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Finite element based fatigue analysis of 6082 Aluminum alloy under random loading

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ABSTRACT

Mechanical and structural components are subject in the most cases during their services to random loading. For this reason, it is necessary to reduce the complex history of these kinds of loading in a series of constant amplitude cycles. There are several counting methods that lead to different results. Among all these methods, it is recognized that the Rainflow Cycle Counting method provides the most conservative results. In this paper, a finite elements analysis technique is presented to predict the fatigue life using this method associate with the S-N method which is used for high cycle fatigue applications that makes no distinction between initiation or growing a crack, but rather, predicts the total life to failure. Comparison between numerical and experimental results is considering in this paper.

1 Introduction

Fatigue is phenomenon that causes failure in machine parts at stress values much lowers than yield strength of the material. Fatigue failure is due to repeated or cyclic loading and unloading or fluctuating reversal in loading after a large number of cycles. This phenomenon is an important consideration for components and structures subjected to random loading in service; it is one of the most difficult design issues to find solution. Experience has shown that large percentage

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of components failure are causing to fatigue and as a result, it is a field which has been and will continue to be the focus of researcher. Finite elements based fatigue analysis of an Aluminum alloy provisions are only recently included in the Aluminum association specialization. The lack in fatigue life assessment despite more than 50 cumulative damage hypotheses [1], the most popular is mostly used Palmgren–Miner-Rule [2]. Three life prediction methods are used to predict life components. These are total life, crack initiation, and crack propagation. Total life is aptly named in that only the total life of the component is of concern and not when a crack will initiate or how quickly it will grow. The three methods are related to each other by the fact that the total number of cycles to failure, N_f, equals the number of cycles to initiate a crack, N_i, plus the number of cycles to propagate that crack N_p. Since most of the time to failure for smooth components are spent in crack initiation [3]. This method is used in mostly defect free, metallic structures or components [4]. It is widely used at present especially when the linear generator engine are started or stopped then it is subjected to a very high stress range [5-6]. This is a fatigue life prediction method commonly referred to as Strain-Life (ε-N), which uses local strain and is mostly accredited to Manson and Coffin, In the 1950s, they independently proposed that the plastic strain component of a fatigue cycle may also be related to life by a simple power law:

$$\varepsilon_p = \varepsilon_p^{'}(2N_f)^c \tag{1}$$

The Stress-Life method (also referred to as the σ-N method) was the first approach used in an attempt to understand and quantify metal fatigue. The Stress-Life approach is generally categorized as a high-cycle fatigue methodology. Basquin in 1910 [7] presented a stress based law, formulated as flaw:

$$\sigma_a \frac{\Delta\sigma}{2} = \sigma_f^{'} \left(2N\right)^b \tag{2}$$

Where σ'_f is the fatigue strength coefficient and b fatigue strength exponent. Most realistic service situations involve non-zero mean stresses. It is, therefore, very important to know the influence that mean stress has on the fatigue process, the following relations are available in the Stress-Life module to take in account the influence of this mean stress:

Goodman: $$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_u} = 1$$

Gerber: $$\frac{\sigma_a}{\sigma_e} + (\frac{\sigma_m}{\sigma_u})^2 = 1$$

Soderberg: $$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_y} = 1$$

Morrow: $$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_f} = 1$$

If the σ-N is plotted on log-log scales, the relationship between alternating stress and number of cycles to failure, N can be described by a straight line. The slope of the line, b can be derived from the following:

$$b = \frac{-\left(\log\sigma - \log\sigma_0\right)}{\left(\log N_0 - \log N\right)} \tag{3}$$

$$\log N = \log N_0 + \frac{1}{b}\log\left(\frac{\sigma}{\sigma_0}\right) \tag{4}$$

$$N = N_0\left(\frac{\sigma}{\sigma_0}\right)^{1/b} \tag{5}$$

The above equation says that if the Basquin [7] slope b it is known, and any other coordinate pair (N_o), then for a given stress amplitude, the number of cycles can be calculated directly. Typically, if N_o is taken to be 10^7 cycles and the corresponding stress amplitude is taken to be an endurance limit, usually denoted as that the above equation may be rewritten as follows:

$$N = \left(\frac{\sigma}{\sigma_0}\right)^{1/b} \times 10^7 \tag{6}$$

From the above discussion it should be clear by now that, prior to contemplating a fatigue analysis, several pieces of information must be to hand. Firstly, a description of the cyclic loading environment, secondly, a characterization of the geometry of the component in question and lastly, details of the cyclic properties of the material from which the component is to be, or was, manufactured. Fig.1 provides a simple block diagram of the process.

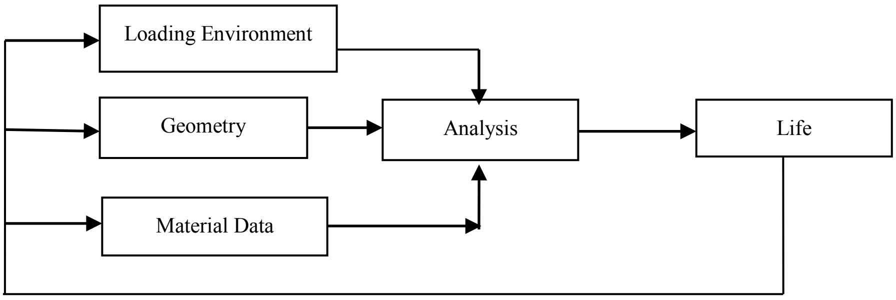


Fig.1- Inputs Required for a Fatigue Analysis

Recently, [8-12] many research efforts in stress and fatigue analysis using finite elements method have been focused on integrating the organizational modeling to predict and calculate life of structures in service.

2 The stress analysis

Before starting the fatigue analysis, must in first go through a stress analysis by determining the stress distribution on the model of the specimen. This analysis should be simple to save computation time, in our case the determination of charging is very important since it is the primary source of fatigue failure this analysis is to identify the critical areas that can create fatigue failure, assess the constraints within that area and determining the surface stress state. Two codes are used in calculating this part, the first is PATRAN 2007 for modeling (as pre-processor), and the second is MD R2.1 NASTRN [13] (as processor) to analyze the stress distribution.

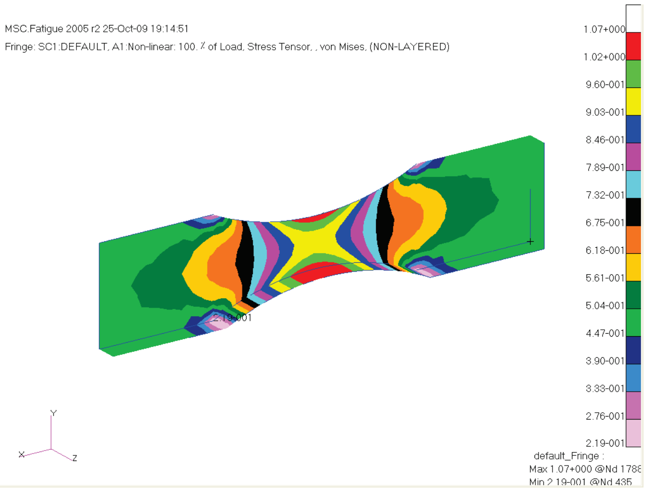


Fig.2- Stress state of Von Miss.

Displaying results on the test specimen on the mesh of the equivalent stress state of Von Miss in Figure 2 shows that the stress concentration area is located at the reduced section of the specimen.

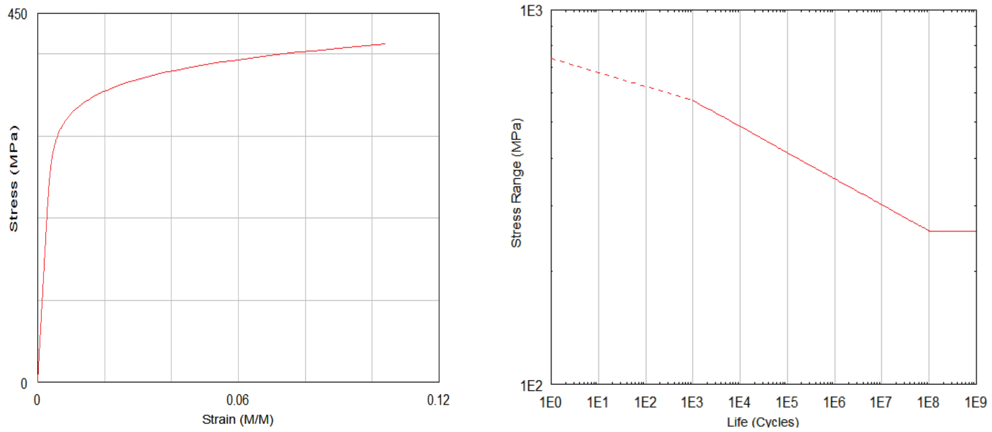
2.1 Material properties

The material is an alloy of 6082 T6 aluminum (for more details, see [5-6]) with mechanical properties that are illustrated in Fig.3.a and S-N curve is represented in Fig.3.b and reported in Table 1. This material has great importance in the technology industry especially in the construction of a transport aircraft that is due to the high mechanical strength and good corrosion resistance and high hardness.

Table 1. Mechanical properties of 6082 Aluminum alloy [14]

Cyclic hardening exponent, n'	0.064
Cyclic hardening coefficient, K' [MPa]	443
Fatigue strength exponent, b	-0.0695
Fatigue strength coefficient, σ'_f [MPa]	485
Fatigue ductility exponent, c	-0.827
Fatigue ductility coefficient, ε'_f	0.773

The data of Table 1 are operated using MSC FATIGUE to plot the S-N curve of the studied material witch is represented in figure Fig .3.a.



(a) (b)

Fig. 3- (a) Stress-strain curve of 6082 aluminum alloy; (b) S-N curve of 6082 aluminum alloy

2.2 Loading for increasing block

The loading used in our study, is identical to that given in [5]. The applied stresses are associated with cycles in increasing order as shown in Fig.4.

This loading history consists of four constant amplitude load segments.

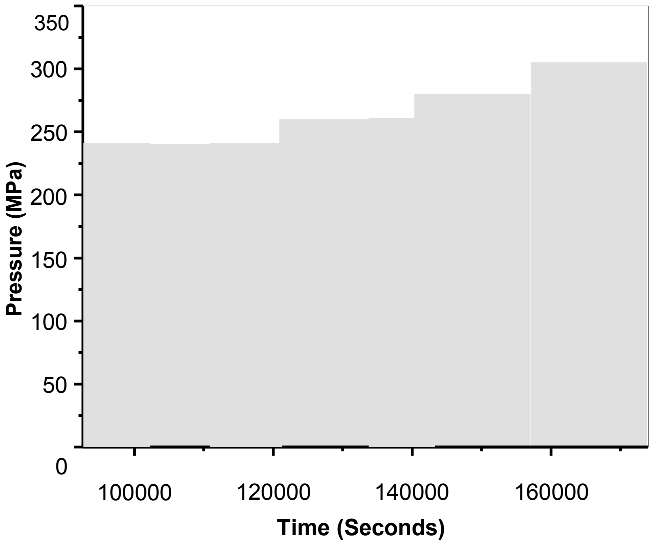


Fig.4- Program loading of increasing blocks

2.3 Results and analysis

Comparisons between the experimental results of tests on specimens in 6082 aluminum alloy [6] Miner [2] and the results obtained using MSC FATIGUE [15] are illustrated in Fig.6 and grouped in Table 1, one can see in the latter figure that the prediction obtained by simulation (FEM) without encouraging because the absolute value of the relative prediction error is lower than that of model laws Miner.

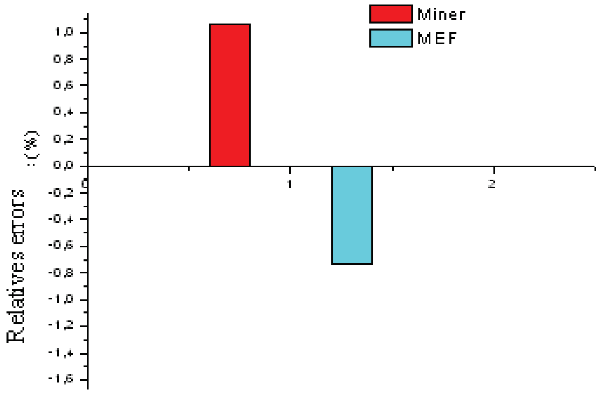


Fig.5- Relative prediction error of the cumulative damage for increasing blocks.

Table .2. Total lifetime, under the damage models and the corresponding relative errors.

Loading	240 MPa	260 MPa	280 MPa	305 MPa		
				Exp	Miner	MEF
Number of cycles per block	103000	26258	19427	16800	14140	18031
Total lifetime				165485	162825	166716
Relative prediction error (%)					1.607	-0.734

3 Uniaxial random loading

Most industrial parts are subjected to variable amplitude loading, for this reason the study of this type loading is of paramount importance. In this section the experimental results [16] are used, an example of an axially loaded uniform random is shown in Fig.6. Predictions on fatigue life of this kind of loading should obviously be more complex than predictions for constant amplitude loading.

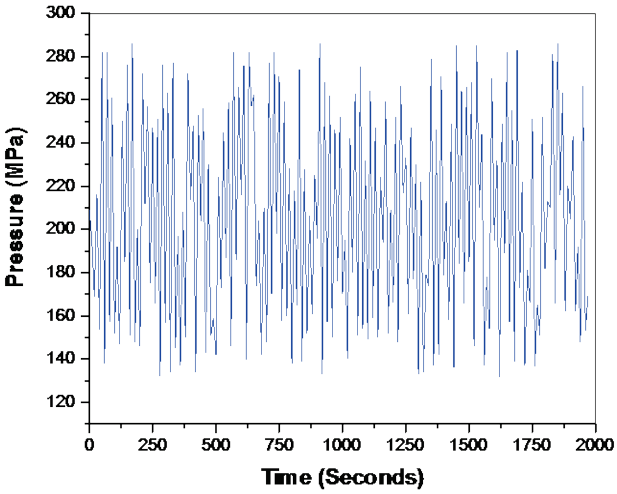


Fig.6- Signal to random loading.

The object of all cycle counting methods is to compare the effect of variable amplitude load histories to fatigue data and curves obtained with simple constant amplitude load cycles, examples for these methods are cited below:

- Rainflow Method
- Level-crossing counting method
- Peak counting method

The use of the method Rainflow is necessary for counting the cycles in the spectrum of Fig.6. Cycles extracted by the method Rainflow are represented in the space (stress amplitude, mean stress, number of cycles in Fig.7). This Method is the most popular and probably the best method of cycle counting.

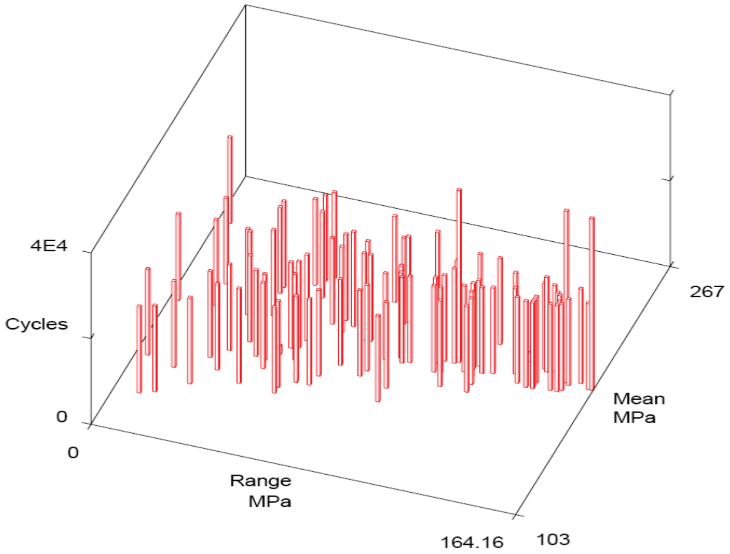


Fig. 7- Result of counting Rainflow applied to the spectrum of fig 6.

This method allows the reconstruction of the random spectrum (Fig 6) to a loading block as shown in Fig 8.

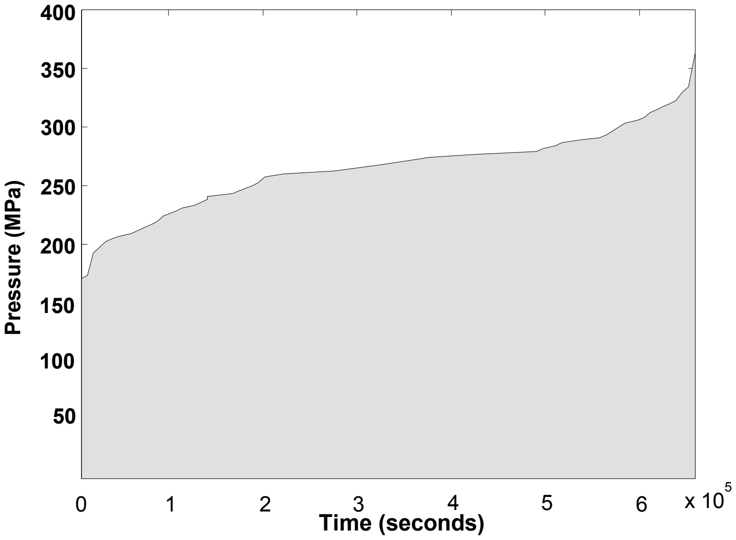


Fig.8- Program loading blocks after reconstruction.

3.1 Simulation Result

In this section, an example of simulation results is presented; concerning calculates the distribution of damage and prediction of lifetime. One can see, in Fig.9, the area most damaged is the reduced section which focuses constraints. Moving away from this section is reduced and the damage tends to zero in the non helpful.

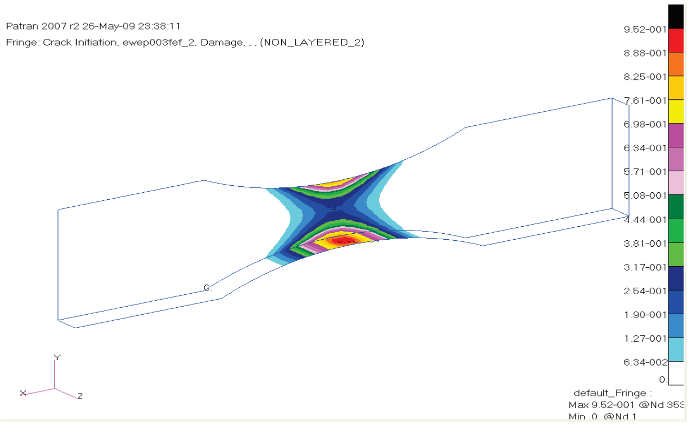


Fig.9- Distribution of damage on the geometric model.

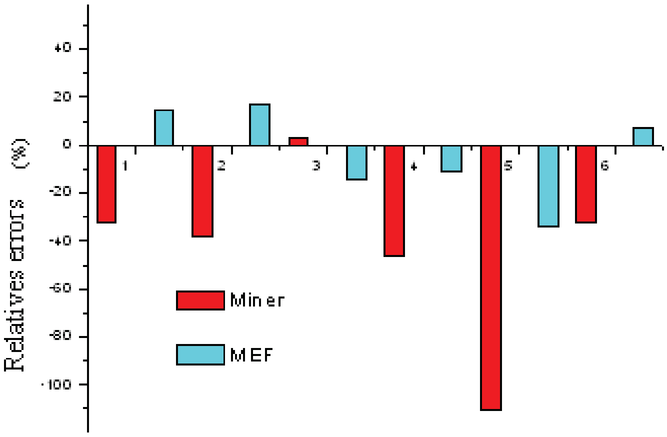


Fig.10- Relative prediction error of the cumulative damage models for random loading

3.2 Comparison of the rules of accumulation and simulation

Table 3 and Fig.10 shows the relative prediction errors of total lifetime calculated from the law of Miner and results by MEF. A first analysis of the results for the six test series studied indicates that the discrepancies between predictions and experimental reality (Relative error forecasting) are much more pronounced for the model of Miner for results by MEF. The Miner rule's is non-conservative in most results.

Table 3- Total lifetime, under the damage models and the corresponding relative errors for random loading

Tests	Experimental	Miner		MEF	
		Lifetime	Relative error	Lifetime	Relative error
Test 1	499370	659267	-32,01	426579	14.58
Test 2	754500	1043893	-38,35	615214	17.13
Test 3	448753	435045	3,05	512861	-14.28
Test 4	450000	658473	-46,32	501187	-11.37
Test 5	440320	925528	-110,19	588844	-33.73
Test 6	646454	855846	-32,39	602559	6.97

4 Conclusion

The presented procedure is an example of engineering analysis with finite elements modeling performed using MSC Tools. A comparison between experimental fatigue behaviors from variable amplitude histories to fatigue curves obtained with procedure using a cycle counting method such as Rainflow method was conducted in this manuscript. The simulation results provide estimates of lifetimes pessimistic, since three out of six results are conservative. It was found that, under each sequence of loading has an effect in the total amount of damage. With this information it is possible to improve the life prediction through the modification of the damage rule and finite elements modeling. It is considered that the stimulation gives good predictions, as most of the relative errors in absolute value are less than 20%. In addition, the advantage of showing the damaged areas in the study structure allows designers to be careful to optimize the life of parts and structures.

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