USE OF THE PARALLEL-PROJECTED AND STAIRCASE METHOD TO PREDICT FATIGUE STRENGTH OF ASTM A743 CA6NM ALLOY STEEL

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Abstract.*The scope of this research is to assess the fatigue behavior of alloy steel used in hydraulic turbine blades. Fatigue testing under fully reversed cycling (R=-1) was performed to determine the fatigue behavior of ASTM A743 CA6NM alloy steel. This paper considers two quantitatively different approaches to evaluate the fatigue limit. The first approach is a method of extrapolation from finite fatigue live, the Parallel-projected method based on Basquin's relation or S-N curve. The second approach is a method of reduction data by Dixon and Mood based on Staircase (up and down method) test data. The methods were employed to obtain values of the average endurance limit corresponding to fixed number of cycles up to two millions. In addition, 22 specimens were used on Parallel-projected method and 15 specimens were experimentally evaluated by Staircase method. The results obtained were compared and they indicated that scatter of first approach was upper than second and its fatigue limit was lower.*

Keywords*: Fatigue limit, Staircase method, Up and down method, Parallel-projected method, ASTM A743 CA6NM*

1. INTRODUCTION

Hydrogenator components, as turbine blades, are designed for infinite life. The stress acting should be less than an endurance limit. Among many fatigue limit tests, the Staircase method is the commonly employed to determine statistical properties of the fatigue strength at any specified life. In addition accelerated testing methods have been developed to determine the statistical properties of an endurance limit of a component. They consider that the endurance limit distribution can be extrapolated by the failure trajectories through low cycle fatigue data. The aim of this research is to evaluate statistical properties of endurance limit of ASTM A743 CA6NM alloy steel.

2. MATERIAL AND EXPERIMENTAL METHODS

2.1. Material

The tested material was a steel alloy, ASTM A743 CA6NM, which has been used in the fabrication of hydraulic turbine components. It requests high mechanical strength and that it resists to the corrosion. Its chemical properties according to ASTM A 743/A 743M (2006) are showed in Tab. (1). The mechanical (Young modulus, E, tensile strength, S_{rt}, and yield strength, S_y.) are showed in Tab. (2).

Table 1. Chemical properties of ASTM A743 CA6NM alloy steel (ASTM A 743/A 743M, 2006)

Composition (%)							
C	Mn	Si	Cr	Ni	Mo	P	S
≤0,06	≤1,00	≤1,00	11,5-14	3,5–4,5	0,4–1,0	≤0,04	≤0,03

Table2. Mechanical properties of ASTM A743 CA6NM alloy steel (DaSilva *et al.,* 2009a)

E (GPa)	S_y (MPa)	S_{rt} (MPa)	Hardness (HB)
198 ± 4	575 ± 35	918 ± 1	273,0 ± 7,0

2.2. Parallel-projected method

The parallel-projected was developed to extrapolate the high cycle fatigue strength data (e.g. 2.10^6 cycles) from small samples of low cycle fatigue data (e.g. 10^4 to 10^6 cycles). The typical low cycle data (S_a, N) is defined by the Eq. (1), where S_a is stress amplitude, A is fatigue strength coefficient, b is fatigue strength exponent and N is cycles to failure.

$$S_a = A(N)^b \tag{1}$$

2.3. Staircase method

The Staircase method is used to determine the statistical properties of a fatigue limit. The fatigue limit has to be estimated and a fatigue life test is then conducted at this stress level. The Dixon-Mood method (DM), based on the maximum likelihood estimation, was popularized by Little (1975). It uses a simple systematic methodology where the specimen is tested at initial stress for a specific fatigue life. Initially, the fatigue limit and its standard deviation are estimated, for example, through Parallel-projected or S-N curve. If the specimen fails before infinite life (say 2.10^6 cycles), the next specimen will be tested at a lower stress level. Otherwise, a new test will be conducted at upper stress level. In that way, each test depends on the previous test results and the experiment continues in this manner in sequence with the stress level being increased or decreased (Lin *et al.*, 2001).The stress increments are usually constant and are in the range of half to twice the standard deviation of the fatigue limit. Lee *et al.* (2005) recommends a value 5% smaller than fatigue limit initially estimated. Collin (1993) recommends running the test at least 15 specimens.

The DM method provides approximate formulas to calculate the mean, μ_{DM} , and standard deviation, σ_{DM} ,of the fatigue limit. It requires that two statistical properties be determined by using the data of the less frequent event, either only the survivals or only the failures. The stress levels S spaced equally with a chosen increment d are numbered i where $i=0$ for the lowest stress level S_0. Denoting by n_i the number of the less frequent event at the stress level i, two quantities can be calculated: A and B, Eqs. (2) and (3), respectively.

$$A_i = \sum i n_i \tag{2}$$

$$B_i = \sum i^2 n_i \tag{3}$$

The Equation (4) shows the estimation of the mean, where the plus sign is used if the more frequent event is survival and otherwise, it is used minus sign. Eqs. (5) and (6) show the estimation of standard deviation.

$$\mu_{DM} = S_0 + d\left(\frac{A}{\sum n_i} \pm \frac{1}{2}\right) \tag{4}$$

$$\sigma_{DM} = 1.62d\left[\frac{B\sum n_i - A^2}{\left(\sum n_i\right)^2} + 0.029\right] \text{ if } \frac{B\sum n_i - A^2}{\left(\sum n_i\right)^2} \geq 0.3 \tag{5}$$

or

$$\sigma_{DM} = 0.53d \text{ if } \frac{B\sum n_i - A^2}{\left(\sum n_i\right)^2} < 0.3 \tag{6}$$

The Staircase method is notably accurate and efficient in order to quantify the mean fatigue strength but it is very hard to predict estimate accurate of fatigue limit standard deviation using these methods with small samples at high cycle fatigue (Pollak *et al.*, 2006). This method concentrates the most experimental points near the mean therefore is more difficult to obtain an accurate standard deviation. Braam and van der Zwaag (1998), Svensson e de Maré (1999), Lin *et al.* (2001) e Rabb (2003) worked in order to evaluate and to improve the reliability of standard deviation and proposed a linear correction factor and found to be an improvement in all maximum-likelihood evaluation procedures.

Eq. (13) shows the estimate of standard deviation corrected by Svensson-Lóren, σ_{SL} , where σ_{DM} is the standard deviation by Dixon-Mood and N is the total specimen number. This correction is a strictly function of sample size and tends to increase the deviation estimate by Dixon-Mood.

$$\sigma_{SL} = \sigma_{DM}\left(\frac{N}{N-3}\right) \tag{13}$$

A modified correction was developed which attempted to allow a greater range of unbiased estimation than the Svensson-Lóren correction. The form of the proposed standard deviation estimate, σ_{PC} , is shown in Eq. (14), where A, B, and m are constants dependent on the number of samples, see Tab. (3).

$$\sigma_{PC} = A\sigma_{DM}\left(\frac{N}{N-3}\right)\left(B\frac{\sigma_{DM}}{d}\right)^{m} \quad (14)$$

In this work the largest deviation will be used, σ_{SL} or σ_{PC} .

Table 3. Constants used in proposed standard deviation correction (Pollak et al., 2006)

Specimens # (*N*)	*A*	*B*	*m*
8	1,30	1,2	1,72
10	1,08	1,2	1,10
12	1,04	1,2	0,78
15	0,97	1,2	0,55
20	1,00	1,2	0,45

3. RESULTS AND DISCUSSIONS

3.1. Parallel-projected method

In order to evaluate the endurance limit, 22 specimens were tested under uniaxial loading, *R* = -1. Table (4) shows the statistical fatigue behavior for such stress level. The fatigue limit is defined for 1.10^6 and 2.10^6 cycles. Starting from obtained experimental data, Fig. (1) shows *S-N* curve and 95% confidence interval.

Table 4. Statistical fatigue behavior

S_a (MPa)	353	364	400	540	509
S_a/S_{rt} (%)	38,4	39,6	52,143,6	47,9	55,5
Mean	1,73 e+06	1,13 e+06	4,53 e+05	2,61 e+05	5,75 e+04
Deviation	5,49 e+05	8,82 e+05	8,32 e+04	1,09 e+03	9,74 e+03
CV (%)	31,6	78,1	18,4	0,4	16,9

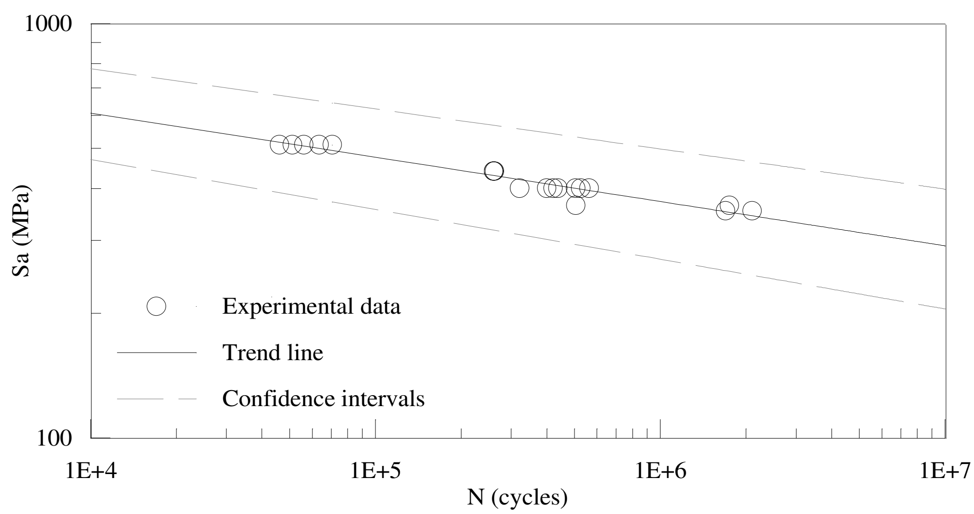

Figure 1. S-N curve

The expression that best describes the experimental results is Eq. (1), where *A* and *b* are presented in Tab. (5). The endurance limit estimated for 1.10^6 and 2.10^6 cycles is shown in the Tab. (6).

Table 5. S-N curve parameters

Parameter	Expected value		Confidence limits	
	Estimative	Deviation	Lower	Upper

A	1659,14	116,40	1416,34	1901,94
b	-0,108	0,006	-0,120	-0,097

Therefore, the endurance for all cases above for 1.10^6 and 2.10^6 cycles, respectively, are shown in Tab. (7).

Table 6. Fatigue strength

	S_a MPa)	
N (cycles)	Mean (MPa)	Deviation (MPa)
1.10^6	370.8	26.0
2.10^6	344.0	24.1

3.2. Staircase method

In order to evaluate the statistical parameters of the fatigue strength for 2.10^6 cycles, 15 specimens were tested under 20 Hz in the universal testing servo hydraulic machine, MTS 810. Tab. (7) shows the fatigue life for such stress level tested. Figure (2) shows the test evolution. For each failure the step was decreased and for each survival the step was increased. The step size was defined starting from the established number of classes. Eight classes were adopted and distributed along equally two standard deviations based on Parallel-projected predicted previously. Therefore, the stress increment was $13.79\,\text{MPa}$ and the endurance limit was $360.1 \pm 11.2\,\text{MPa}$. Fig. (2) presents detailed results of Staircase method. Starting from this plot one can conclude that all classes included by results are above average, except lower stress level, S_0. However, the Staircase method predicts a bad result for the standard deviation according to Polak *at al* (2006). Adopting the Svensson-Lóren correction (Svensson *et al*, 2000), the standard deviation is $14.0\,\text{MPa}$.

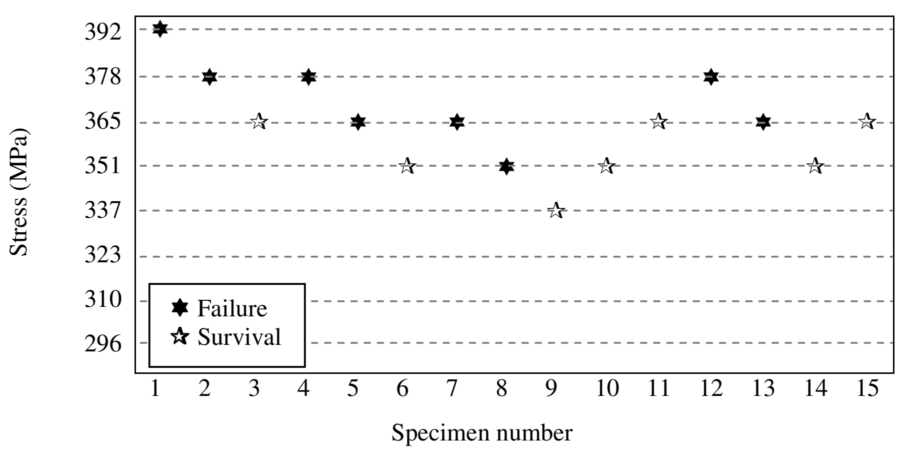

Figure 2. Plot of staircase testing results

4. CONCLUSION

The fatigue limit of ASTM A743 CA6NM presents big scatter when evaluated by different approaches. The Staircase method is a powerful tool to predict average fatigue limit (Pollak *et al.*, 2006) therefore we will consider the obtained results by up-and-down method as more acceptable, $360.1 \pm 14.0\,\text{MPa}$. The Parallel-projected has bigger scatter than Dixon-Mood method and lower endurance limit. However, the use of the accelerated and Staircase methods together is very successful as it can be seen.

Table 7. Staircase testing results for 2.10^6 cycles (R = -1)

Specimen	σ (MPa)	N (cycles)

1	392	$3.03.10^5$
2	378	$7.27.10^5$
3	365	run out
4	378	$6.16.10^5$
5	365	$4.63.10^5$
6	351	run out
7	365	$1.65.10^6$
8	351	$1.22.10^6$
9	337	run out
10	351	run out
11	365	run out
12	378	$5.94.10^5$
13	365	run out
14	351	run out
15	365	$1.,15.10^6$
$S_f = 360.1 \pm 11.2$ MPa		

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6. REFERENCES

ASTM / A 743 / A 743M – 06, (2006), "Standard Specification for Castings, Iron–Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Application".

Braam, J. J., van der Zwang, S. (1998), "A statistical evaluation of the staircase and arcsin $\sqrt{P}$ methods for determining the fatigue limit", J. Testing Eval, 26:125-131.

Collin, J. A. (1993), "Failure of materials in mechanical design – analysis, prediction, prevention", 2. ed, New York: John Wiley and Sons, Inc.

Lee, Y-L., Pan, J., Hathaway, R. B., Barkey, M. E., (2005), "Fatigue Testing and Analysis (Theory and Practice)", Elsevier Butterworth-Heinemann, Oxford, UK.

Lin, S-K., Lee, Y-L., Lu, M-W. (2001), "Evaluation of the staircase and the accelerated test methods for fatigue limit.

Little, R. E. (1975), "Statistical Design of Fatigue Experiments", John Wiley & Sons, New York.

Pollak, R., Palazotto, A., Nicholas, T. (2006), "A simulation-based investigation of the staircase method for fatigue strength testing", Mechanical of Material, 38, pp. 1170-1181.

Rabb, B. R. (2003), "Staircase testing – confidence and reliability", Trans. Eng. Sci., 40:447-464.

Svensson, T., Lorén, S., de Maré, J. (1999), "Random features of the fatigue limit", Project paper. Available from: <http://www.sp.se/mechanics/Engelska/FoU/ModFatigue.htm>

Svensson, T., Lorén, S., de Maré, J., Wadman, B. (2000), "Statistical models of the fatigue limit", Extremes 2, pp. 165-176.

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