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Approximate determination of a strain-controlled fatigue life curve for aluminum alloy sheets for aircraft structures ☆

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ABSTRACT

This paper deals with selected methods of approximate determination of a strain-controlled fatigue life curve for aluminum alloy sheets used in aircraft structures. Authors based their analysis of those methods on the results of own research of 2024-T3 alloy and its Russian equivalent D16CzATW. The approximate strain-fatigue life curves were compared with the experimental curves. The influence of inconsistencies between those curves on the calculation results was analyzed on computational examples by means of the Palmgren–Miner's rule.

1. Introduction

Fatigue curves serve as the basis for the calculation of fatigue strength [1,2]. As fatigue tests are characterized by high labor and time consumption and are very costly, it is not always possible to perform full range fatigue tests or, for comparison purposes, it is sufficient to approximately determine the fatigue curve based e.g. on relatively simple and quick monotonic tensile tests or on available literature data. Such approach has been introduced, among others, to expert systems used to estimate fatigue properties [3].

A strain-controlled fatigue life curve is characterized by the following relationship:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E} \cdot (2N_f)^b + \varepsilon_f' \cdot (2N_f)^c. \quad (1)$$

One of the first methods for approximate determination of the relationship (1) based on the monotonous tensile test was proposed by Manson [4]. The first of them – Four–Point–Correlation Method has been later modified by Ong [5]. The second of them – Universal Slopes Method – has been modified by Muralidharan and Manson [6].

Socie et al. [7] presented relationships designed to determine factors of the formula (1) for steel. Another method, intended particularly for steel grades with hardness value below 500 HB, was proposed by Mitchell [8]. Bäumel and Seeger [9] presented Uniform Material Law Method which is suitable for metals. Its coefficients are very similar to those of the Modified Universal Slopes Method. Roessle and Fatemi [10] proposed the method used for steel and based on the hardness value and the Young's modulus only. Hatscher et al. presented the Variable Slopes Method empirically verified for steel sheet [11], while as regards Polish literature, we can mention the study by Flasińska and Łagoda that includes attempts to find the relationship between selected static and fatigue properties [12].

Studies by Ong [13] (for 49 steel grades) as well as Kim et al. [14] (for eight steel grades) also include empirical analysis of methods for approximate determination of a strain-controlled fatigue life curve. Park and Song [15] analyzed several methods used for 138 types of material (116 steel grades, 16 aluminum alloys and six titanium alloys) and they concluded that methods proposed by Bäumel and Seeger [9], Muralidharan and Manson [6] as well as by Ong [5] provide better approximation of experimental data than the remaining ones. Song and Park [16] analyzed six methods used for five groups of materials and they found out that Universal Slopes Method seems to be the best for steel while the method developed by Bäumel and Seeger gives satisfactory results when monotonous properties exclude necking [9]. They also proposed a new method (a Modified Mitchell's Method) which better estimates fatigue properties of aluminum alloys [8]. Meggiolaro and Castro presented Medians Method based on statistical analysis of parameters used in the relationship (1) performed for 724 steel grades and 81 aluminum alloys [17].

2. Selected methods of fatigue curve determination for aluminum alloys

2.1. Four-Point-Correlation Method (FPCM) – [4]

The Four-Point-Correlation Method proposed by Manson [4] is based on plastic strain and elastic strain values represented by lines $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$. Those lines are determined upon the basis of

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Nomenclature

$2N_f$	reversals to failure (2 reversals = 1 cycle)
b	fatigue strength exponent
c	fatigue ductility exponent
E	Young's modulus, MPa
N_{cal}	calculating fatigue life obtained on the basis of the approximate strain-controlled fatigue life curve, cycles
N_{exp}	calculating fatigue life obtained on the basis of the experimental strain-controlled fatigue life curve, cycles
RA	reduction in area
S_u	ultimate tensile strength, MPa
ε_f	true fracture ductility
ε_f'	fatigue ductility coefficient
$\Delta\varepsilon$	total strain range
$\Delta\varepsilon_e$	elastic strain range
$\Delta\varepsilon_p$	plastic strain range
σ_f	true fracture strength, MPa
σ_f'	fatigue strength coefficient, MPa
FPCM	Four-Point-Correlation Method
USM	Universal Slopes Method
MUSM	Modified Universal Slopes Method
UMLM	Uniform Material Law
MFPCM	Modified Four-Point-Correlation Method
MMM	Modified Mitchell's Method
MM	Median Method

two points. Coefficients used in formula (1) for this method can be characterized by the following relationships:

$$\sigma_f' = \frac{E}{2} \times 10^{b\cdot\log 2 + \log\left[\frac{2.5S_u\cdot(1+\varepsilon_f)}{E}\right]}, \quad \varepsilon_f' = \frac{1}{2} \times 10^{c\cdot\log\frac{1}{20} + \log\left(\frac{1}{4}\cdot\varepsilon_f^{3/4}\right)},$$
$$b = \frac{\log\left[\frac{2.5\cdot(1+\varepsilon_f)}{0.9}\right]}{\log\left(\frac{1}{4\times10^5}\right)}, \quad c = \frac{1}{3}\log\left(\frac{0.0132 - \Delta\varepsilon_e^*}{1.91}\right) - \frac{1}{3}\log\left[\frac{1}{4}\cdot\varepsilon_f^{3/4}\right], \tag{2}$$

where ε_f is dependent on reduction in the RA area of the specimen

$$\varepsilon_f = \ln\left(\frac{1}{1-RA}\right), \tag{3}$$

whereas $\Delta\varepsilon_e^*$ is the range of the elastic strain for 10,000 load cycles and it can be characterized by the following relationship

$$\Delta\varepsilon_e^* = 10^{b\cdot\log(4\times10^4) + \log\left[\frac{2.5S_u(1+\varepsilon_f)}{E}\right]}. \tag{4}$$

2.2. Universal Slopes Method (USM) – Manson [4]

Universal Slopes Method [4] assumes that inclination of lines $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$ characterized by exponents b and c does not depend on material type. The fatigue strength coefficient as well as the fatigue ductility coefficient used in formula (1) take the following form:

$$\sigma_f' = 1.9018\cdot S_u, \quad \varepsilon_f' = 0.7579\cdot\varepsilon_f^{0.6}, \tag{5}$$

where ε_f is determined according to the relationship (3), while exponents b = –0.12 and c = –0.6 assume constant values.

2.3. Modified Universal Slopes Method (MUSM) – Muralidharan and Manson [6]

Like the original one, the Modified Universal Slopes Method [6] assumes that the exponents b and c do not depend on the material type. Coefficients used in formula (1) can be calculated based on the following relationships:

$$\sigma_f' = E\cdot 0.623\cdot\left(\frac{S_u}{E}\right)^{0.832}, \quad \varepsilon_f' = 0.0196\cdot\varepsilon_f^{0155}\cdot\left(\frac{S_u}{E}\right)^{-0.53}, \tag{6}$$

where ε_f is determined according to the relationship (3), while the exponents assume constant values: b = –0.09 and c = –0.56.

2.4. Uniform Material Law Method (UMLM) – Bäumel and Seeger [9]

Uniform Material Law Method [9] assumes that the value of exponents b and c as well as the coefficient ε_f' is constant for the whole group of materials. Only the coefficient σ_f' depends on the material properties. Coefficients used in formula (1) for this method for aluminum alloys can be characterized by the following relationships:

$$\sigma_f' = 1.67\cdot S_u, \tag{7}$$

while constants value is assumed by: b = –0.095, $\varepsilon_f' = 0.35$, c = –0.69.

2.5. Modified Four-Point-Correlation Method (MFPCM) – Ong [5]

Modified Four Point Correlation method (MFPC) proposed by Ong [5] differs slightly from the original method proposed by Manson [4]. According to Modified Four Point Correlation method, a strain-controlled fatigue life curve is determined by calculating the elastic strain amplitude at the load reversal level of 10^0 and 10^6 and the plastic strain amplitude at the load reversal level of 10^0 and 10^4. In this method, coefficients used in formula (1) assume the following form:

$$\sigma_f' = S_u\cdot(1+\varepsilon_f), \quad \varepsilon_f' = \varepsilon_f,$$
$$b = \frac{1}{6}\cdot\left[\log\left(0.16\cdot\left(\frac{S_u}{E}\right)^{0.81}\right) - \log\left(\frac{\sigma_f}{E}\right)\right],$$
$$c = \frac{1}{4}\cdot\log\left(\frac{0.00737 - \frac{\Delta\varepsilon_e^*}{2}}{2.074}\right) - \frac{1}{4}\cdot\log\sigma_f, \tag{8}$$

where ε_f is determined according to the relationship (3), while the elastic strain range $\Delta\varepsilon_e^*$ for $2N_f$ = 10,000 reversals is calculated using the formula:

$$\frac{\Delta\varepsilon_e^*}{2} = \frac{\sigma_f}{E}\times 10^{\frac{2}{3}\cdot\left[\log\left(0.16\cdot\left(\frac{S_u}{E}\right)^{0.81}\right) - \log\left(\frac{\sigma_f}{E}\right)\right]}. \tag{9}$$

2.6. Modified Mitchell's Method (MMM) – Song and Park [16]

Song and Park Modified Mitchell's Method [8] by adapting it specially for aluminum alloys. This method assumes that coefficients used in formula (1) can be calculated based on the following relationship:

$$\sigma_f' = S_u + 335, \quad b = -\frac{1}{6}\cdot\log\left(\frac{S_u+335}{0.446\cdot S_u}\right), \quad \varepsilon_f' = \varepsilon_f, \tag{10}$$

where ε_f is determined based on the relationship (3), while the fatigue ductility exponent assumes constant value c = –0.664.