2004-01-2219

A Critical Evaluation of Fatigue Crack Initiation Parameter Estimates

Marco Antonio Meggiolaro
Jaime Tupiassú Pinho de Castro
Mechanical Engineering Department
Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil
e-mails: meggi@mec.puc-rio.br, jtcastro@mec.puc-rio.br

ABSTRACT

Several estimates of Coffin-Manson's parameters have been proposed in the literature. However, most of the existing methods for estimating εN parameters are based on a limited amount of experimental data. In addition, statistical evaluation of the popular rules of thumb used in practice to estimate fatigue properties are scarce, if available. In this work, an extensive statistical evaluation of the existing Coffin-Manson parameter estimates is presented based on monotonic tensile and uniaxial fatigue properties of 845 different metals, including 724 steels, 81 aluminum alloys, and 15 titanium alloys. From the collected data, a new estimation method which uses the medians of the individual parameters of the 845 materials is proposed.

Keywords: Low-cycle fatigue; Estimation methods; Strain-life estimates; Statistical evaluation

INTRODUCTION

The εN fatigue design method correlates the number of cycles N to initiate a fatigue crack in any structure with the life of small specimens made of the same material and submitted to the same strain history that loads the critical point in service. This method models macroscopic elastic-plastic events at the notch roots and uses the local strain range (a more robust parameter to describe plastic effects) instead of the stress range to quantify them. Therefore, the εN method must be used to model low cycle fatigue problems, when the plastic strain range $\Delta\varepsilon_p$ at the critical point is of the same order or larger than the elastic range $\Delta\varepsilon_e$, but it can be applied to predict any crack initiation life.

The classical εN method works with real (logarithmic) stresses and strains, uses a Ramberg-Osgood description for the $\Delta\sigma\,\Delta\varepsilon$ elastic-plastic hysteresis loops, and considers the cyclic softening or hardening of the material, but not its transient behavior from the monotonic $\sigma\varepsilon$ curve [1-5]. Hence, a single equation is used to describe all loops

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \qquad (1)$$

where E is the Young's modulus, K' is the hardening coefficient and n' is the hardening exponent of the cyclically stabilized $\Delta\sigma\Delta\varepsilon$ curve.

The relationship between the stress range $\Delta\varepsilon$ at the critical point and its fatigue crack initiation life N is usually given by the classical Coffin-Manson equation

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E}(2N)^b + \varepsilon'_f(2N)^c \qquad (2)$$

where σ'_f, ε'_f, b and c are the fatigue strength and ductility coefficients and exponents measured in fully alternated tension-compression fatigue tests.

Assuming that Ramberg-Osgood's elastic and plastic strain ranges perfectly correlate with the correspondent Coffin-Manson's ranges, then only four of the six material parameters $\{n', K', \sigma'_f, \varepsilon'_f, b, c\}$ would be independent. Thus, from Eqs. (1-2),

$$\frac{\Delta\sigma}{2} = \sigma'_f(2N)^b = K'\varepsilon'^{\,n'}_f(2N)^{c\cdot n'} \;\Rightarrow$$

$$n' = \frac{b}{c}; \quad K' = \frac{\sigma'_f}{\varepsilon'^{\,n'}_f} \tag{3}$$

Note however that the Ramberg-Osgood and Coffin-Manson equations are not physical laws. Instead, Eq. (3) must be regarded as a measure of the coherence between those equations. Therefore, such estimates should not be used to replace experiments. Whenever possible, all six material parameters should be independently obtained from actual measurements.

However, for initial design studies it is desirable to estimate these six εN parameters based only on readily available monotonic tensile test data. The main estimation methods proposed in the literature are discussed next.

CLASSICAL ESTIMATION METHODS

Several estimates of Coffin-Manson's parameters have been proposed in the literature since Morrow [6], who in 1964 correlated the b and c exponents of Coffin-Manson's equation with the cyclic hardening exponent n':

$$b = \frac{-n'}{1+5n'}, \quad c = \frac{-1}{1+5n'} \tag{4}$$

Manson [7] proposed two different methods based on experimental data on 69 metals to estimate their Coffin-Manson curve: the Universal Slopes method (5), in which b and c are assumed constant for all metals, and the Four-Point Correlation method (6), defined through estimates of the elastic or the plastic strain ranges $\Delta\varepsilon_e/2$ or $\Delta\varepsilon_p/2$ at four different lives (N = 1/4, 10, 10^4 and 10^5 cycles). Both Manson's estimates make use of the ultimate strength S_U and the reduction in area RA:

$$\sigma'_f = 1.9 \cdot S_U, \quad \varepsilon'_f = 0.76 \cdot \left[ln\left(\frac{1}{1-RA}\right)\right]^{0.6},$$
$$b = -0.12, \quad c = -0.6 \tag{5}$$

$$\sigma'_f = 1.25 S_U (1+\varepsilon_f) \cdot 2^b,$$
$$\varepsilon'_f = \frac{0.125}{20^c} \cdot \left[ln\left(\frac{1}{1-RA}\right)\right]^{3/4}, \quad b = \frac{log(0.36 \cdot S_U/\sigma_f)}{5.6},$$
$$c = \frac{1}{3} log \frac{0.0066 - \sigma'_f (2 \cdot 10^4)^b / E}{0.239 \{ln[1/(1-RA)]\}^{3/4}} \tag{6}$$

Raske and Morrow [8] proposed an estimate for the fatigue ductility coefficient ε'_f from σ'_f, n', and the cyclic yielding strength S'_Y:

$$\varepsilon'_f = 0.002 \cdot (\sigma'_f / S'_Y)^{1/n'} \tag{7}$$

Mitchell [9] stated that the exponent b is also a function of S_U, estimated ε'_f directly from the true fracture ductility ε_f, and assumed proposed two universal slopes for "ductile" or "strong" alloys:

$$\sigma'_f = S_U + 345\text{MPa}, \quad \varepsilon'_f = \varepsilon_f, \quad b = \frac{1}{6} log \frac{0.5 \cdot S_U}{S_U + 345},$$
$$c = -0.6 \text{ ("ductile") or } -0.5 \text{ ("strong")} \tag{8}$$

Muralidharan and Manson [10] revised the Universal Slopes idea, increasing both Coffin-Manson's exponents to b = –0.09 and c = –0.56, and introducing the parameter S_U/E to estimate both coefficients σ'_f and ε'_f:

$$\sigma'_f = 0.623 E \left(\frac{S_U}{E}\right)^{0.832},$$
$$\varepsilon'_f = 0.0196 (S_U/E)^{-0.53} \cdot [ln(\frac{1}{1-RA})]^{0.155},$$
$$b = -0.09, \quad c = -0.56 \tag{9}$$

Bäumel and Seeger [11] recognized the importance of separating the εN estimates by alloy family, proposing different methods for low-alloy steels and for aluminum (Al) and titanium (Ti) alloys in their Uniform Material laws. They also ignored any monotonic measure of the material ductility (such as the reduction in area RA) when estimating the fatigue ductility coefficient ε'_f:

$$\sigma'_f = 1.5 \cdot S_U, \quad \varepsilon'_f = 0.59 \text{ if } S_U/E \leq 0.003 \text{ or } 0.812 - 74 \cdot S_U/E,$$
$$b = -0.087, \quad c = -0.58 \quad \text{(steels)} \tag{10}$$

$$\sigma'_f = 1.67 \cdot S_U, \; \varepsilon'_f = 0.35, \; b = -0.095, \; c = -0.69 \quad \text{(Al \& Ti)} \tag{11}$$

Ong [12] proposed a few modifications in Manson's Four-Point Correlation method to better fit the experimental data of 49 steels from the SAE J1099 Technical Report on Fatigue Properties [13], estimating ε'_f in the same way as Mitchell proposed:

$$\sigma'_f = S_U \cdot (1+\varepsilon_f), \quad \varepsilon'_f = \varepsilon_f, \quad b = \frac{1}{6} log \frac{(S_U/E)^{0.81}}{6.25 \sigma_f / E},$$
$$c = \frac{1}{4} log \frac{0.0074 - \sigma'_f (10^4)^b / E}{2.074 \cdot \varepsilon_f} \tag{12}$$

Roessle and Fatemi [14], assuming the same constant slopes as Muralidharan and Manson did, while estimating both Coffin-Manson's coefficients as a function of the Brinnell hardness HB:

$$\sigma'_f = 4.25 \cdot HB + 225\text{MPa},$$
$$\varepsilon'_f = [0.32 \cdot HB^2 - 487 \cdot HB + 191000\text{MPa}] / E,$$
$$b = -0.09, \; c = -0.56 \tag{13}$$

It is no surprise that σ'_f can be estimated from the hardness HB, since S_U and HB present a very good correlation for steels: if S_U is given in MPa and HB in kg/mm^2, S_U is approximately $3.4 \cdot HB$ with a (small) coefficient of variation $V = 3.8\%$, from a study on 1924 steels from the ViDa software database [15-16].

Several works have been published since 1993 evaluating the life prediction errors associated with each of the estimation methods discussed above [14, 17-20]. Ong [17] evaluated Manson's and Mitchell's original methods based on properties of 49 steels. He concluded that Mitchell's method resulted in overly non-conservative predictions.

Brennan [18] compared all of Manson's methods and concluded that Muralidharan-Manson's revised Universal Slopes [10] resulted in good predictions, however his analysis was based on only six steels.

Park and Song [19] evaluated several methods using published data on 138 materials. They found that both Manson's original methods are excessively conservative for long life predictions, but slightly non-conservative for short lives. In contrast, Muralidharan-Manson's method is slightly conservative at shorter lives, but is non-conservative at long lives, being selected as the best overall estimation method together with Bäumel-Seeger's uniform material laws. Park and Song also confirmed that Mitchell's method leads to non-conservative predictions over the entire life range.

Roessle and Fatemi [14] studied measured properties of 20 steels plus the 49 steels from the SAE J1099 Technical Report [13], arriving at basically the same conclusions as Park and Song did. In addition, no strong correlation was found between σ'_f and the true fracture strength. They also found that using the true fracture ductility ε_f to estimate ε'_f can result in significant error.

Kim et al. [20] presented an evaluation of all available estimation methods, based on measured properties of 8 steels. It was found that the best life predictions were obtained using Bäumel-Seeger's, Roessle-Fatemi's and Muralidharan-Manson's methods.

From the evaluations in the literature, it is possible to conclude that the best estimation methods are all based on constant values of the exponents b and c, while in general σ'_f is well estimated (directly or indirectly) as a linear function of the ultimate strength S_U. It is also suggested that ε'_f does not correlate well with any monotonic measure of the material ductility, such as RA or ε_f. Comparing to the existing estimates for ε'_f, from a statistical point of view assuming it is a constant would result in better predictions. Based on these conclusions, a new εN estimate called the Medians method is proposed in this work. A statistical evaluation of this method and all others discussed above is presented in the following sections.

MATERIALS DATA

The tensile and εN properties of 845 materials have been collected from the literature, totaling 724 different steels, 81 aluminum, 15 titanium, 9 nickel alloys, and 16 cast irons. These materials were tested under several conditions or heat treatments, at temperatures varying from 21 to 800°C, according to the ASTM standards E606 and E8 [21-22]. This sample included only the metals which reportedly had fully measured Coffin-Manson, cyclic Ramberg-Osgood, and monotonic tensile properties among the more than 13,000 different materials listed on the ViDa software database [15-16], a powerful PC-based academic program developed to automate all traditional local approach methods used in fatigue design, including the SN, the IIW (for welded structures) and the εN for crack initiation, and the da/dN for crack propagation. Its comprehensive materials database has been compiled from several sources in the literature and carefully filtered to avoid suspicious data. In particular, all materials considered in this study can be found in [11, 13-14, 18, 20, 23-25], and their experimental Coffin-Manson curves are shown in Figures 1 and 2.

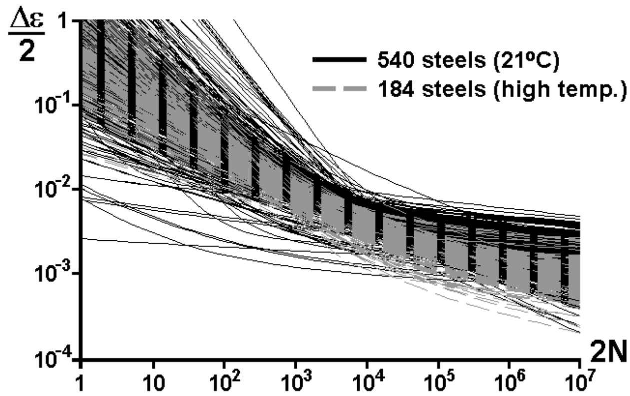

Figure 1. Coffin-Manson curves of 724 steels under temperatures between 21°C and 800°C.

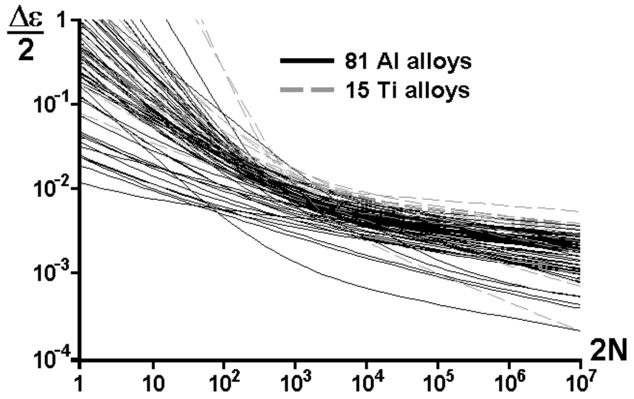

Figure 2. Coffin-Manson curves of 81 aluminum and 15 titanium alloys.

From the large size and diversity of the steel and aluminum samples, they may be considered representative of the behavior of these alloy families. Among the 724 steels, 540 were tested at room temperature, while the other 184 were tested under temperatures between 400 and 800°C. As suggested in Figure 1, temperature does not influence decisively on the scatter of the Coffin-Manson curves of the analyzed steels, therefore the low and high temperature data are evaluated together. However, the high-cycle fatigue resistance is significantly lowered under high temperatures (Figure 1). Part of this temperature effect can be accounted for by all discussed estimation methods, because the lower values of the ultimate strength S_U or the Brinnell hardness *HB* found at high temperatures always result in lower estimates of the fatigue resistance coefficient σ'_f. In the next section, the Coffin-Manson and Ramberg-Osgood parameter estimates are statistically evaluated.

STATISTICAL EVALUATION OF εN PARAMETER ESTIMATES

The Coffin-Manson and Ramberg-Osgood parameters and their estimates are individually studied in this section based on the data of the 845 metals described above. For the statistical study, each data set is sorted in ascending order, and then each data point is associated to its mean rank. Then, each data set is fitted using 12 continuous probability distributions: Beta, Birnbaum-Saunders, Gamma, Inverse Gauss, Logistic, Log-Logistic, Normal, Log-Normal, Pearson, Gümbel (extreme value), and Weibull [26-27]. The chi-square and Anderson-Darling tests [28-29] are used to evaluate the goodness-of-fit of each of the considered distributions for each set. In particular, both tests show that the Log-Logistic distribution [27] is the one that best fits the Coffin-Manson parameters *b*, *c*, and ε'_f, the cyclic hardening exponent *n'*, and the ratios σ'_f/S_U and $n'/(b/c)$ of the considered steels and aluminum alloys. This does not necessarily mean that these variables follow the Log-Logistic distribution, it is only an indication that among the 12 considered distributions this is the one that most likely produced the specific data sets used in this analysis. The best-fitted distributions and their mean, median, and coefficient of variation *V* (defined as the ratio between the standard deviation and the mean) are shown in Figure 3.

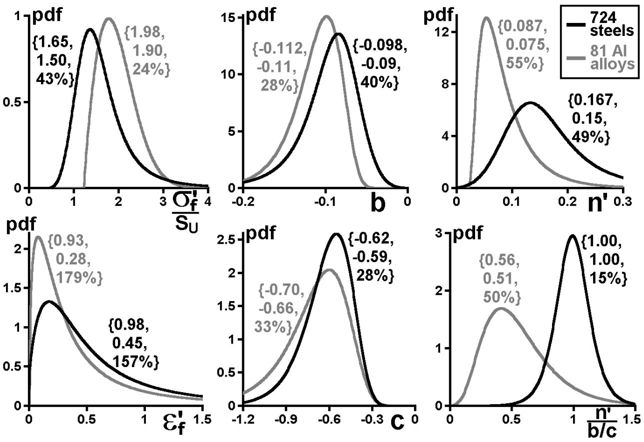

Figure 3. Probability density functions and {mean, median, coefficient of variation} of Coffin-Manson and Ramberg-Osgood parameters of 724 steels and 81 aluminum alloys.

It has been found that all 845 metals have σ'_f/S_U ratios between 0.5 and 10, with average 1.65 and median 1.5 for steels, suggesting that Manson's estimate $\sigma'_f = 1.9 \cdot S_U$ is potentially non-conservative for these materials. The fatigue ductility coefficient ε'_f has the greatest scatter of all studied properties (coefficient of variation *V* up to 179%), with values ranging from 0.001 to 400. It must be noted that ε'_f values much greater than 2.3 are very likely a result of bad fitting of the Coffin-Manson curve, because such values would imply in a reduction in area *RA* much greater than 90% at $2N = 1$. Also, all considered metals have cyclic hardening coefficients *K'* ranging between $E/1000$ and $E/20$, cyclic hardening exponents *n'* between 0.01 and 0.6, fatigue strength exponents *b* between −0.35 and −0.01, and fatigue ductility exponents *c* between −1.5 and −0.1. More specifically, 93% of the steels have $0.06 < n' < 0.35$, 92% have $-0.2 < b < -0.05$, and 94% are in the range $-0.9 < c < -0.3$. In addition, 94% of the aluminum alloys have $0.03 < n' < 0.2$, 91% have $-0.2 < b < -0.08$, and 88% present $-1.0 < c < -0.4$.

The coherence between Coffin-Manson's and Ramberg-Osgood's elastic and plastic strain ranges is verified from the evaluation of the correlations presented in Eq. (3) for the considered steels and aluminum alloys, see Figure 4. From this study on 724 steels, it is found that there is a reasonable (but not exact) correlation between the cyclic hardening exponent *n'* and the ratio *b*/*c*, with a coefficient of variation $V = 15\%$. The cyclic hardening coefficient *K'* estimate based on *n'* and on Coffin-Manson's coefficients is also fairly good for steels, despite the somewhat significant scatter in the experimental data, V = 15% as well. However, for the considered 81 aluminum alloys it is found that Eq. (3) tends to overestimate both n' and K', see Figs. 3 and 4. This is an indication that the coherence between the stress-strain and strain-life relationships used in the traditional εN method is better verified in steels than in aluminum alloys.

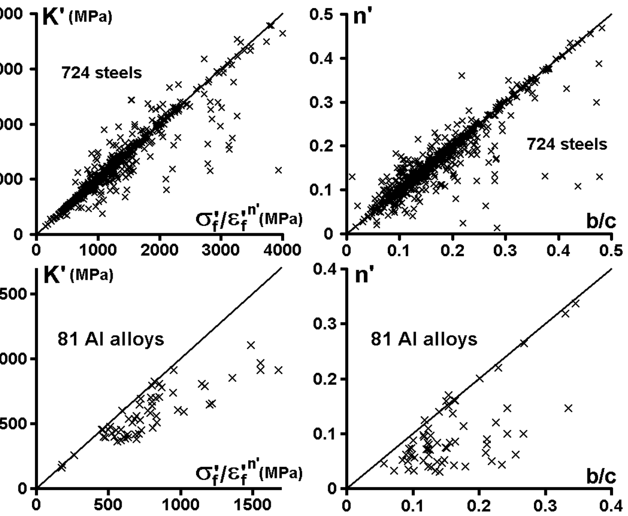

Figure 4. Coherence between Coffin-Manson and Ramberg-Osgood parameters for steels and aluminum alloys.

As seen in Figure 5, Manson's estimate for the fatigue strength coefficient σ'_f is non-conservative for most steels, while Mitchell's method results in better values. However, due to the 345MPa offset in Mitchell's estimate, σ'_f is overestimated in materials with low ultimate strength S_U, such as steels under high temperatures (Figure 5). Muralidharan-Manson's method provides a much better σ'_f estimate for steels, however it is overly conservative for aluminum and titanium alloys. Also, it is found that Muralidharan-Manson's σ'_f estimate for steels can be successfully approximated by $1.5 \cdot S_U$, a much simpler and equally effective expression. Interestingly, the factor 1.5 is also the median value of the σ'_f / S_U ratio for the 724 steels.

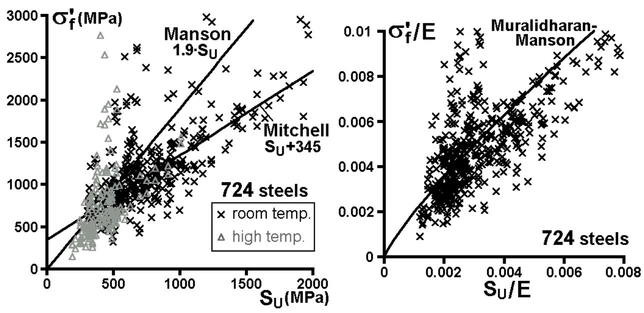

Figure 5. Estimates of Coffin-Manson's coefficient σ'_f .

The correlations between the fatigue strength exponent b and RA or S_U are poor for all studied metals: Manson's Four-Point method underestimates b for most materials, while Mitchell's correlation has a large scatter (Figure 6). Even though b and c correlate fairly well with the hardening exponent n', estimating these exponents as constants results in a smaller coefficient of variation if compared to the available estimates. In addition, Morrow's b estimate is non-conservative for almost all studied aluminum and titanium alloys. It is found that better predictions are obtained from constant b and c estimates: b = –0.09 and c = –0.59 for the 724 steels, and b = –0.11 and c = –0.66 for the 81 aluminum alloys (Figure 7).

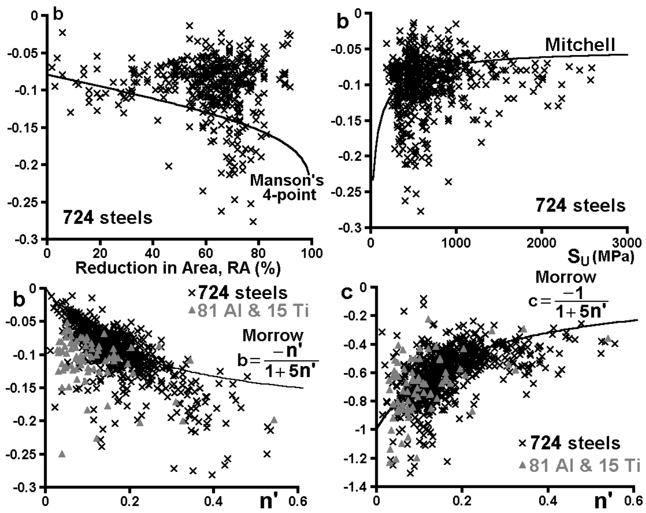

Figure 6. Estimates of Coffin-Manson's exponents b and c.

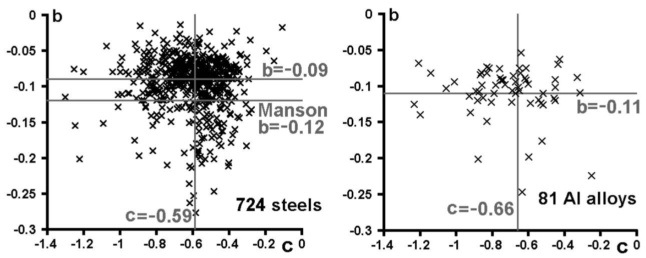

Figure 7. Coffin-Manson's exponents b and c for 724 steels and 81 aluminum alloys.

As seen in Figure 8, the fatigue ductility coefficient ε'_f does not correlate well with the reduction in area RA or the true fracture ductility ε_f. Mitchell's and Manson's ε'_f estimates are non-conservative. Also, there's a large scatter in Muralidharan-Manson's and Bäumel-Seeger's ε'_f estimates to justify a suitable correlation with S_U/E. One limitation of Bäumel-Seeger's method is that it is only valid if the ultimate strength S_U is much smaller than 2.2GPa, otherwise negative values of ε'_f may be obtained. Raske-Morrow's ε'_f estimate has also a large scatter, because it implicitly assumes a perfect correlation between the elastic and plastic strain ranges in Ramberg-Osgood and Coffin-Manson.

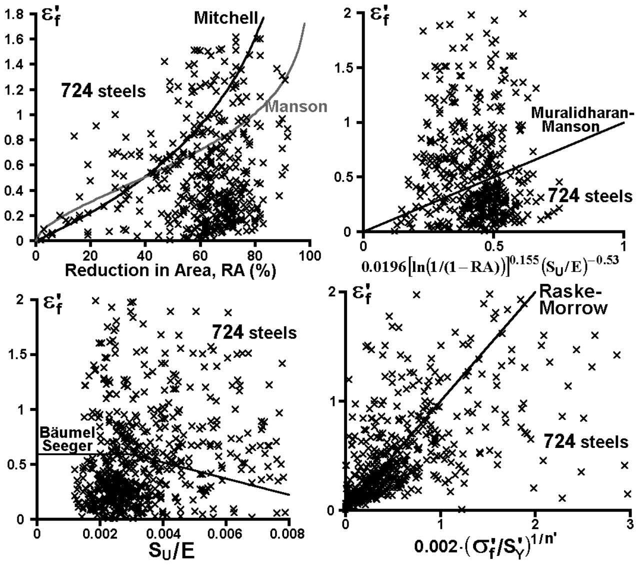

Figure 8. Estimates of Coffin-Manson's coefficient ε'_f.

Manson's method based on fixed points also results in poor estimates for the studied materials. The elastic and plastic strain ranges in Manson's Four-Point Correlation are overestimated at N = 1/4, 10 and 10^4 cycles for steels. The only fixed point with a fair correlation is $N = 10^5$ cycles, where the elastic strain amplitude is slightly underestimated by $0.45 \cdot S_U/E$. The Coffin-Manson coefficients σ'_f and ε'_f are overestimated from the Four-Point Correlation method, the exponent b is underestimated, and for 93% of the steels c results in the narrow range $-0.7 < c < -0.5$. Ong's proposed modification to the Four-Point Correlation method results in better average estimates for σ'_f, b and c, however, as in Mitchell's method, it overestimates ε'_f.

Roessle-Fatemi's method results in a fair correlation between σ'_f and the Brinnell hardness HB. From the good correlation $S_U = 3.4 \cdot HB$ for steels, this σ'_f estimate can be rewritten as $1.25 \cdot S_U$ + 225MPa, an intermediate function in between Manson's and Mitchell's. However, Roessle-Fatemi's estimate for ε'_f does not correlate well with the analyzed data, see Figure 9.

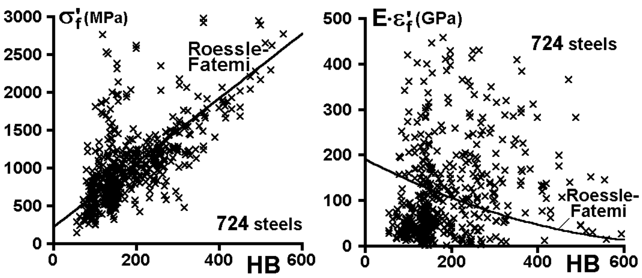

Figure 9. Roessle-Fatemi's estimates for Coffin-Manson coefficients σ'_f and ε'_f based on the Brinnell Hardness HB.

Therefore, from a statistical viewpoint, sophisticated equations surprisingly tend to increase the dispersion in ε'_f. The least scatter in those cases was obtained assuming a constant value such as its median 0.45 for steels or 0.28 for aluminum alloys (Figure 3).

Based on the above conclusions, an εN estimate called the Medians method is proposed, which estimates σ'_f/S_U, ε'_f, b and c as constants equal to their medians for each alloy family:

$$\frac{\Delta\varepsilon}{2} = 1.5\frac{S_U}{E}(2N)^{-0.09} + 0.45 \cdot (2N)^{-0.59} \quad (14)$$

(from 724 steels)

$$\frac{\Delta\varepsilon}{2} = 1.9\frac{S_U}{E}(2N)^{-0.11} + 0.28 \cdot (2N)^{-0.66} \quad (15)$$

(from 81 aluminum alloys)

Interestingly, the Medians estimate for steels is almost insensitive to the operating temperature. The only parameter with a significant temperature dependence is the fatigue ductility coefficient ε'_f: the median value for 540 steels at room temperature is $\varepsilon'_f = 0.51$, while 184 steels at temperatures between 400°C and 800°C have $\varepsilon'_f = 0.35$. Using these values, separate Medians estimates can then be proposed for high and low temperature steels. The fatigue strength coefficient σ'_f has also a significant temperature dependence, however the median of the σ'_f/S_U ratio remains unchanged.

Other Medians estimates for $\{\sigma'_f, \varepsilon'_f, b, c\}$ are obtained for three alloy families: $\{1.9 \cdot S_U, 0.50, -0.10, -0.69\}$ from a study on 15 titanium alloys; $\{1.2 \cdot S_U, 0.04, -0.08, -0.52\}$ calculated from 16 cast irons; and $\{1.4 \cdot S_U, 0.15, -0.08, -0.59\}$ from 9 nickel alloys. However, these three estimates should be used with caution, because they were based on a very limited sample.

Other useful estimates based on median values are E = 205GPa (median value of 3157 steels at room temperature from the ViDa database [15-16], with a coefficient of variation V = 3.1%), E = 71GPa (from 551 Al alloys, V = 4.0%), E = 108GPa (139 Ti alloys, V = 7.4%), E = 140GPa (22 cast irons, V = 24%), and E = 211GPa (376 Ni alloys, V = 3.4%).

STATISTICAL EVALUATION OF εN FATIGUE LIFE ESTIMATES

In the previous section, all fatigue estimates were evaluated by treating the εN parameters as independent random variables. However, for fatigue life estimation purposes, Coffin-Manson's coefficients and exponents are not independent. For instance, it is possible to obtain fair life predictions using a method that overestimates the fatigue strength coefficient σ'_f while underestimating the corresponding exponent b, since both errors may cancel each other. Therefore, to validate εN estimates, a statistical study must be performed comparing the predicted lives (and not only the individual Coffin-Manson parameters) with the experimentally measured ones.

From measured Coffin-Manson data on 724 steels and 81 aluminum alloys, it is found that the scatter in the εN specimen lives for the different materials is minimum between 1000 and 3000 cycles. This is perhaps a good reason to continue estimating Wöhler's curve using $N = 10^3$ cycles as a fixed point in the SN methodology. Also, the average strain amplitude at 10^3 cycles in both steels and aluminum alloys is approximately $\Delta\varepsilon(10^3)/2 = 0.8\%$. Even though the scatter is minimum around 0.8%, εN specimen lives varying from less than 50 cycles (for a few wet welds) up to $2\cdot10^4$ cycles (for a hot-worked H11 tool steel) can be obtained at this strain amplitude. The high scatter observed at lives greater than 10^5 cycles is expected, due to the large variation in the fatigue resistance of several steels and aluminum alloys.

The performance of each fatigue estimate is now evaluated through the life prediction ratio (LPR), defined as the ratio between the life (in cycles) predicted by any of the presented methods, $N_{predicted}$, and the observed experimental life, $N_{observed}$. Therefore, LPR values between zero and 1.0 are a result of conservative estimates, while values greater than 1.0 are non-conservative. It must be noted that all mean values and standard deviations of the LPR will be calculated based on the logarithmic representation of $N_{predicted}/N_{observed}$, in order to give equal weight to, e.g., ratios 3 and 1/3, since both imply on a factor of 3 in the life estimation error.

The probability density functions (pdf) that best-fitted the εN specimen LPR of the 724 steels are shown in Figure 10, obtained under the strain amplitude $\Delta\varepsilon/2 = 1.0\%$. Under such strain amplitude, Manson's Universal Slopes method results in average non-conservative prediction errors of 97% (since its mean LPR is 1.97), Bäumel-Seeger's in 38%, and the Medians method in 3%, with similar standard deviations. Except for Mitchell's method, which presents a high scatter in the LPR, it is found that all studied estimates result in roughly the same standard deviations when represented in the logarithmic scale at each strain range level. However, these standard deviations do vary with the strain amplitude level, presenting a minimum near $\Delta\varepsilon/2 = 1.0\%$. The poor performance of Mitchell's method in this study is mainly a result of its non-conservative ε'_f estimate, since the great majority of steels and aluminum alloys have ε'_f much smaller than the true fracture ductility ε_f.

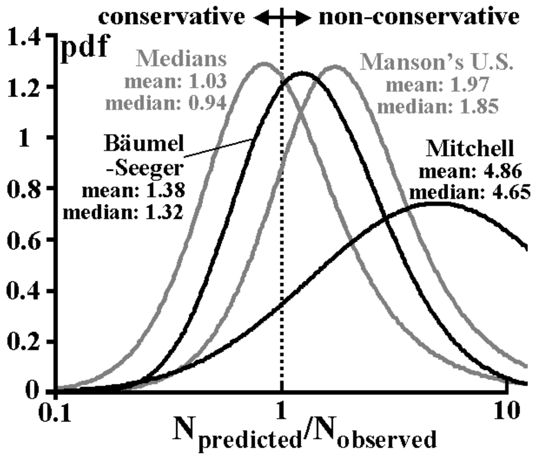

Figure 10. Statistics of the life prediction ratio obtained by a few estimation methods for 724 steels, obtained under the strain amplitude $\Delta\varepsilon/2 = 1.0\%$.

Each estimation method is further evaluated as follows through the average values of the LPR probability density functions obtained under several strain amplitudes $\Delta\varepsilon/2$, see Figure 11. Mitchell's method is not represented in this figure, because its average LPR is greater than 4.0 in the entire life range.

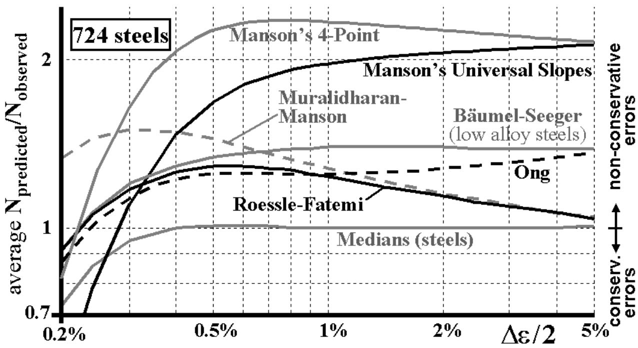

Figure 11. Average life prediction ratios obtained by several estimation methods for 724 steels, under strain amplitude levels between 0.2% and 5%.

Both Manson's Universal Slopes and Four-Point Correlation methods are non-conservative for short lives, with average life prediction errors of over 100%. Also, these two methods are highly conservative for long lives, underestimating the elastic strain amplitude $\Delta\varepsilon_e/2$ at 10^5 cycles using $0.44\cdot S_U/E$ or $0.45\cdot S_U/E$. A better correlation for the 724 steels is obtained from the Medians estimate

$$\frac{\Delta\varepsilon_e}{2}(10^5\,cycles) = 1.5\frac{S_U\cdot(2\cdot10^5)^{-0.09}}{E} = 0.5\frac{S_U}{E} \qquad (16)$$

Even though significantly non-conservative predictions may be obtained at strain amplitudes $\Delta\varepsilon/2$ below 1.0%, Muralidharan-Manson's and Roessle-Fatemi's methods result in reasonable average LPR for steels (Figure 11). Bäumel-Seeger's and Ong's methods also result in fair predictions, however they are slightly non-conservative at high $\Delta\varepsilon/2$ levels because of the poor estimates for ε'_f, which does not correlate with S_U/E or ε_f for the 724 steels. The lowest average prediction errors are obtained from the Medians estimate for steels, with LPR very close to 1.0 in all strain amplitudes between 0.4% and 5%, and conservative errors below this interval. However, this could be expected as the parameters from the Median method were calibrated using the same material data set used in the comparisons.

It is found that better predictions are obtained from the Medians method for aluminum and titanium alloys, followed by Bäumel-Seeger's Uniform Material law, very likely because both are based on constant σ'_f/S_U, ε'_f, b and c. Also, Bäumel-Seeger's estimate $c = -0.69$ may be appropriate for titanium but a little low for aluminum alloys. Therefore, it is always a good idea to consider separate estimates for each alloy family, separating the aluminum from the titanium alloys such as in the Medians method.

CONCLUSIONS

In this work, the existing Coffin-Manson parameter estimates were statistically evaluated, based on monotonic tensile and uniaxial fatigue properties of 845 metals. From this analysis it is concluded that, in average, steels present significantly higher b and c exponents than aluminum and titanium alloys. Therefore, different estimates for the Coffin-Manson parameters should be considered for each alloy family. Also, correlations between Coffin-Manson's b, c and ε'_f and the monotonic tensile test properties are poor, however the fatigue strength coefficient σ'_f presents a fair correlation with the ultimate strength S_U. The relatively large scatter in this correlation does not justify the use of non-linear estimates such as Muralidharan-Manson's, or linear estimates with offsets such as Mitchell's or Roessle-Fatemi's, which overestimate σ'_f for low values of S_U or HB. Constant estimates for the ratio σ'_f/S_U were found to better agree with the studied data. In addition, the correlations between σ'_f and σ_f and between ε'_f and ε_f should not be used.

From the studied data, it is found that better life predictions are obtained simply from constant estimates of the parameters b, c, σ'_f/S_U and ε'_f, such as in the proposed Medians method. Other estimates that resulted in good predictions are Roessle-Fatemi's, Bäumel-Seeger's, and Muralidharan-Manson's methods for steels. However, the estimates of the fatigue ductility coefficient ε'_f in these three methods are not very good. The main reason for the good performance of these methods is the combination of constant values for the b and c exponents and reasonable estimates for the fatigue strength coefficient. Ong's method also results in reasonable predictions, despite its poor σ'_f and ε'_f estimates. It must also be noted that Muralidharan-Manson's method should not be applied to aluminum or titanium alloys, which present significantly lower b and c exponents. Manson's Universal Slopes and Four-Point Correlation methods are very conservative for steels at long lives, as pointed out by Park and Song. Also, both methods result in average in significantly non-conservative life predictions at short lives.

Finally, for future work, improved Medians estimates could be obtained for both uniaxial and torsional fatigue properties using larger samples of material data. Nevertheless, it must be pointed out that all the presented estimates should never be used in design, because for some materials even the best methods may result in life prediction errors of an order of magnitude. The use of such estimates, even the proposed Medians method, is only admissible during the first stages of design, otherwise all fatigue properties should be obtained experimentally.

REFERENCES

[1] Dowling NE. Mechanical Behavior of Materials. Prentice-Hall 1999.

[2] Stephens RI, Fatemi A, Stephens RR, Fuchs HO. Metal Fatigue in Engineering. Interscience 2000.

[3] Hertzberg RW. Deformation and Fracture Mechanics of Engineering Materials. Wiley 1995.

[4] Rice RC, editor. Fatigue Design Handbook. SAE 1997.

[5] Sandor BI. Fundamentals of Cyclic Stress and Strain. U.Wisconsin 1972.

[6] Morrow JD. Cyclic Plastic Strain Energy and Fatigue of Metals. Internal Friction, Damping, and Cyclic Plasticity - ASTM STP 378. American Society for Testing and Materials, Philadelphia, PA, 1964:45-87.

[7] Manson SS. Fatigue: a Complex Subject - Some Simple Approximations. Experimental Mechanics - Journal of the Society for Experimental Stress Analysis 1965;5(7):193-226.

[8] Raske DT, Morrow J. Mechanics of Materials in Low Cycle Fatigue Testing, Manual on Low Cycle Fatigue Testing - ASTM STP 465. American Society for Testing and Materials, Philadelphia, PA, 1969:1-25.

[9] Mitchell MR, Socie DF, Caulfield, EM. Fundamentals of Modern Fatigue Analysis. Fracture Control Program Report No. 26, University of Illinois, USA. 1977:385-410.

[10] Muralidharan U, Manson SS. Modified Universal Slopes Equation for Estimation of Fatigue Characteristics. Journal of Engineering Materials and Technology - Transactions of the American Society of Mechanical Engineers 1988;110:55-8.

[11] Bäumel A Jr., Seeger T. Materials Data for Cyclic Loading - Supplement I. Amsterdam: Elsevier Science Publishers, 1990.

[12] Ong JH. An improved technique for the prediction of axial fatigue life from tensile data. International Journal of Fatigue 1993;15(3):213-9.

[13] SAE J1099 Technical Report on Fatigue Properties. SAE Handbook 1982.

[14] Roessle ML, Fatemi A. Strain-controlled fatigue properties of steels and some simple approximations. International Journal of Fatigue 2000;22:495-511.

[15] Meggiolaro MA, Castro JTP. ViDa - a Visual Damagemeter to Automate the Fatigue Design under Complex Loading (in Portuguese). Brazilian Journal of Mechanical Sciences - RBCM 1998;20(4):666-85.

[16] Miranda ACO, Meggiolaro MA, Castro JTP, Martha LF, Bittencourt TN. Fatigue Crack Propagation under Complex Loading in Arbitrary 2D Geometries. In: Braun AA, McKeighan PC, Lohr RD, editors. Applications of Automation Technology in Fatigue and Fracture Testing and Analysis, vol. 4. ASTM STP 1411, 2002:120-46.

[17] Ong JH. An evaluation of existing methods for the prediction of axial fatigue life from tensile data. International Journal of Fatigue 1993;15(1):13-9.

[18] Brennan FP. The Use of Approximate Strain-Life Fatigue Crack Initiation Predictions. International Journal of Fatigue 1994;16:351-6.

[19] Park JH, Song JH. Detailed Evaluation of Methods for Estimation of Fatigue Properties. International Journal of Fatigue 1995;17(5):365-73.

[20] Kim KS, Chen X, Han C, Lee HW. Estimation methods for fatigue properties of steels under axial and torsional loading. International Journal of Fatigue 2002;24:783-793.

[21] ASTM Standard E606-92, Standard Practice for Strain-Controlled Fatigue Testing. Annual Book of ASTM Standards, vol. 03.01. American Society for Testing and Materials, West Conshohocken, PA. 1997:523-37.

[22] ASTM Standard E8-96a, Standard Test Methods for Tension Testing of Metallic Materials. Annual Book of ASTM Standards, vol. 03.01. American Society for Testing and Materials, West Conshohocken, PA. 1997:56-76.

[23] Böller C Jr., Seeger T. Materials Data for Cyclic Loading. Elsevier Science Publishers 1987.

[24] ASM Metals Reference Book. ASM International 1993.

[25] ASM Source Book on Industrial Alloy and Engineering Data. ASM International 1978.

[26] Evans M, Hastings N, Peacock B. Statistical Distributions. John Wiley and Sons, 1993.

[27] Johnson NL, Kotz S, Balakrishnan N. Continuous Univariate Distributions. John Wiley and Sons 1994.

[28] Stephens MA. EDF Statistics for Goodness of Fit and Some Comparisons. Journal of the American Statistical Association 1974;69:730-7.

[29] D'Agostino RB, Stephens MA. Goodness-Of-Fit Techniques. Marcel-Dekker NY 1986:97-193.

[30] Juvinall RC. Stress, Strain & Strength. McGraw-Hill, 1967.

[31] Shigley JE, Mischke CR. Mechanical Engineering Design. McGraw-Hill, 1989.