EXPERIMENTAL EVALUATION OF WÖHLER CURVE FOR MILD STEEL PLATES MANUFACTURED IN NEPAL

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Abstract

This research work was carried out to explore the fatigue behavior of Mild Steel Plates manufactured in Nepal and determine the Wöhler Curve of the plates by preparing test specimens and conducting fatigue experiment of the specimens in the rotating cantilever bending fatigue test machine. The laboratory data thus obtained were plotted to generate the Wöhler Curve of the material. Along with the curve the Basquin's Coefficients and Endurance limitup to 10^6 cycle were determined.Specimen was designed in accordance to ASME E 466-15 and the machining was done in accordance to IS 1075-1985 and then was subjected to various different loads. Exploratory tensile test of the material was also done in order to find out the proportion of the applied load with respect to the ultimate strength of the material. Surface crack was also inspected.Micro void coalescence and Micro cleavage formations were noticed in the fractured section.

Keywords: *Basquin Coefficient, Endurance limit, Fatigue, Wöhler Curve*

1. INTRODUCTION

Failure of a machine component or a structure, when subjected under a repeated or cyclic load, within the elastic limit, by initiation, development and propagation of crack, is called fatigue. The component fails its ability to withstand the load even when it is working well below its yield strength[1]. It is one of the major causes of failure of machinery items. This study aimed at determining the Wöhler curve of the Mild Steel plates that are manufactured in Nepal using Nominal Stress Approach. The study is also focused in determining the endurance limit, Basquin's coefficient[2] and the mode of failure in the fractured surfaces.

Nominal Stress life approach is an approach where constant amplitude loading is applied in the test. Generally, the tests apply tensile or compressive or cyclic load to the test specimen to determine the fatigue behavior of the test material.

The constant amplitude loading for nominal stress approach is given as usually be given as demonstrated in the figure below.

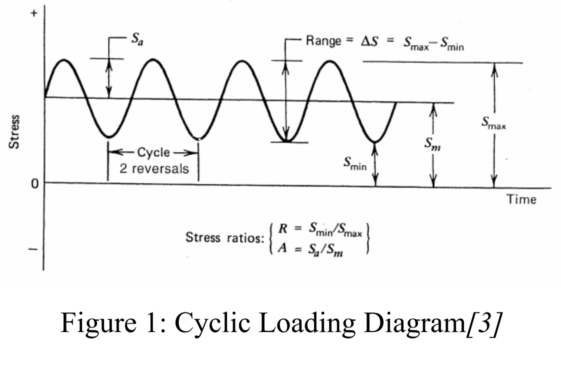


Figure 1: Cyclic Loading Diagram*[3]*

Where,

S_{min} =is the minimum stress applied

S_{max}= is the maximum stress applied

S_m= is the mean stress applied

S_a= is the alternating stress applied

Stress Ratio, $R = S_{min}/S_{max}$

$A= S_a/S_m$

Common reference testing in the constant amplitude tests are R = -1, i.e. fully reversed or $S_{min} = -S_{max}$and R = 0, i.e. pulsating tension conditions.

Thus, the load/stress applied to the test specimen and the number of cycles to failure of the test specimen could be gained via. Experiment and be plotted to the in the graph known as S-N curve or the Wöhler curve, named after August Wöhler, who did first ever systematic fatigue tests and generated the stress vs life diagrams. Additionally, further work on the S-N diagram was carried out by [4] and [5] for better life prediction using Wöhler curve.

One of the most important finding from the Wöhler curve would be the determination of the coefficients of the Basquin's equation of the given material. The Basquin equation gives the S-N relationship as $S_{Nf} = S_u \times (N_f)^B$

Where,

S_{Nf}= Applied load amplitude

N_f = Number of cycles to failure

S_u = Ultimate Strength

B = slope of log-log S-N curve.

Thus the so found coefficients A and B of the relation will now help to determine the N_f of the material if the material is to be designed under the premises of the certain loading conditions.

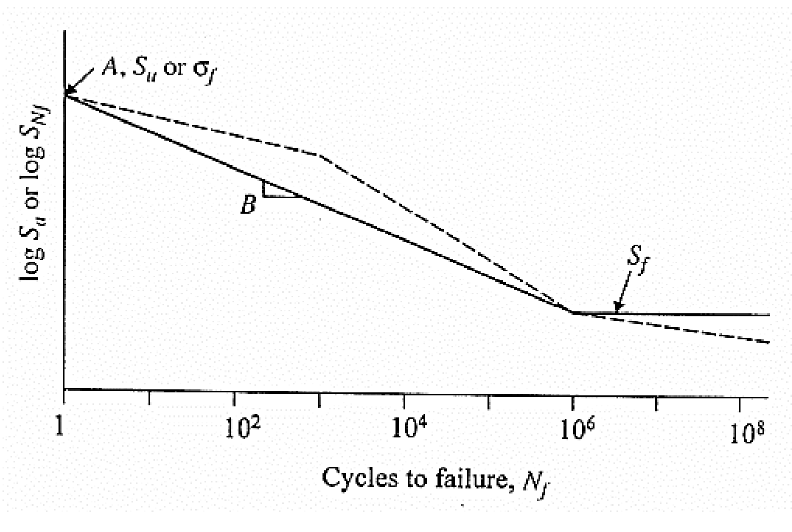


Figure 2: Representation of Basquin's coefficients in S-N Curve*[6]*

2. Methodology

Research Outline

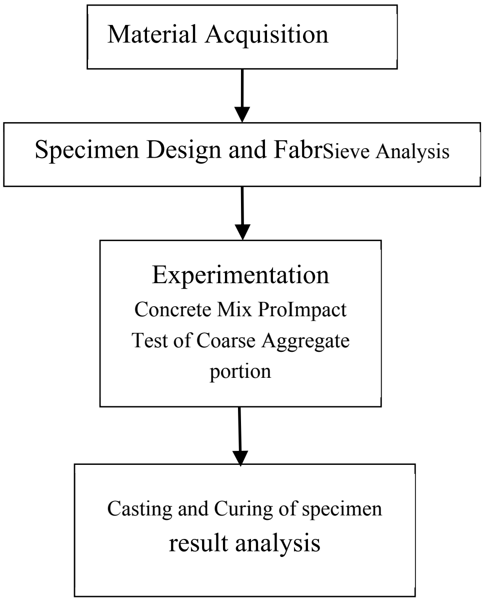
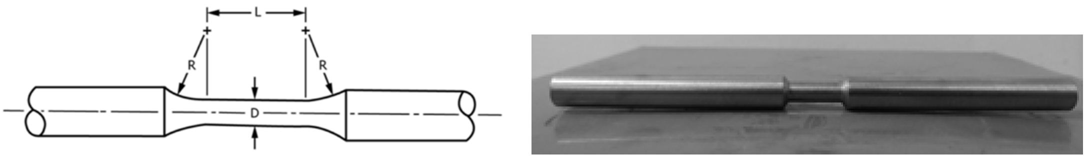


Figure 3: Research Outline

The fig 3 shows the research outline of the research. In the beginning, the materials were brought from the market in the form of various different rods, which were cut through the mild steel plates that are manufactured in Nepal. The rods were then required to machined and fabricated according to the standards available for fatigue test specimen preparations.

Test specimen

The specimens were to be made in accordance to the standards available. ASTM E 466-15[7]was followed forthe design of the specimen



(a) (b)

Figure 4: Specimen (a) ASTM E 466 -15*[7]* (b) Manufactured for testing

Experimental work requires defined number of samples and was adopted accordingly[6][8].These standards made it possible to reduce stress concentrations, surface irregularitiesand uniformities in specimen while applying various different loads[8].

Test Setup

The rotating cantilever bending fatigue test machine in the laboratory of the Thapathali Campus, IoE, TU is as below.

As we can see from figure 5 that an electric motor is coupled with one of the bearing, namely main bearing. The motor gives rotational motion to the main bearing, which holds the specimen tightly via. Chuck. The test piece is centered correctly with another bearing, namely load bearing, mounted on to the chuck. The extension below the load bearing is where the load is applied to. The load was available in the form of standard weights of 5 N, 10 N or standard mass of 1 Kg, 0.5 Kgs, 2 Kgs and 8 Kgs approximately.

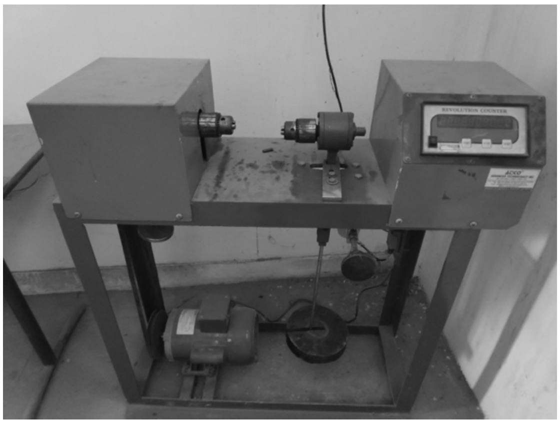


Figure 5: Rotating Cantilever Bending Fatigue Machine

In a rotating cantilever bending fatigue test the fully reversed load are applied, hence $S_a = S_{max}$. The bending moment is non-uniform across the specimen length is given by

$$S = My/I$$

Where,

S =Stress amplitude applied to the specimen

M = Bending moment at due to load on critical point of the specimen

y =Distance from the specimen axis to radial direction (y_{max} = Specimen Radius)

I = Moment of Inertial of the cross section of the test specimen

The combination of different load was madeduring the test.Furthermore, an exploratory tensile test or monotonic loading test was also done for the same material in order to find the approximateultimate stress of the material.

Failure Surface Analysis

As the test specimen were subjected to different loadings, the specimen failed under various different cycles. The fracture of the specimen was magnified through macro lens extension at the zoomed condition of the mobile phone camera. The picture of the fractured section was then captured and analyzed for the detection of crack growth in the surfaces

3. Result and Discussion

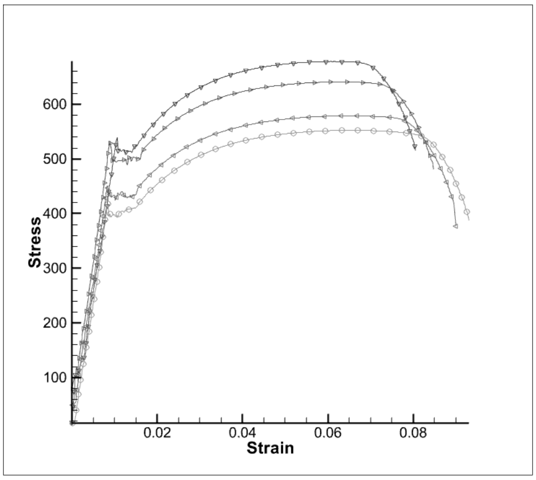
Monotonic Loading

In the beginning tensile test of 4 samples, made especially for the test, were done. The following values were obtained.

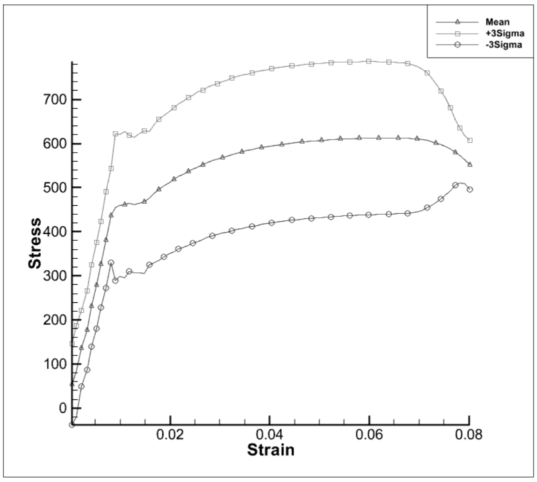
Table 1: Data from the tensile test

S.N	Upper yield strength (MPa)	Lower YieldStrength (MPa)	Tensile Strength (MPa) S_u
1	540.2	509.9	679.1
2	532.8	489.6	641.2
3	418.1	392.7	552.4
4	451.3	424.9	579

The machine gave 100s of data for individual tests and provided the required values too. But, the data for the same strain were not available, sothe data were interpolated at an equal interval of strain and then plotted against the respective stress thus obtained after the interpolation.



(a)



(b)

Figure 6: Stress vs Strain curve (a) of four specimen (b) Mean value and three times of standard deviation

As it can be seen from figure6 (a) that there is a huge difference of data from specimen to specimen of the same material. In figure 6 (b), mean stress strain curve and 3 times standard deviation is plotted.The tensile test presented us with an outlook on how the given stresses in the fatigue test were proportionate to the average value of the ultimate stresses of the material.

After the completion of the tensile test, Fatigue test was done to find the number of life before failure. Since the failure could be inspected up to any number of cycle, this research is limited up to the 10^6 cycle of loading before failure and the result was obtained as table 2 below.

Table 2: Fatigue failure data

Specimen Number	**Stress**	**No of Cycle**	**Remarks**
1	0.35 S_u	6.93E+05	Failed
2	0.35 S_u	2.83E+06	Not Failed
3	0.40 S_u	2.49E+05	Failed
4	0.40 S_u	8.24E+05	Failed
5	0.43 S_u	2.18E+05	Failed
6	0.46 S_u	1.76E+05	Failed
7	0.46 S_u	1.98E+05	Failed
8	0.57 S_u	8.79E+04	Failed
9	0.57 S_u	1.76E+05	Failed
10	0.63 S_u	1.27E+05	Failed
11	0.75 S_u	1.92E+05	Failed
12	0.75 S_u	4.85E+03	Failed

Following the standards while preparing the specimen is one thing, but attaining the prowess to exactly prepare the specimen as desired is another. Hence, surface irregularities, machining stress, machine condition etc. were beyond the control of the researcher. So, the value might have been deviated significantly with those uncontrollable parameters. However, a test controlling the loads and a working curve has been obtained for the given material and could be used in fatigue life designing of the machine components from the material.

The average of the valueswas also taken and the table of the average is as follows

Table 3: Average cycle in the respective load

S.N	Stress	No of cycles
1	0.35 S_u	1.76E+06
2	0.40 S_u	5.37E+05
3	0.43 S_u	2.18E+05
4	0.46 S_u	1.87E+05
5	0.57 S_u	1.32E+05
6	0.63 S_u	1.27E+05
7	0.75 S_u	9.82E+04

The Table 3 was plotted and then an exponential curve was auto generated in the graph. The curve is in the elastic range and hence can be taken as a Wöhler curve thus generated from the experiment done for the mild steel plates manufactured in Nepal via rotating cantilever beam fatigue test.

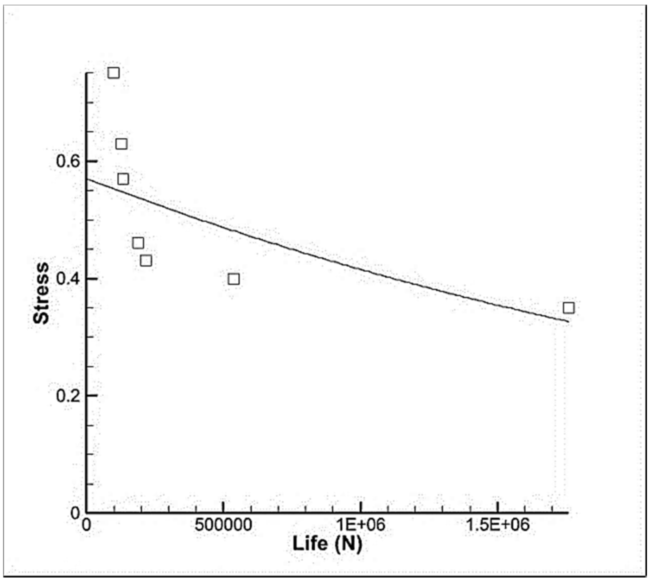


Figure 7: Wöhler curve of the mild steel plates manufactured in Nepal

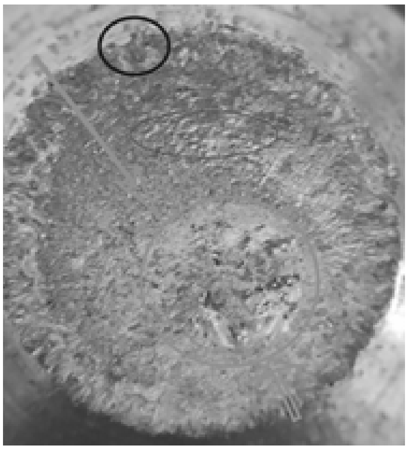
Also, from the acquired data, Basquin's coefficient for the material is determined from the relation

$$S_a = S_u (N_f)^B$$

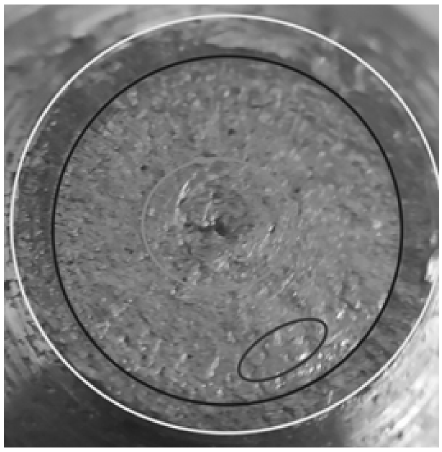
Where, S_u is the ultimate stress of the material which is 612.45 MPa, S_a is the load from the curve, N_f is the number of cycles to failure in the corresponding value of load from the curve. From the curve of figure 7 the Basquin's coefficient B was found to be -0.0613.

Failure Surfaces

The broken specimen was further inspected for the type of fracture associated with the specimen. The pictures were taken using macro lens extension in the mobile phone camera and then zooming through it. Following are some of the surfaces of fracture and their interpretation.



(a)



(b)

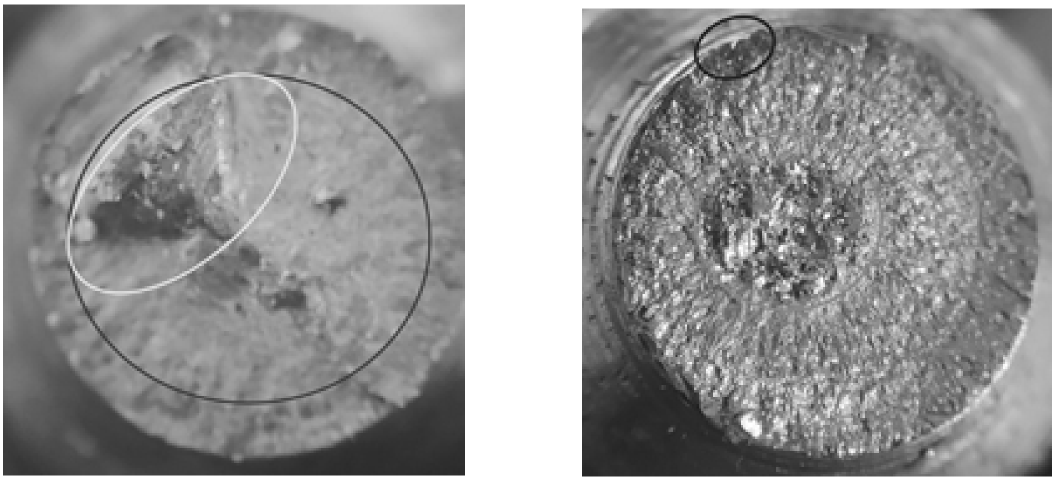
Figure 8: Failure Surface (a) of 6th Specimen (b) of 10th Specimen

The orange circle in the figure8 (a) demonstrates the final section before abrupt rupture of the specimen. The orange arrows at the both directionsshow that the growth of crack was uneven and the specimen was not broken in the axis, rather the fracture was lengthened in one side and shorted in another and was slightly eccentric.The blue circle demonstrates the propagation of crack across the surface irregularities. In this cross section it could be seen that all the initial crack was propagated through the surface irregularities.The green region demonstrates a region with microcleavage as the region is shinier and has fibrous like structure. Micro void coalescence is also noticed in some of the region. The presence of striations is very hard to find under the available magnification of the cross section. However, it cannot be denied with the fact that striations could be present within the cross section because in the presented specimen,most of the part of the cross section is seen smooth too. However it could only be properly verified magnifying through electron microscope around 1μm.

In the figure8 (b), the orange circle depicts the final region of fracture. The fracture process propagated evenly throughout the section as the final region of fracture coincides with the axis of the specimen body.The white circle depicts the initial region of fracture and the blue circle depicts the intermediate region. The blue and white region are separated because a sloped region is seen between the blue and white region where the blue region forms a small crest behind the white line. The microvoid coalescence is seen clearly in the green region. The specimen survived 1.92 E+5 cycles and was given the highest loading in the above testing.

Looking at the surfaces, it the smoothness of the surface, presence of striations could be anticipated but cannot be verified at the present magnification. So of the micro cleavage was also anticipated by looking at the fibrous texture of the surface.

The abrupt change in length between blue and white circle could be explained by the presence of surface irregularities in the tested specimen.



(a) (b)

Figure 9: Failure Surface (a) of 11th Specimen (b) of 3rd Specimen

In the figure 9 (a), the specimen was broken at 4.85E+03 cycles. As we can clear see that the initial crack growth propagated up to the blue circle and because of the irregularity seen in the yellow circle, the specimen was broken quickly. These types of irregularities could happen because of the presence of impurities in the material.

In the figure 9 (b), uneven crack generation is seen inside the orange region as the final section of the rupture does not coincide with the axis of the body. Also in the specimen it is prominent that the crack growth developed initially from the surface irregularities. This could be verified from the blue region. And the presence of micro void coalescence and micro cleavage could be clearly verified. The presence of striations cannot be verified under present magnification.

4. Suggestion and recommendation

During the test it was seen that in most of the fracture, the crack grew from the surface irregularities and its stress concentrations at such irregularities. This could be mainly due to machining defect. The micro void coalescence and micro cleavage were prominent while striations could not be verified but was anticipated looking at the surface structure. Some of the failure was due to impurities present within the material. Keeping these aspects in mind it is recommended to increase the test samples and proper care needs to be taken while machining the samples. Similarly Finite element modeling of the test sample is suggested for the future work.

References

1. R. Ritchie and J. Knott, "Micro cleavage cracking during fatigue crack propagation in low strength steel," *Material Science and Engineering,* pp. 7-14, 1974.

2. O. Basquin, "The exponential law of endurance test," in *Proceeding of the American Society for Testing and Materials*, 1910.

3. A. B. Fatemi, Metal Fatigue in Engineering, Second Edition ed., New York: John Wiley & Sons, 2000.

4. G. Schott, B. Donat and M. Schaper, "The Consecutive Wohler Curve Approach to Damage Accumulation," *Fatigue & Fracture of Engineering Materials & Structures,* vol. 19, no. 2/3, pp. 373-385, 1996.

5. Seddik, Sghaier, Atig and Fathallah, "Fatigue reliability prediction of metallic shot peened parts based on Wohler curve," *Journal of Constructional Steel Research,* vol. 130, pp. 222-233, 2017.

6. S. Suresh, Fatigue of Materials, second edition ed., Boston: Cambridge University Press, 1998.

7. I. ASTM, "Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials," West Conshohocken,.

8. P. C. Gope, "Determination of Minimum Number of Specimens in S-N Testing," *Journal of Engineering Materials and Technology,* pp. 421-427, 2002.

9. R. Sunder, W. Porter and N. Ashbaugh, "Fatigue voids and their significance," *Fatigue Fracture of Engineeering Materials and Structures,* pp. 1015-1024, 2002.

10. B. o. I. Standards, "IS 5075: Method of Rotating Bar Bending Fatigue Testing of Metals," Institution, Indian Standards, New Delhi, 1985.