parameter. The values of β and η are estimated from the data distribution.

$$f(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{7}$$

Methodology

The strain events were collected during the axial fatigue test. The tests were run accordingly to the ASTM standards that will be described in next section.

The number of cycles to failure from the experiments and strain life model calculated using specific software were calculated. Also the strain range, r.m.s and kurtosis were determined using the strain events. All the parameters collected were then plotted using the Weibull distribution plot. The overall experimental process and procedure is shown in Figure 1.

Specimen Preparation

SAE 1045 medium carbon steel has been used as the specimen and cut to a flat specimen, according to ASTM E8 with 146 mm, 20 mm and 3 mm of length, width and thickness, respectively as shown in Figure 2. This type of carbon has been widely used in many applications such as automotive, power plants, oil and gas industries. Prior to this, the specimens has been polished using several grades of silicon carbide abrasive papers. This is to ensure that the surface is free from any scratch as well as to remove residual stress caused by the machining process [11].

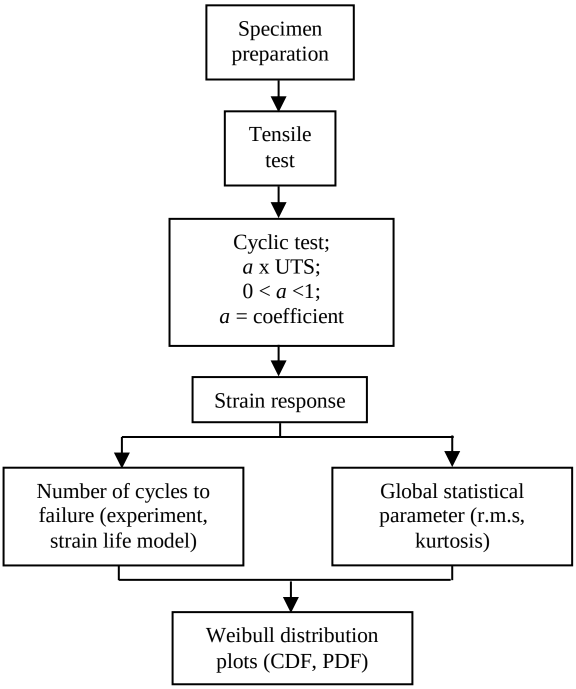
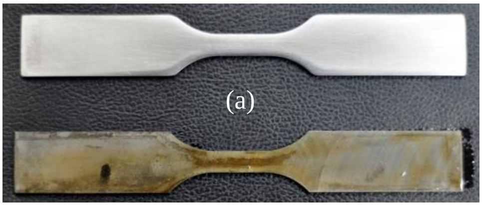


Figure 1. Process flow throughout the research



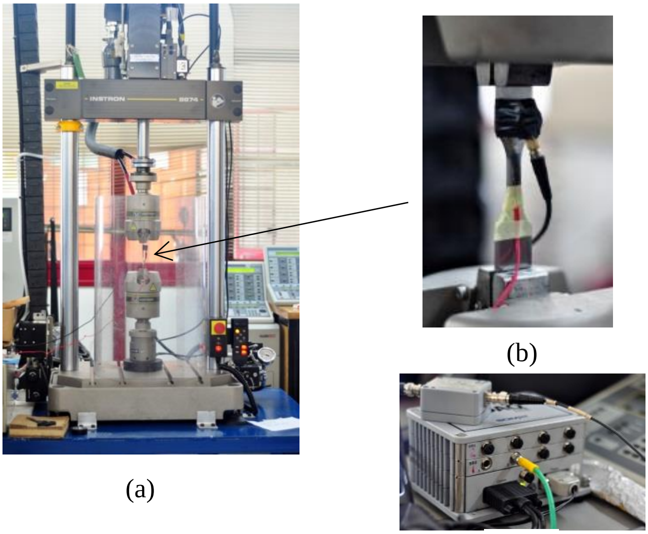
(a)

(b)

Figure 2. Image of specimen images (a) after; (b) before polishing process

Testing Procedure

The tensile test was performed according to the ASTM E8 to obtain the monotonic properties such as ultimate tensile strength (σ_u), yield stress (σ_y) and Young modulus (E). The test has been performed using the 100 kN universal testing machine) with a cross speed rate of 1.2 mm/min. The uniaxial cyclic tests were then carried out at stress ratio, R=-1 using the 25 kN servo hydraulic machine at 60 %, 65 %, 70 %, 80 % and 85 % of the σ_u value, as indicated in the ASTM 466-96. A 2-mm strain gauge was attached to the specimen using a cyano-acrylate type adhesive material to collect strain events during the test. The strain gauge was then connected to the data acquisition system of Somat EDAQ at the sampling rate of 100 Hz as shown in Figure 3.



(a) (b) (c)

Figure 3. Experimental setup (a) servo hydraulic 25 kN machine (b) location of strain gauge on the specimen (c) Somat EDAQ data acquisition system

Results and Discussion

The monotonic properties collected from the tensile test are tabulated in Table 1. The ultimate tensile stress (UTS), σ_u was at 798 MPa when the yield stress, σ_y is at 414 MPa. The fatigue cyclic test was run based on the value of UTS gathered from the tensile test. The tests were carried out at 60, 65,70, 80 and 85 % of the UTS value as shown in Table 2.

Table 1. Monotonic properties for SAE 1045 from the tensile test

Properties	Value
Ultimate Tensile Stress, σ_u	798 MPa
Yield Stress, σ_y	414 MPa
Young Modulus, E	196 GPa

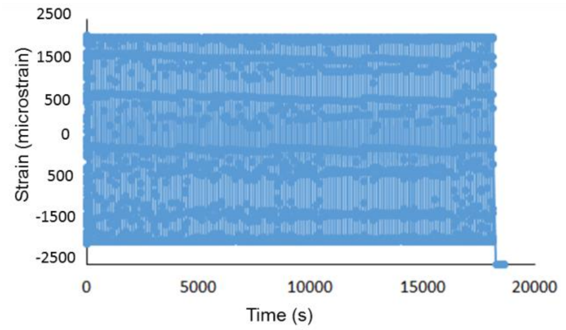
Table 2. Applied stress for the cyclic test

Percentage of σ_u (%)	Stress Value (MPa)
60	480
65	520
70	570
80	640
85	680

The strain events collected from the cyclic test are shown in Figure 4. The events shows the range of the signal as well as the time taken for the specimen to fail. Specimens at loads 480 MPa stress value took four days to break, where else two days for loads at 520 MPa. For other stress loading, the specimen break only in one day. The signals tabulated in the figure are showing the failing stage of every specimens under their respective applied stress. Table 4 shows the failing time and the strain range readings for each specimens under different applied stress. It is shows that higher applied stress will shorten the failing time but increased the strain range reading. As the stress increase, the vibrational effect will increase and produce higher strain range due to high shear stress [12]. Therefore the time for specimens to fail is decreased compared to lower stress.

Table 4. Time to failure and strain range reading of the SAE 1045 at different applied load

Applied Stress (MPa)	Time to fail (s)	Strain Range Reading ($\mu\varepsilon$)
480	87300	2294
520	33900	3200
570	15000	4059
640	1800	4565
680	250	5800



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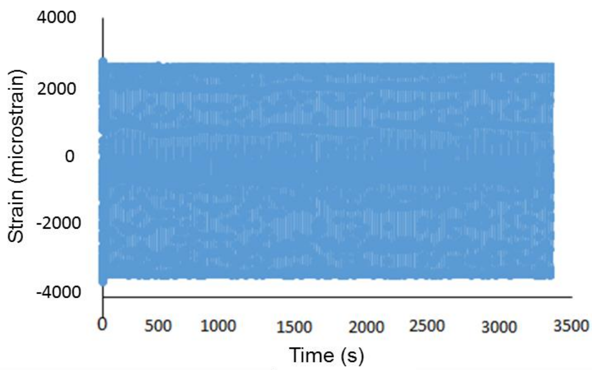

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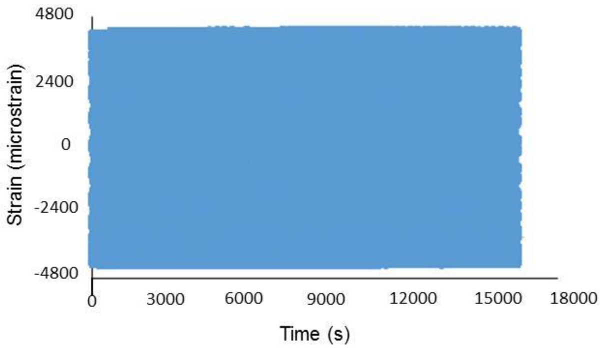

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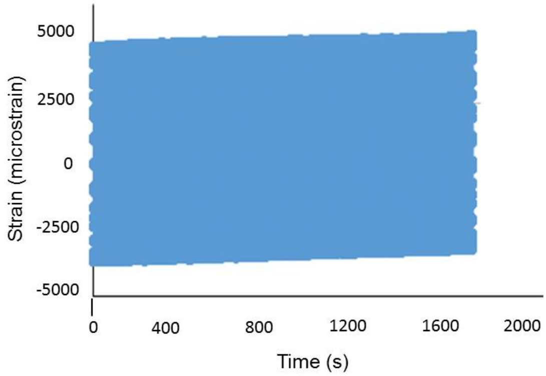

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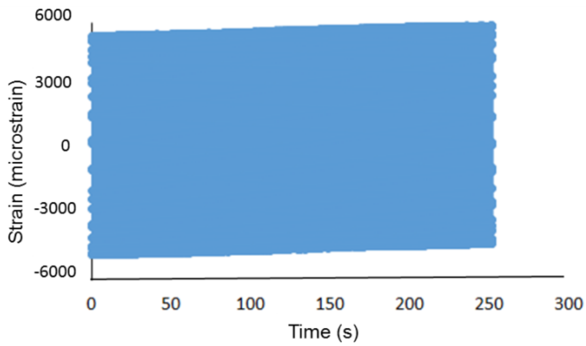


(e)

Figure 4. The strain responce collected from the cyclic fatigue test; (a) 480 MPa (b) 520 MPa (c) 570 MPa, (d) 640 MPa, (e) 680 MPa

Table 5 shows the number of cycle to failure collected from experimental analysis were calculated cycle using the strain life model. The three strain life model i.e. Coffin-Manson (CM) equation, Smith-Watson-Topper (SWT) and Morrow models were analysed using spesific software. The strain life is counted using the rain-flow counting using the strain events as the input. The materials properties are determined from the database of the software, where it is very similar to the theoritical and acual material properties. The number of cycle to failure is tabulated from 2 x 10^3 for 680 MPa and 7 x 10^5 for 480 MPa applied stress for all strain model and experiment value. Figure 5 shows the trend of number of cycles to failure toward different value of applied stress. It can be concluded that the number of cycles to failure is decreasing with the increment of the applied stress. More stress experienced by the specimen will contributes more vibrational force that shorten the fatigue life of the specimen [13].

Table 5 The number of cycle to failure between strain life model and experiment

Stress (MPa)	Number of cycle to failure, N_f			
	Coffin Manson (CM)	Morrow	SWT	Experiment
480	5.55 x 10^5	5.91 x 10^5	5.62 x 10^5	7.58 x 10^5
520	4.45 x 10^5	5.67 x 10^5	2.15 x 10^5	2.27 x 10^5
570	1.42 x 10^5	1.13 x 10^5	8.38 x 10^5	1.24 x 10^5
640	2.53 x 10^4	2.50 x 10^4	2.55 x 10^4	1.41 x 10^4
680	3.35 x 10^3	3.27 x 10^3	2.64 x 10^3	2.64 x 10^3

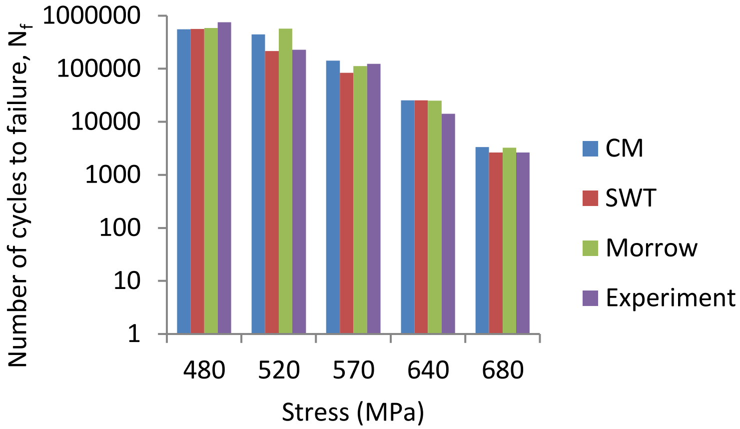


Figure 5. The trend of number of cycle to failure towards the different applied stress

To make sure that the predicted fatigue life using the strain life model are satisfactory the experiment value, Figure 6 is plotted. The figure shows the correlation between the experimental fatigue life towards the predicted fatigue life using the strain life model i.e CM, SWT and Morrow. The plot shows majority of the points were placed within range of factor of 2 and only one point was located beyond the 2:1 correlation line. Therefore, the fatigue life experiment that has been carried out is within acceptable accuracy.

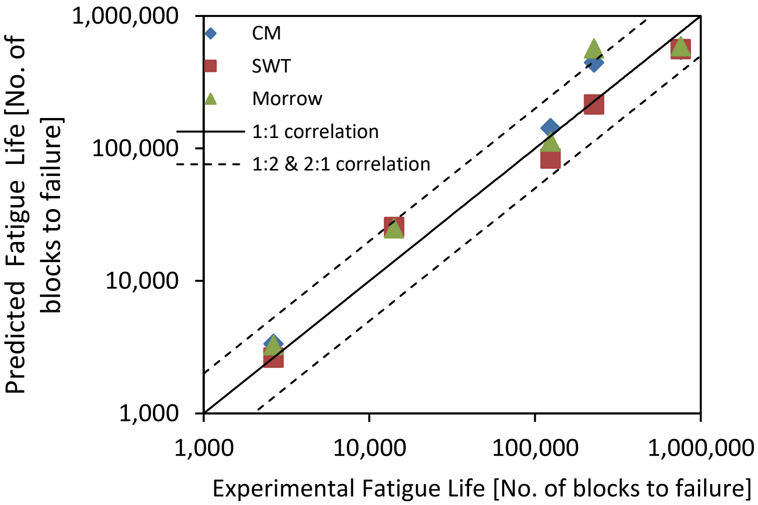


Figure 6. The correlation of predicted and experimental fatigue life

Besides the fatigue life, the strain events also has been analysed to determine the r.m.s and kurtosis as shown in Table 6. The r.m.s value is tabulated between 1600 to 2150 $\mu\varepsilon$ and increasing with the increment of stress value. The value of r.m.s is important to evaluate the overall discrete energy of a periodic signal where higher energy will produce higher vibrational effect that will increase the value of r.m.s [14]. Value of kurtosis seems to have the same situation of the r.m.s. The kurtosis is increasing with the increment of stress because kurtosis is calculated the peak value of the signal that contributes to damage. The trend of the r.m.s and kurtosis towards the different applied stress is plotted in Figure 7.

Table 6 r.m.s and kurtosis value of strain events at different applied stress

Stress (MPa)	r.m.s ($\mu\varepsilon$)	Kurtosis
480	1603.52	1.48
520	1680.24	1.50
570	1770.95	1.51
640	1892.48	1.53
650	2146.60	1.70

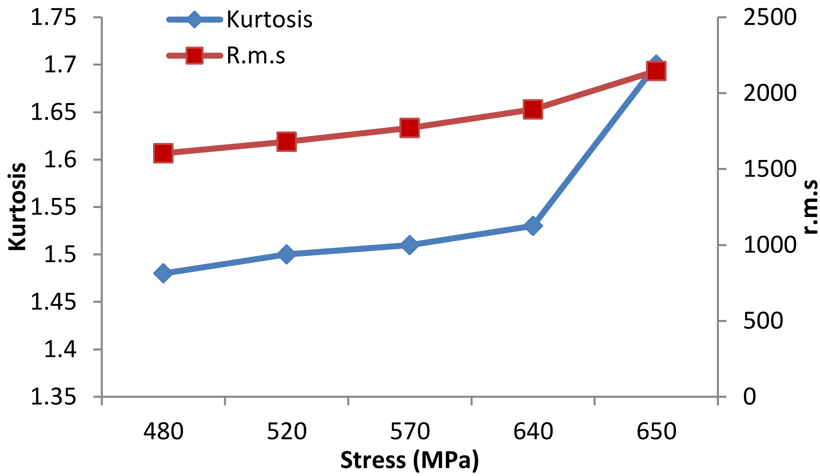
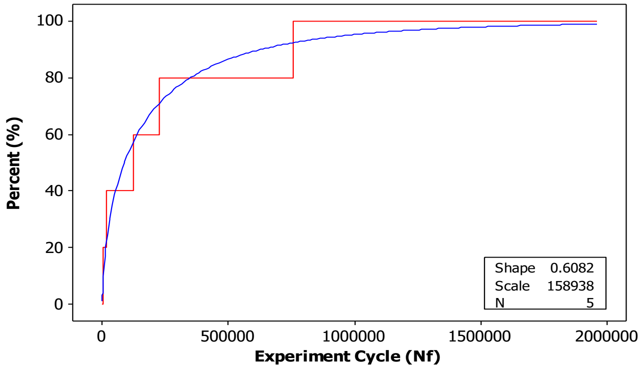


Figure 7. The trend of r.m.s and kurtosis of the strain events at different applied stress

Besides that, the probability distribution can be used to analyse as well as to predict fatigue life also. In this research, the Weibull distribution has been used to predict the fatigue life of the specimen due to its versatility that has been proved through previous research [10]. Figure 8 shows the cumulative distribution failure (CDF) plots of the experiment data (Figure 8 (a)) and cycles predicted by the three strain life model (Figure 8 (b)). The empirical CDF graph plotted to compare the fitted distributions for every cases and it can be used to estimate the failure percentile. An empirical CDF is alike the probability plot except both axes in CDF are linear making interpretation of data to be more flexible computationally [15]. The 2-parameter Weibull distribution plots are shown in Figure 9. The observed failure cycles are plotted on the x-axis to the y-axis that estimating the cumulative probabilities. The 95% of confidence intervals for the fitted line are considered in this paper.

From Figure 8, it shows that the shape factor of all fatigue life collected from the experiment and the strain life model tabulated from 0.60-0.69. The scale parameter is tabulated from 139000 to 200000 based on the cycles of the model. These two parameters were in order to suit the data with the type of distribution and percentile chosen. Using the plots, the fatigue life can be predicted at any percent probability of failure. For 10 % probability of failure are extrapolated to 3 x 10^3, 7 x 10^3, 5 x 10^3 and 6 x 10^3 cycles for experiment, CM, SWT and Morrow, respectively. There are limited sources of carbon cases but previous study on magnesium alloy showed fatigue failure at 1 x 10^4 at same probability percentage [15]. It is because the different properties and microstructure between the component materials. Similarly at 50 % of probability of failure, the experiment and SWT model extrapolated 8 x 10^4 cycles while CM and Morrow model gives higher fatigue life at 1 x 10^5 cycles.



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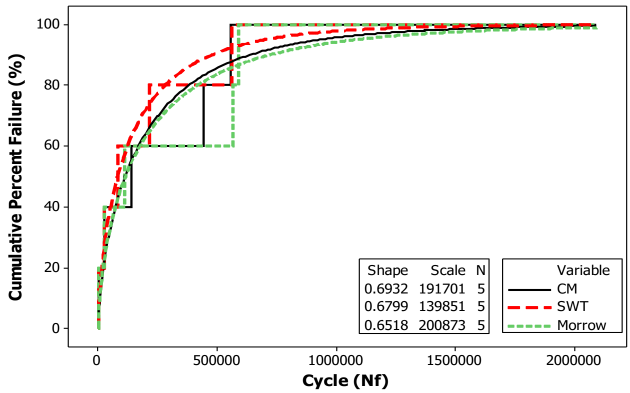
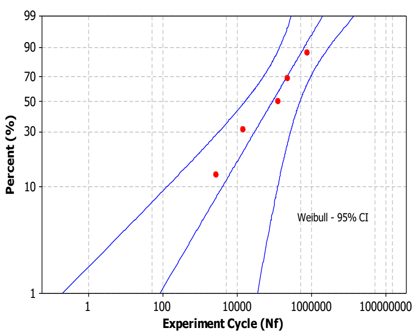


(b)

Figure 8. Empirical CDF to failure (a) experiment cycle (b) strain life model



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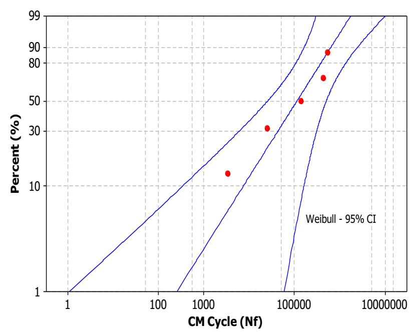

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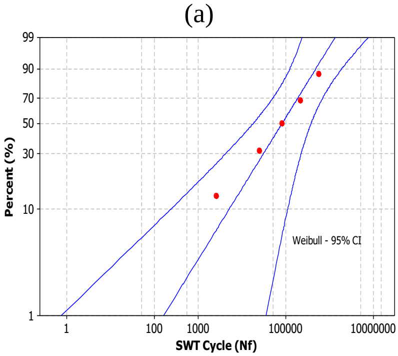

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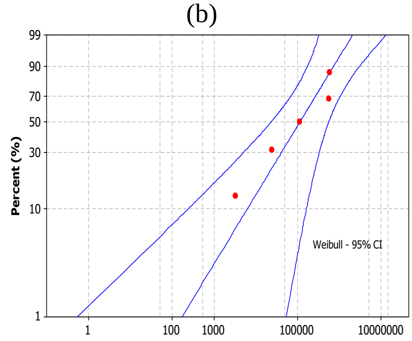

(d)

Figure 9. Probability plot for failure cycle (a) experiment (b) Coffin-Manson (c) Smith-Watson-Topper (d) Morrow model

Conclusion

The fatigue life of SAE 1045 carbon steel can be predicted using Weibull distribution. The number of cycles to failure for five different loadings from the uniaxial cyclic test and strain life model i.e CM, Morrow and SWT were presented in this paper. The predicted strain life value calculated by the strain life model seems fitted nicely within the factor of 2 line of the experiment value. The r.m.s and kurtosis value also has been determined. The value of r.m.s tabulated from 1603 to 2146 $\mu\varepsilon$ while kurtosis showed a value range 1.48-1.70. It shows that the value of r.m.s and kurtosis is increased with the applied stress increment experienced by the specimens. The numbers of cycles to failure that have been extracted from the experiment and the strain events were fitted nicely in the 95 % confidence intervals of Weibull PDF and CDF plots. From the plots, the shape factor of all fatigue life collected from the experiment and the strain life model tabulated from 0.60 to 0.69. In a meantime, the scale parameter is found to be tabulated from 139000 to 200000 which are based on the cycles of the strain life model. Using the Weibull distribution, the life of the specimens can be determined. For instance, the 50% of probability of failure, the experiment and SWT model extrapolated 8 x 10^4 cycles while CM and Morrow model gives higher fatigue life at 1 x 10^5 cycles.

Acknowledgement

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