

Article

Comparison of Fatigue Property Estimation Methods with Physical Test Data

Sebastian Raczek ^{1,2}, Adam Niesłony ^{1,*}, Krzysztof Kluger ¹ and Tomasz Łukasik ²

¹ Department of Mechanics and Machine Design, Opole University of Technology, ul. Mikołajczyka 5, 45-271 Opole, Poland; sebastian.raczek@student.po.edu.pl (S.R.); k.kluger@po.edu.pl (K.K.)

² Tenneco Automotive Eastern Europe Sp. z o.o., ul. Usługowa 20, 44-100 Gliwice, Poland; t Lukasik@tenneco.com

* Correspondence: a.nieslony@po.edu.pl

Abstract

Cost reduction has always been a high priority target in modern management. Concentrating on material strength, the huge potential is recognized for cost reduction in finding the material fatigue coefficients by reduction the number and time required for testing specimens. The aim of this study is to evaluate the accuracy of several fatigue parameter estimation methods by comparing them with reference test data obtained for six different steel materials. In the literature, several estimation methods can be found. Those methods rely on tension or hardness tests. The concern is about the accuracy of those methods; therefore, a basic case was investigated involving estimation methods and comparing them to reference data from a physical test. The case was selected in a manner that allowed the verification of combined low and high cycle fatigue. As a result, the estimation methods produced a very wide range of fatigue life predictions, but some of them were quite accurate. This leads to the conclusion that estimation methods can be a step forward for finding the fatigue material properties; however, a study should be undertaken on which methods are the most suitable for the material family used.

Keywords: Manson–Coffin–Basquin; Ramberg–Osgood; fatigue coefficients; estimation method; cyclic loading



Academic Editor: Alberto Campagnolo

Received: 27 May 2025

Revised: 4 July 2025

Accepted: 7 July 2025

Published: 9 July 2025

Citation: Raczek, S.; Nieslony, A.; Kluger, K.; Łukasik, T. Comparison of Fatigue Property Estimation Methods with Physical Test Data. *Metals* **2025**, *15*, 780. <https://doi.org/10.3390/met15070780>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Fatigue analysis allows the assessment of the durability and failure risk of machine parts or structures affected by repetitive loading conditions. The damage criterion is usually the moment of first crack occurrence, because most machine or structure elements, due to safety and economic losses, are not intended for use with any form of damage or loss of strength. Material fatigue as a phenomenon was already noticed in the 19th century, and the first attempts to describe it appeared. One of the popular and still-used fatigue principles was proposed by Basquin in 1900, which relates the stress amplitude to the number of load reversals leading to failure using a power-law relationship [1]:

$$\sigma_a = \sigma'_f (2N_f)^b. \quad (1)$$

Later, in 1955, Coffin and Manson independently came to the plastic strain amplitude vs. reversals to failure relation (Equation (2)) [1]:

$$\frac{\Delta \epsilon_p}{2} = \epsilon'_f (2N_f)^c. \quad (2)$$

After simple mathematical transformation the two above equation can be combined, resulting in the total strain amplitude vs. reversals to failure relation (Equation (3)).

$$\frac{\Delta\epsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \epsilon'_f (2N_f)^c \quad (3)$$

The presented relations are expressed in Figure 1 [1]. This formula is not the only one describing the relationship between the number of cycles and strain amplitude. Alternative models can also be found, for example, in the work of Tridello et al. [2]. The strain-based description of material fatigue behavior has brought significant benefits compared to the description using stresses, including the determination of fatigue life in the range of low cycle fatigue.

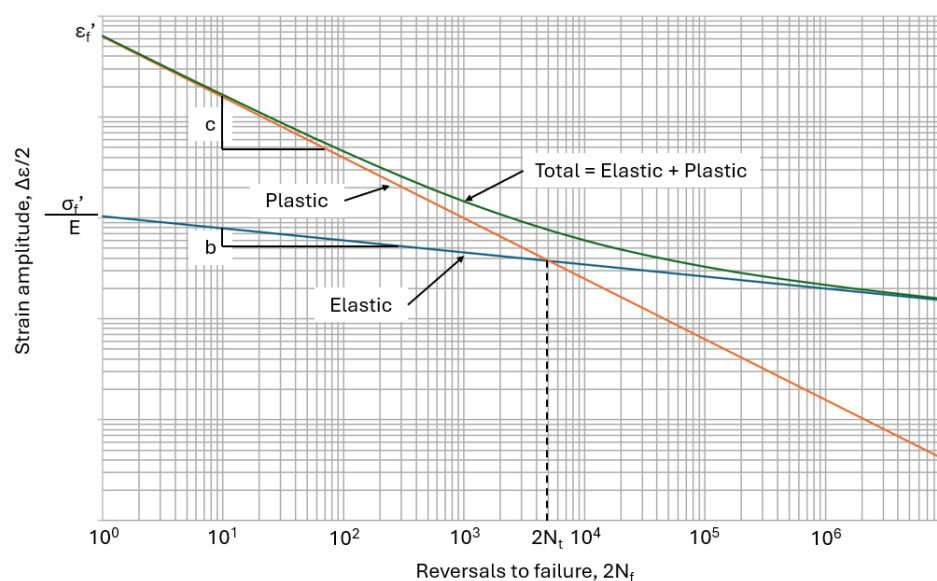


Figure 1. Graphic representation of strain amplitude vs. reversals to failure relation in log–log scale.

When conducting a strength analysis, the most important thing is to determine the number of load cycles that a given part of a structure can withstand before failure. Since there is no direct analytical solution for obtaining the number of cycles N_f , a numerical method for solving nonlinear equation needs to be used. In this study the Newton–Raphson and Levenberg–Marquardt methods were chosen [3]. Equation (3) is defined by four parameters, σ'_f , ϵ'_f , b , and c . To find them, a physical test needs to be conducted. Durability tests are expensive and time-consuming. Some authors share their work describing in detail the monotonic, cyclic, and fatigue properties. Even the failure mechanisms have been deeply studied. Gomes et al. [4] investigated the 51CrV4 steel used for leaf springs of railway rolling stock. Moreover, not only is material data considered, but also, fatigue models are used to validate the obtained material parameters. Despite the shared material data, Ramirez-Acevedo et al. [5] put forward the evolution of damage depending on the test stage, highlighting the discrepancies between the test and the often-implemented material models. Furthermore, Ramirez-Acevedo et al. [5] used two methods of measurement of the accumulated damage. It is very important to share high-quality and complete material data between scientists, since that data can be used in validating and establishing new ideas. In the literature, estimation methods are available for determining the material fatigue parameters that require only a tension test [6].

The Coffin–Manson–Basquin equation requires an elastic–plastic material definition. That kind of material definition has often been implemented using the Ramberg–Osgood relation, shown in Equation (4) [7].

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'} \right)^{\frac{1}{n'}}. \quad (4)$$

An illustration of such a connection was presented by Niesłony et al. [7], where they proposed a three-dimensional graph, built based on stress, strain, and cycles till failure. Initially, fatigue relation (strain amplitude–cycles till failure) needs to be created; then, such a curve can be projected on two planes (stress amplitude–strain amplitude, stress amplitude–cycles till failure). The stress amplitude–strain amplitude plane projection can be described using the Ramberg–Osgood relation (Equation (4)) with good agreement.

Durability analyses are often performed using a linear–elastic material definition. This is not a problem when using the Basquin model (Equation (1)). Since the Basquin proposition does not consider the plastic strain, it is limited to high cycle fatigue. Therefore, for low and moderate cycle fatigue, a plastic correction needs to be implemented. Neuber proposed a method of assessing the local plastic stress and strain from linear calculations (Equation (5)) that rely on the product of the multiplication of stress and strain. He assumed the product remains constant for both elastic and elastic–plastic material representation. Moreover, he included the possibility of the existence of stress concentration in the investigated region [8].

$$\sigma_{corrected} \cdot \varepsilon_{corrected} = K_t^2 \cdot \sigma_{elastic} \cdot \varepsilon_{elastic}. \quad (5)$$

Graphical representation from Figure 2 explains why the multiplication product is called a Neuber hyperbola. The Neuber plastic correction method can be used for both monotonic and cyclic strength computation.

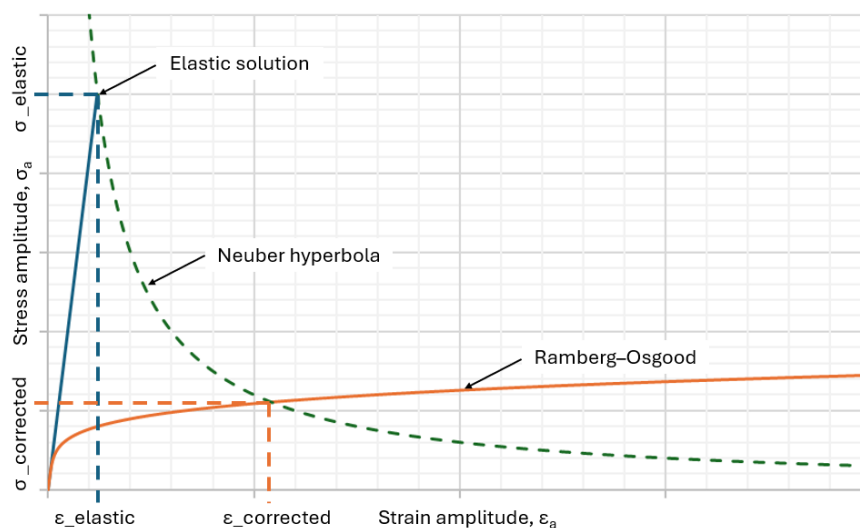


Figure 2. Graphic representation of Neuber plastic correction.

This paper confronts the accuracy of estimation methods with strain-controlled fatigue tests for steel materials. The use of estimation methods reduces the cost of durability analysis; however, it must maintain a reasonable accuracy.

A review of the available literature reveal that this topic was, and still is, under investigation. Lipski et al. [6] investigated how the approximation methods prove themselves for aluminum alloy sheets. The authors suggested caution when using approximation methods, as they may lead to high error in life calculations. They compare each fatigue parameter separately and notice sufficient confirmation in the elastic range; however, the

plastic range was exposed to larger error. Wollmann et al. [9] investigated similar methods on steel components but also including the elevated temperature. The study acknowledged that approximation curves lie above the experiment data and due to that are not conservative. For 20 °C the best estimation results were obtained from Roessle's and Fatemi's method, with very good correlation. For 600 °C the results were less accurate, although the authors claim that it is still beneficial to use them. Harun et al. [10] performed a study on UNS C70600 copper/nickel 90/10 in a range below 10,000 cycles. The authors put forward that the accuracy of the estimation methods depends on the band of the cycles concerned. They observed that for below 1000 cycles, a better solution shows a modified universal slope method, but in higher cycles, a better correlation was obtained for universal slope or modified four-point correlation methods. Basan et al. [11] considered only three estimation methods but confronted them with material groups like unalloyed, low-alloy, and high-alloy steel, divided into subgroups of low- and high-strength steel and low and high cycle fatigue. This division into groups allowed the authors to conclude that estimation methods work better for low-strength materials in the low cycle fatigue range. Also, different methods achieve greater effectiveness for different presented subgroups. The authors point out that further investigation in estimation methods relying on vast data may bring new more accurate methods. Shamsaei et al. [12] gives insight into the Roessle and Fatemi hardness method. Here, however, a multiaxial fatigue condition involving three different steel materials was considered. Analysis showed that the life predicted was fairly accurate for the low and high cycle range. Basan et al. [13] summarize a number of estimation methods and criteria used for evaluating the accuracy of those methods. The review of existing methods brings an overview of how the methods were established, as well as the quantity of datasets used. It is beneficial to divide the investigated steel datasets into groups like unalloyed, low-, and high-alloy steels, as this prevents too much averaging of data. This paper recommends the modified universal slopes method, as it performs the best and can be used universally in all proposed groups. Park et al. [14] made a similar study to those of the other scientists. They challenged multiple materials, divided into groups as follows: unalloyed steels, low-alloy steels, high-alloy steels, aluminum alloys, titanium alloys, and all materials together. The modified universal slopes method was proposed as the best for steels and all materials, while Mitchell's method gave the best results for aluminum, and the modified four-point correlation method for titanium. Also, it is worth noticing that despite the good correlation in some cases, the results may be unconservative.

2. Empirical Methods for Determining Material Fatigue Parameters

In preparing this publication, a review was made of methods for determining the fatigue parameters of materials without the need for their direct fatigue testing. It was noted that these methods were established and later tested based on extensive data from test samples, which came from other publications, datasets, and results obtained by the authors themselves. In this section, selected most-interesting methods are presented. They are not universal and have limitations, for example regarding the type of material. Steel and aluminum are expressed in different equations in most cases. Another factor limiting the use of estimation formulas is the chemical composition. This article focuses exclusively on steel materials [9,10], especially in the context of the later application of the strain fatigue curve to determine fatigue life.

Some parameters evaluated in estimation methods require additional calculations (Equations (6) and (7)) conducted on monotonic strength parameters. Since these calcula-

tions are recurring in estimation methods, they were put before the method description [14], i.e., ductility,

$$Z = \ln\left(\frac{1}{1 - RA}\right), \quad (6)$$

and true fracture strength,

$$\sigma_f = \sigma_{UTS} \cdot (1 + \varepsilon_f) \quad (7)$$

The following Sections 2.1–2.7 introduce material fatigue parameter estimation methods that later will be subject to accuracy validation. Equations from Equation (8) to Equation (36) are used to find the fatigue parameters based on method assumptions.

2.1. FPCM—Four-Point Correlation Method

FPCM is dedicated to all metallic materials. The equations were derived from four points, two for the Manson–Coffin relation and two for Basquin [9,10,13,14].

$$\sigma'_f = 1.25 \cdot \sigma_f \cdot 2^b, \quad (8)$$

$$b = \frac{\log\left(0.36 \cdot \frac{\sigma_{UTS}}{\sigma'_f}\right)}{5.6}, \quad (9)$$

$$c = \frac{1}{3} \cdot \log\left(\frac{0.0066 - \sigma'_f \cdot \frac{(2 \cdot 10^4)^b}{E}}{0.239 \cdot Z^{\frac{3}{4}}}\right), \quad (10)$$

$$\varepsilon'_f = \frac{0.125}{20^c} \cdot Z^{\frac{3}{4}}. \quad (11)$$

2.2. USM—Universal Slope Method

USM is dedicated to all metallic materials. The main assumption is that the slope for both the plastic and elastic strain is constant for all materials [6,9,10,13,14].

$$\sigma'_f = 1.9018 \cdot \sigma_{UTS}, \quad (12)$$

$$b = -0.12, \quad (13)$$

$$\varepsilon'_f = 0.7579 \cdot Z^{0.6}, \quad (14)$$

$$c = -0.6. \quad (15)$$

2.3. MUSM—Modified Universal Slope Method

MUSM is dedicated to all metallic materials. This modification of USM comes from changing the slope of the plastic and elastic strain. Moreover, a Young modulus is introduced into the equation [6,9,10,13,14].

$$\sigma'_f = E \cdot 0.623 \cdot \left(\frac{\sigma_{UTS}}{E}\right)^{0.832}, \quad (16)$$

$$b = -0.09, \quad (17)$$

$$\varepsilon'_f = 0.0196 \cdot Z^{0.155} \cdot \left(\frac{\sigma_{UTS}}{E}\right)^{-0.53}, \quad (18)$$

$$c = -0.56. \quad (19)$$

2.4. UMLM—Uniform Material Law Method

UMLM is dedicated to unalloyed and low-alloy steel. A variant for aluminum and titanium alloys can also be found in the literature. The authors propose a parameter depending on the fracture of ultimate tension strength and the Young modulus, mostly affecting the low cycle range [6,9–11,13,14].

$$\sigma'_f = 1.5 \cdot \sigma_{UTS}, \quad (20)$$

$$b = -0.087, \quad (21)$$

$$\epsilon'_f = 0.59 \cdot \psi, \quad (22)$$

$$c = -0.58, \quad (23)$$

$$\psi = 1 \text{ for } \frac{\sigma_{UTS}}{E} \leq 0.003, \quad \psi = 1.375 - 125 \cdot \frac{\sigma_{UTS}}{E} \text{ for } \frac{\sigma_{UTS}}{E} \geq 0.003. \quad (24)$$

2.5. MFPCM—Modified Four-Point Correlation Method

MFPCM is dedicated to all metallic materials. It differs from FPCM in estimating the slope in the plastic and elastic range by using the ultimate tension strength and true fracture strain. The principals do not change [6,9,10,13,14].

$$\sigma'_f = \sigma_{UTS} \cdot (1 + \epsilon_f), \quad (25)$$

$$b = \frac{1}{6} \cdot \log \left(\frac{\left(\frac{\sigma_{UTS}}{E} \right)^{0.81}}{6.25 \cdot \frac{\sigma_f}{E}} \right), \quad (26)$$

$$\epsilon'_f = \epsilon_f, \quad (27)$$

$$c = \frac{1}{4} \cdot \log \left(\frac{0.0074 - \frac{\sigma'_f \cdot (10^4)^b}{E}}{2.074 \cdot \epsilon_f} \right). \quad (28)$$

2.6. MM—Median Method

MM is dedicated to steel. A variant for aluminum alloys can also be found in the literature. The authors assume that only ultimate tension stress is needed to determine the fatigue coefficients. Most of the parameters are constant [6,9–11,13].

$$\sigma'_f = 1.5 \cdot \sigma_{UTS}, \quad (29)$$

$$b = -0.09, \quad (30)$$

$$\epsilon'_f = 0.45, \quad (31)$$

$$c = -0.59. \quad (32)$$

2.7. RF—Roessle–Fatemi Method

The RF method is dedicated to steels in the hardness range of 100–700 HB. The main assumption of this method is to use the surface hardness for estimating the fatigue parameters. Mostly, a fatigue crack initiation is expected on the surface of the component where the hardness can be measured [9–13].

$$\sigma'_f = 4.25 \cdot HB + 225, \quad (33)$$

$$b = -0.09, \quad (34)$$

$$\varepsilon'_f = \frac{0.32 \cdot HB^2 - 487 \cdot HB + 191,000}{E}, \quad (35)$$

$$c = -0.56. \quad (36)$$

2.8. Physical Test Data

The abovementioned methods require a tension or hardness test to collect the required input. Where it is possible, the tension or hardness test should be performed according to a standard. The necessary data to be collected from the tests are as follows:

- Tension strength (σ_{UTS})—The maximum stress a material can withstand while being subject to uniaxial tension load.
- Elongation at break (ε_f)—The measure of a material's expandability, indicating how much it can stretch before breaking.
- Reduction of the cross-section area (RA)—The decrease in cross-sectional area at the point of fracture, reflecting the material's ability to undergo plastic deformation before failure. This value can be obtained only from a test or the literature.
- Young modulus (E)—The measure of a material's stiffness, defined as the ratio of tension stress to tension strain in the linear elastic region.
- Hardness (HB)—The measure of material resistance to surface deflection.

ISO standard 6892-1 [15] is a widely recognized standard that outlines the methods for tension-testing of metallic materials at room temperature. It provides in detail the specimen shape and test conditions for determining key mechanical parameters. Considerations regarding the material's processing history, environmental conditions, and specific application are essential when interpreting test outcomes.

While static properties like ultimate tension strength, yield strength, and ductility influence fatigue properties, fatigue behavior is more complex due to cyclic loading effects, crack initiation, and propagation mechanisms. High-static-strength materials do not always guarantee high fatigue resistance, and factors like microstructure, surface finish, and environmental conditions play a crucial role [16]. ISO standard 12106 [17] outlines procedures for strain-controlled fatigue testing of nominally homogeneous materials under uniaxial loading conditions. This procedure is primarily used to assess the fatigue properties of materials subjected to cyclic loading resulting in plastic strains, leading to failure within relatively low cycles (under 100,000 cycles).

The cyclic relation of stress amplitude vs. strain amplitude is obtained from stabilized hysteresis loops of strain-controlled fatigue tests. This relation can be characterized by a Ramberg–Osgood expression (Equation (4)) for materials with a cyclic hardening/softening effect [7,16]. The estimation of the cyclic curve and the stress amplitude–strain amplitude relation can proceed from material fatigue parameters based on the so-called compatibility between Equations (37) and (38) [1,7]:

$$n' = \frac{b}{c}, \quad (37)$$

$$K' = \frac{\sigma'_f}{\varepsilon'_f(n')}. \quad (38)$$

The Brinell method was used to measure hardness according to ISO standard 6506 [18], as this coincides with Roessle–Fatemi fatigue estimation method. The Brinell hardness test is dedicated for soft to medium-hard metals, including aluminum, copper, and steel. A tungsten carbide ball is used to create an indenter under specific conditions. The diameter of the created indentation after the force removal indicates the hardness of the surface. In case a different method of hardness measurement is used, a recalculation to Brinell

hardness can be performed using tables from ISO standard 18265 [19]. Additionally, ISO standard 18265 [19] also includes tables, allowing the estimation of hardness based on tension strength.

2.9. Validation of Accuracy of the Fatigue Parameter Estimation Methods

This paper concentrates on the comparison of cyclic and fatigue properties; therefore, a number of error estimation methods were proposed. The stress amplitude vs. strain amplitude was compared using an integral of squared differences (Equation (39)). The equation measures an overall energy difference between curves. Since the material strength is commonly describe as an area under the curve, this method should suit well.

$$L = \sqrt{\int (f(x) - g(x))^2 \cdot dx}. \quad (39)$$

The fatigue results cannot be compared with the same method, as the results are expressed in the logarithmic scale. However, error is calculated based on life for the same level of strain (Equation (40)). This is more closely related to the steps required for durability estimation, where from load, strains are calculated, and based on them, the fatigue property life is estimated.

$$RMSLE = \sqrt{\frac{1}{N} \sum_{i=1}^N (\log_{10}(f(N_i)) - \log_{10}(g(N_i)))^2}. \quad (40)$$

In addition, to better understand the differences between functions' maximum error, Equation (41) was calculated:

$$E_{max} = \max_i |\log_{10}(f(N_i)) - \log_{10}(g(N_i))|. \quad (41)$$

Analyzing a specific load case where the final result (life) can be directly calculated, the difference to reference value can be expressed by Equation (42):

$$E_{\%} = \frac{\log_{10}(2Nf_{ref}) - \log_{10}(2Nf_{actual})}{\log_{10}(2Nf_{ref})} \cdot 100\%. \quad (42)$$

3. Load Case Description

To verify all factors affecting the fatigue calculations, a simple load case, shown in Figure 3, was proposed. This includes a specimen with the circular cross-section of diameter D equaling 4 mm. It is assumed that no stress concentration exists in the considered region ($K_t = 1$). The surface is polished, and the temperature is constant for the full loading block. The specimen is subject to tension–compression cyclic loading by a random load signal generated by the adequate scaling of a white noise signal, collected in Table 1. Each studied material would have a different loading signal due to strength differences; however, for a single material, all estimation methods would be exposed to the same loading.

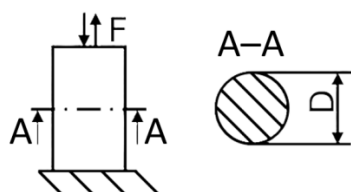
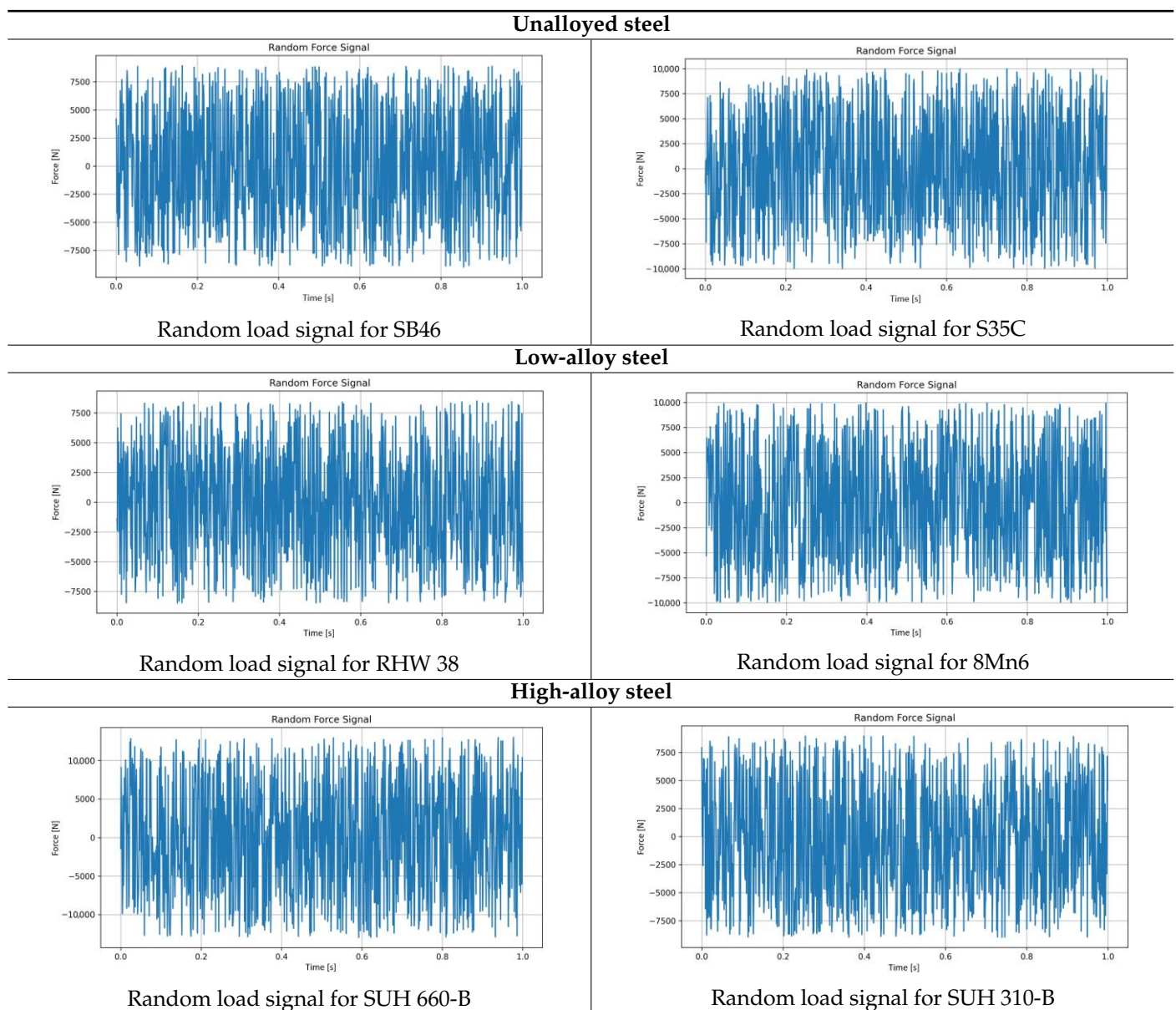
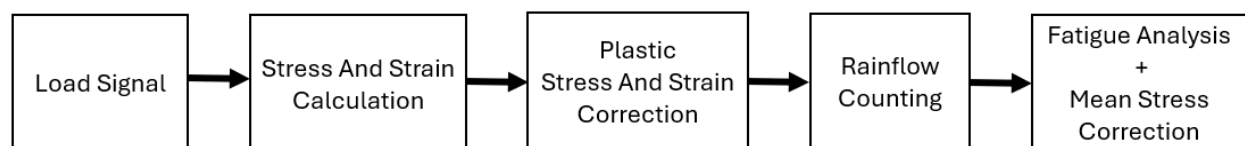


Figure 3. Boundary conditions of proposed load case.

Table 1. Load blocks used in fatigue analysis.

Since the estimation methods allow the calculation of life in low and high cycle fatigue, a cyclic material behavior including plasticity needs to be included. The Neuber plastic correction (Equation (5)) was implemented in the calculations together with the Ramberg–Osgood relation (Equation (4)). In addition, the random load signal requires decomposition for strain cycles and consideration of a mean stress effect. For simplicity of application a rainflow counting and Morrow mean stress correction (Equation (43)) was used. The process map of the durability analysis is presented in Figure 4.

**Figure 4.** Fatigue analysis process map.

In real-life situations a subject is loaded in such a manner that mean stress of cyclic loading is different than 0. Typical strain amplitude vs. reversal relation (EN) curves are established for a stress ratio of -1 ; this is for mean stress equals zero. Morrow studies of the mean stress effect on fatigue life have led to the conclusion that the mean stress effect becomes more significant with increasing life. Furthermore, it has been observed that a life change on a low cycle range is small enough to be neglected. Due to that, the mean stresses were only introduced to the elastic component (Equation (43)) of the Manson–Coffin–Basquin relation (Equation (3)) [20].

$$\frac{\Delta\epsilon}{2} = \frac{\sigma'_f - \sigma_m}{E} \cdot (2N_f)^b + \epsilon'_f \cdot (2N_f)^c. \quad (43)$$

The σ_m correction factor offsets the elastic curve without changing its slope. The dotted lines in Figure 5 represent the curves changed by the Morrow mean stress correction.

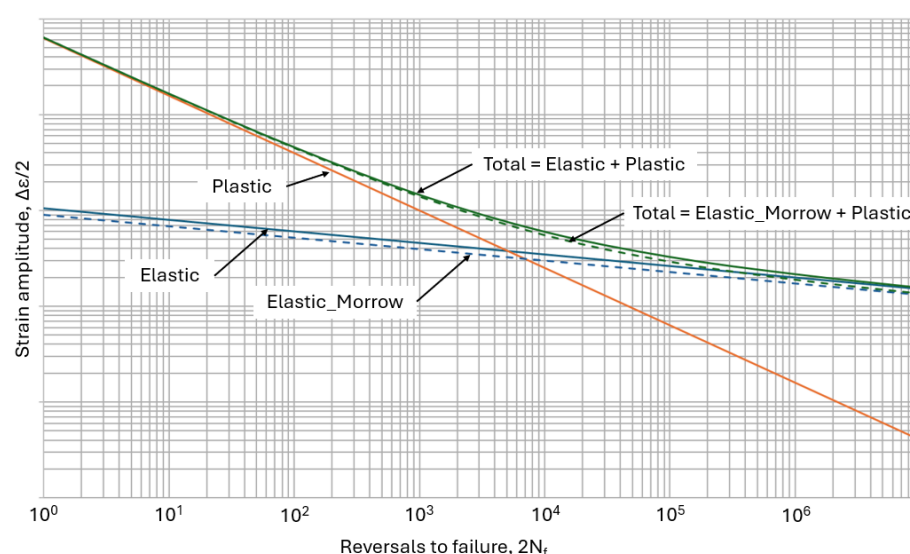


Figure 5. Graphic representation of strain amplitude vs. reversals to failure relation, including Morrow mean stress correction.

4. Analysis and Discussion

Herein, the proposed document load case was calculated using a Python 3.11 script. The script was built based on the equations mentioned in this paper. The material data used as a reference to assay the accuracy of the estimation methods was taken from Böller et al. [21]. The table below consists of different type of steel materials. Three groups were examined, with each represented by two materials; see Table 2.

Table 2. Studied materials by type [21].

Material Type	Designation Usual Commercial Designation (e.g., ASTM, SAE, JIS)
Unalloyed steel	SB46 S35C
Low-alloy steel	RHW 38 8Mn6
High-alloy steel	SUH 660-B SUH 310-B

The monotonic strength data have been collected in Table 3. The values correspond to a test temperature of +23 °C.

Table 3. Materials' monotonic strength properties [21].

Designation	σ_{UTS} [MPa]	σ_Y [MPa]	E [MPa]	A5 [%]	RA [%]	Hardness [HB]
SB46	500	310	210,000	30	64	151
S35C	669	513	210,000	29	70	210
RHW 38	661	517	205,000	22	62	202
8Mn6	965	862	198,000	12	57	266
SUH 660-B	1158	777	210,000	23	52	319
SUH 310-B	630	271	210,000	45	69	155

The results for the fatigue material properties comparison are gathered in Tables 4–9 and presented in Figures 6–11. The generated curves were compared and quantified using root mean squared log error (Equation (40)) with maximum difference error (Equation (41)).

The results presented in Figure 6 show good convergence of the estimated curves. The differences are small enough that they require numerical representation to choose the best agreement. Collected quantified errors are collected in Table 4. RMSLE in all cases is below 1. Maximum deviation however gives worse agreement, still acceptable good. In case of higher E_{max} values user should verify if this error affects the region of interest. Overall, the best answer was achieved for FPCM where RMSLE and E_{max} are smallest.

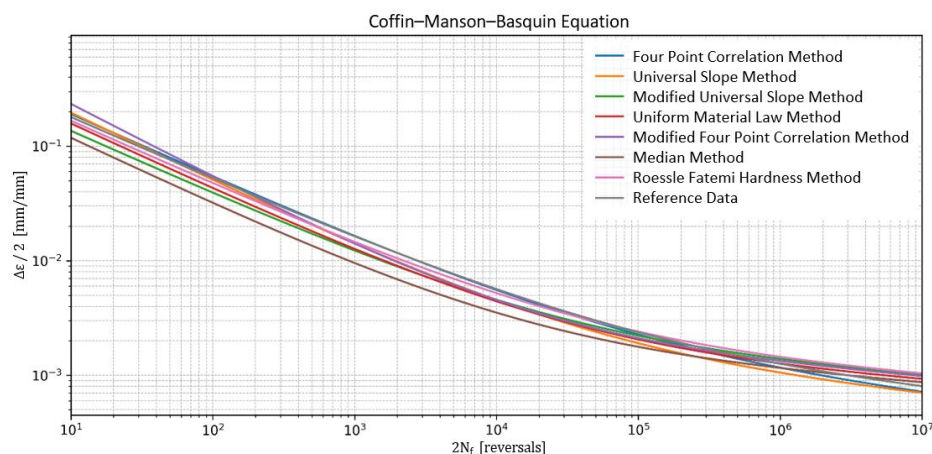


Figure 6. Strain amplitude–reversals to failure relation for SB46.

Table 4. Fatigue material properties for SB46.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	E_{max}
Four-point correlation method	1151.60	−0.1338	0.6760	−0.5581	0.25	0.70
Universal slope method	950.90	−0.1200	0.7677	−0.6000	0.53	0.84
Modified universal slope method	859.34	−0.0900	0.4831	−0.5600	0.89	2.65
Uniform material law method	750.00	−0.0870	0.5900	−0.5800	0.59	1.81
Modified four-point correlation method	1010.83	−0.1005	1.0217	−0.6466	0.71	2.17
Median method	750.00	−0.0900	0.4500	−0.5900	0.91	1.19
Roessle–Fatemi method	866.75	−0.0900	0.5941	−0.5600	0.86	2.77
Reference data	1000.00	−0.1180	0.6190	−0.5460	0.00	0.00

S35C unalloyed steel fatigue curves are put forward in Figure 7, showing good convergence for higher cycles, above 1000 cycles. Analysis of the Table 5 and the RMSLE allow acceptable agreement to be claimed for all curves except the USM and FPCM. E_{max}

increases with the RMSLE, so this might be a local disagreement. The best results were obtained for MUSM.

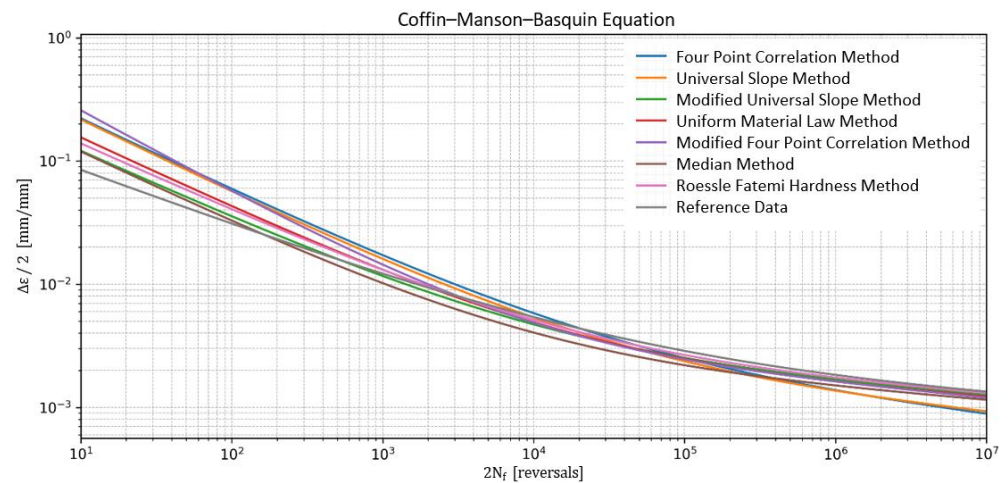


Figure 7. Strain amplitude–reversals to failure relation for S35C.

Table 5. Fatigue material properties for S35C.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	E_{max}
Four-point correlation method	1672.02	−0.1405	0.8449	−0.5914	1.26	2.50
Universal slope method	1272.30	−0.1200	0.8472	−0.6000	1.26	2.49
Modified universal slope method	1094.90	−0.0900	0.4247	−0.5600	0.50	0.94
Uniform material law method	1003.50	−0.0870	0.5773	−0.5800	0.72	1.41
Modified four-point correlation method	1474.46	−0.1108	1.2040	−0.6775	0.99	2.20
Median method	1003.50	−0.0900	0.4500	−0.5900	0.93	1.39
Roessle–Fatemi method	1117.50	−0.0900	0.4897	−0.5600	0.50	1.19
Reference data	845.00	−0.0750	0.2350	−0.4600	0.00	0.00

High deviation from the reference data for low cycles, below 1000, can be observed in Figure 8. From Table 6, the RMSLE is between 1.0 and 2.0; also, the E_{max} , only in one case, the MUSM, is below 2. Based on that, the calculated life might be burdened with error. All curves seem to group in a range between 10,000 and 1,000,000 cycles. The best estimation is given from MUSM. The worst estimation is from FPCM and USM.

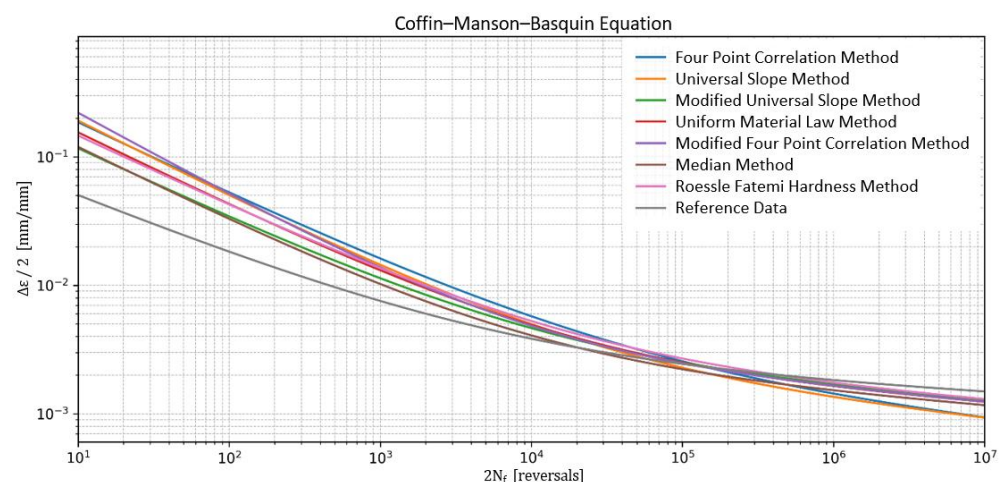
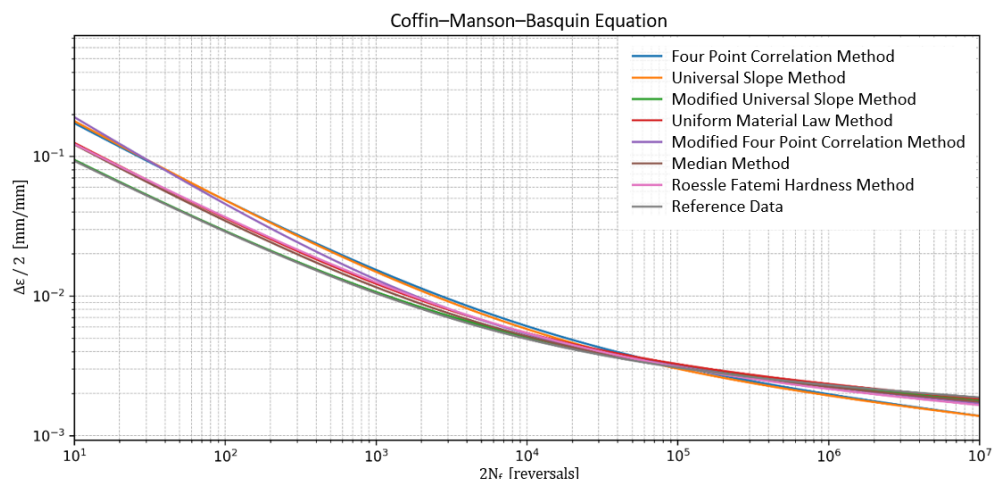


Figure 8. Strain amplitude–reversals to failure relation for RHW 38.

Table 6. Fatigue material properties for RHW 38.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	E_{max}
Four-point correlation method	1483.86	−0.1317	0.6669	−0.5672	1.75	2.92
Universal slope method	1257.09	−0.1200	0.7431	−0.6000	1.73	3.22
Modified universal slope method	1079.62	−0.0900	0.4079	−0.5600	1.05	1.78
Uniform material law method	991.50	−0.0870	0.5744	−0.5800	1.33	2.27
Modified four-point correlation method	1300.57	−0.1027	0.9676	−0.6523	1.45	2.75
Median method	991.50	−0.0900	0.4500	−0.5900	1.21	2.41
Roessle–Fatemi method	1083.50	−0.0900	0.5155	−0.5600	1.30	2.19
Reference data	799.00	−0.0620	0.1440	−0.4860	0.00	0.00

The estimated fatigue parameters calculated for 8Mn6 give good correlation to reference. The offset from the reference data in low cycle fatigue is shown in Figure 9. For high cycle, only USM has visible discrepancies. Comparing the RMSLE from Table 7 shows that most curves are below 1, while others are just above. MUSM has RMSLE of only 0.20, which is very close to the reference data. The second most accurate estimation was given by MM 0.38; however, the UML has 0.39 RMSLE, but E_{max} is lower, which indicates that it is more parallel.

**Figure 9.** Strain amplitude–reversals to failure relation for 8Mn6.**Table 7.** Fatigue material properties for 8Mn6.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	E_{max}
Four-point correlation method	2037.30	−0.1267	0.6375	−0.5863	1.04	2.35
Universal slope method	1835.24	−0.1200	0.6846	−0.6000	1.07	2.46
Modified universal slope method	1470.46	−0.0900	0.3208	−0.5600	0.20	0.70
Uniform material law method	1447.50	−0.0870	0.4523	−0.5800	0.39	0.61
Modified four-point correlation method	1779.43	−0.1037	0.8440	−0.6618	0.69	1.40
Median method	1447.50	−0.0900	0.4500	−0.5900	0.38	0.88
Roessle–Fatemi method	1355.50	−0.0900	0.4247	−0.5600	0.56	1.37
Reference data	1087.00	−0.0680	0.3120	−0.5490	0.00	0.00

Estimation methods seem to be conservative in the cycle range below 2000, which is indicated in Figure 10. Higher cycle ranges have good correlation. The RMSLE from Table 8 presents good correlation below 1.0, except for MUSM and RF, where RMSLE was 1.10. The best estimation was obtained from MFPCM. E_{max} presents discrepancies mostly in low cycles, but for USM and MUSM, also in high cycles.

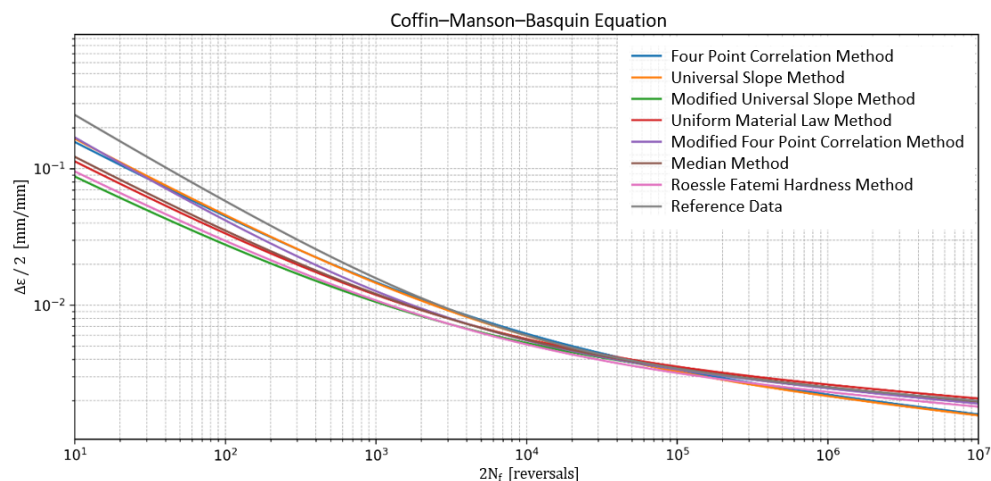


Figure 10. Strain amplitude–reversals to failure relation for SUH 660-B.

Table 8. Fatigue material properties for SUH 660-B.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	E_{max}
Four-point correlation method	2306.53	−0.1219	0.5730	−0.5857	0.74	1.89
Universal slope method	2202.28	−0.1200	0.6295	−0.6000	0.78	2.05
Modified universal slope method	1728.33	−0.0900	0.2941	−0.5600	1.10	2.24
Uniform material law method	1737.00	−0.0870	0.4049	−0.5800	0.81	1.64
Modified four-point correlation method	2007.94	−0.1010	0.7340	−0.6557	0.42	0.62
Median method	1737.00	−0.0900	0.4500	−0.5900	0.70	1.44
Roessle–Fatemi method	1580.75	−0.0900	0.3248	−0.5600	1.10	2.06
Reference data	1574.00	−0.0830	1.1090	−0.6610	0.00	0.00

The reference curve from Figure 11 crosses estimation curves starting in the low cycle range as the minimum, through the mid cycles, where the curves show maximum values, to the high cycle, where, once more, minimum values are represented. This results in a large E_{max} but a smaller RMSLE; see Table 9. RMSLE is between 0.66 for FPCM and 1.51 for MUSM. Confronting this with the E_{max} , the deviation in results is much larger, starting with 1.58 for USM to 5.11 for MUSM. Three estimation methods give RMSLE below 1.0: the aforementioned FPCM, USM, and RF.

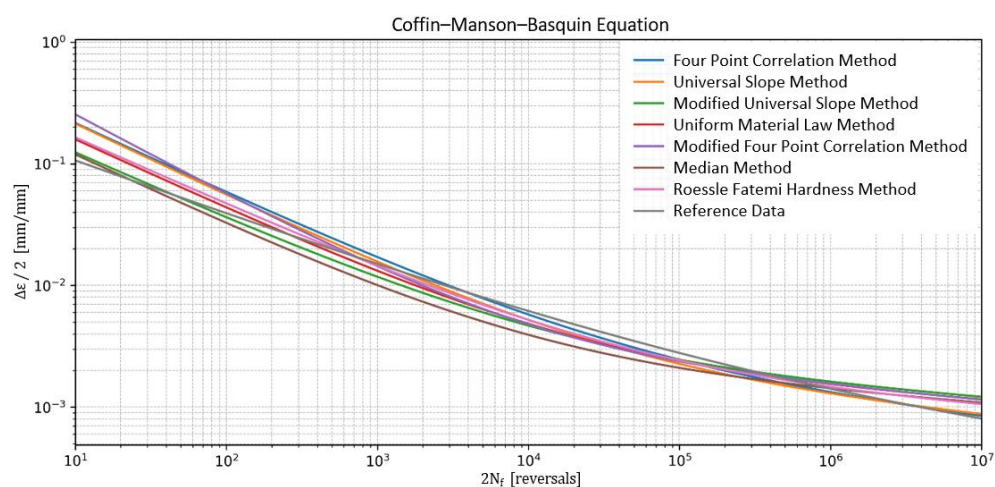


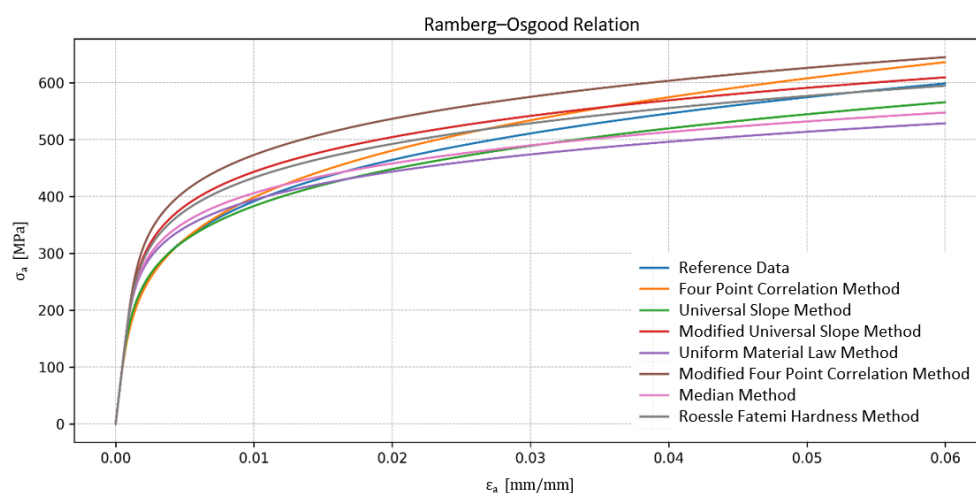
Figure 11. Strain amplitude–reversals to failure relation for SUH 310-B.

Table 9. Fatigue material properties for SUH 310-B.

Method	σ'_f [MPa]	b [-]	ϵ'_f [-]	c [-]	RMSLE	$E_{\max}$
Four-point correlation method	1552.37	−0.1394	0.8111	−0.5847	0.66	1.60
Universal slope method	1198.13	−0.1200	0.8333	−0.6000	0.70	1.58
Modified universal slope method	1041.53	−0.0900	0.4365	−0.5600	1.51	5.11
Uniform material law method	945.00	−0.0870	0.5900	−0.5800	1.36	4.75
Modified four-point correlation method	1367.85	−0.1089	1.1712	−0.6714	1.30	3.80
Median method	945.00	−0.0900	0.4500	−0.5900	1.26	4.03
Roessle–Fatemi method	883.75	−0.0900	0.5867	−0.5600	0.96	3.37
Reference data	1492.00	−0.1520	0.2890	−0.4540	0.00	0.00

The fatigue material properties are not enough to predict the life of the specimen in the low and high cycle range. The stress amplitude vs. strain amplitude relation is necessary. These were characterized by the Ramberg–Osgood Equation (4). The collected material properties (Tables 10–15) and their related curves (Figures 12–17) were compared to reference using the integral of squared differences (Equation (39)).

The reference data presented in Figure 12 crosses some lower curves and ends in the middle of the estimated ones. The yield point is different between curves; however, the reference yield point is very close to the FPCM and USM. Table 10 also shows the best correlation for the USM and FPCM, with L 4.21 and 4.48. The worst results were obtained for MFPCM, with L 15.03.

**Figure 12.** Cyclic material relation of stress amplitude vs. strain amplitude for SB46.**Table 10.** Cyclic material properties for SB46.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	1264.98	0.2398	4.48
Universal slope method	1002.53	0.2000	4.21
Modified universal slope method	965.93	0.1607	8.48
Uniform material law method	811.77	0.1500	7.59
Modified four-point correlation method	1007.46	0.1555	15.03
Median method	847.15	0.1525	5.34
Roessle–Fatemi method	942.41	0.1607	6.29
Reference data	1118.00	0.2180	0.00

The yield point of the reference data correlates with the best with USM and FPCM; see Figure 13. The reference curve is also the minimum one. From Table 11, the smallest L of 12.22 was calculated for the UML, and the largest, 71.96, for MFPCM.

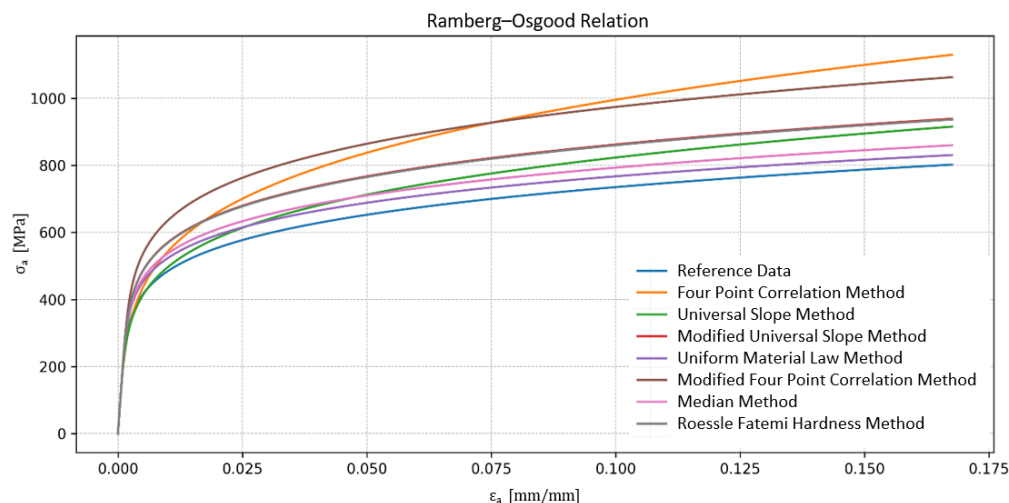


Figure 13. Cyclic material relation of stress amplitude vs. strain amplitude for S35C.

Table 11. Cyclic material properties for S35C.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	1740.34	0.2376	71.96
Universal slope method	1315.21	0.2000	23.92
Modified universal slope method	1256.47	0.1607	40.27
Uniform material law method	1089.71	0.1500	12.22
Modified four-point correlation method	1430.38	0.1635	74.79
Median method	1133.49	0.1525	19.89
Roessle–Fatemi method	1253.36	0.1607	39.61
Reference data	1081.00	0.1650	0.00

As presented in Figure 14, the reference curve is not the minimum one for RHW 38. The yield point is smaller only for the MFPCM, but the curve changes slope more rapidly than the others, ending with a maximum stress higher only from the UMLM. From Table 12, L values indicate good correlation for MM 3.32 and UMLM 5.95. The largest L was calculated for MFPCM 29.85 and FPCM 29.75.

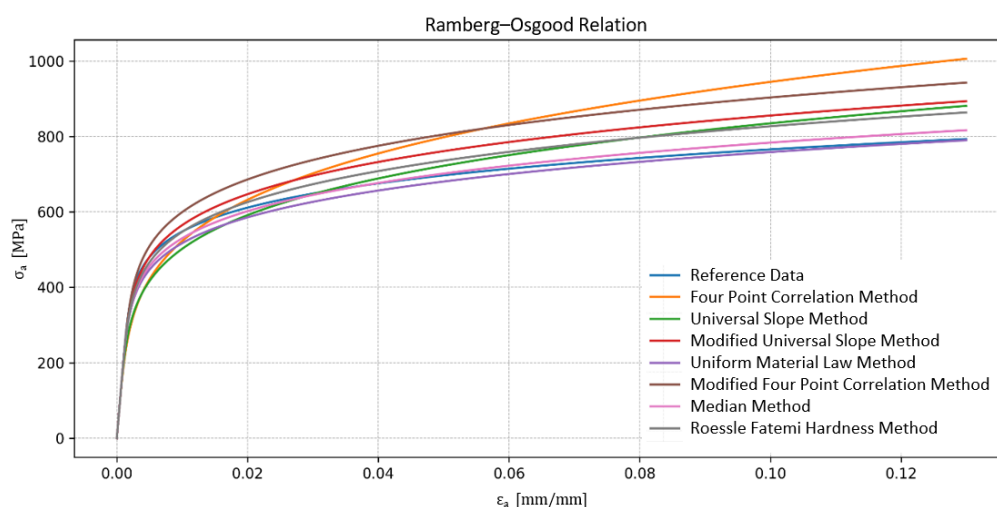
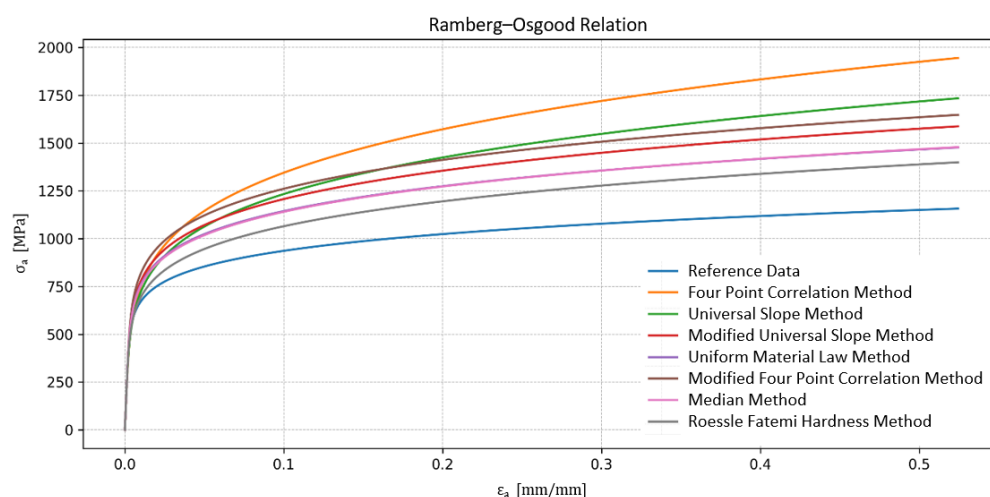


Figure 14. Cyclic material relation of stress amplitude vs. strain amplitude for RHW 38.

Table 12. Cyclic material properties for RHW 38.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	1630.23	0.2322	29.75
Universal slope method	1334.02	0.2000	11.18
Modified universal slope method	1246.98	0.1607	17.69
Uniform material law method	1077.48	0.1500	5.95
Modified four-point correlation method	1307.34	0.1575	29.85
Median method	1119.93	0.1525	3.32
Roessle–Fatemi method	1205.24	0.1607	11.00
Reference data	1038.00	0.1300	0.00

For 8Mn6 the reference curve is the minimum one, as shown in Figure 15. The yield point is also noticeably lower. In Table 13 there are only high values of L , from 93.82 for RF to 300.77 for FPCM, indicating that none of the estimated curves correlates well with the reference.

**Figure 15.** Cyclic material relation of stress amplitude vs. strain amplitude for 8Mn6.**Table 13.** Cyclic material properties for 8Mn6.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	2245.43	0.2161	300.77
Universal slope method	1979.75	0.2000	219.58
Modified universal slope method	1765.24	0.1607	183.18
Uniform material law method	1630.42	0.1500	138.80
Modified four-point correlation method	1827.37	0.1567	215.25
Median method	1635.00	0.1525	137.61
Roessle–Fatemi method	1555.48	0.1607	93.82
Reference data	1256.00	0.1250	0.00

The bad correlation of the estimation methods with the reference data is presented in Figure 16. The reference is the minimum curve with the minimum yield point. The L values from Table 14 start from 91.20 for RF and end with 268.37 for FPCM.

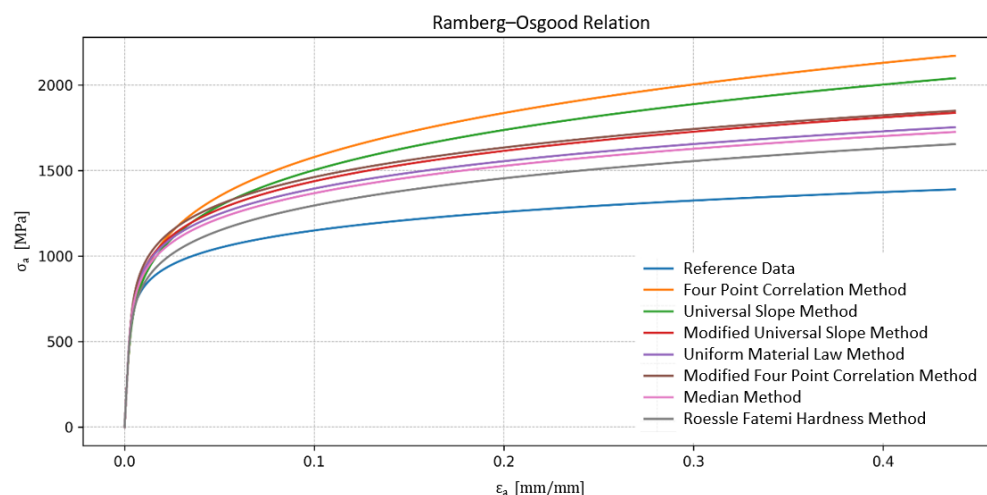


Figure 16. Cyclic material relation of stress amplitude vs. strain amplitude for SUH 660-B.

Table 14. Cyclic material properties for SUH 660-B.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	2590.04	0.2082	268.37
Universal slope method	2415.85	0.2000	221.85
Modified universal slope method	2104.04	0.1607	169.98
Uniform material law method	1989.26	0.1500	142.48
Modified four-point correlation method	2105.87	0.1540	181.10
Median method	1962.00	0.1525	128.27
Roessle–Fatemi method	1893.87	0.1607	91.20
Reference data	1543.00	0.1250	0.00

The extraordinary curve of the stress amplitude vs. strain amplitude representation of the reference data is shown in Figure 17. There is a very low yield point and a mild change of curvature till the maximum stress is reached. The yield point for all estimation methods is at least twice the reference. From Table 15 the smallest L was obtained for FPCM, with a value of 8.41. The second most accurate is USM, with a value of L equaling 9.46. The largest calculated error is 21.72 for MFPCM.

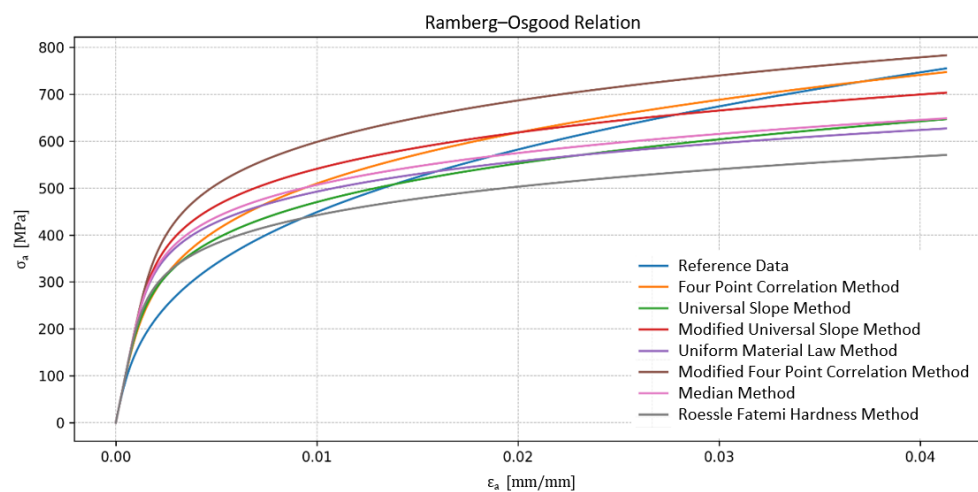


Figure 17. Cyclic material relation of stress amplitude vs. strain amplitude for SUH 310-B.

Table 15. Cyclic material properties for SUH 310-B.

Method	K' [MPa]	n' [-]	L [-]
Four-point correlation method	1631.81	0.2383	8.41
Universal slope method	1242.65	0.2000	9.46
Modified universal slope method	1189.94	0.1607	12.83
Uniform material law method	1022.83	0.1500	12.02
Modified four-point correlation method	1333.24	0.1622	21.72
Median method	1067.41	0.1525	11.30
Roessle–Fatemi method	962.83	0.1607	16.99
Reference data	2242.00	0.3320	0.00

To fully understand the effect of estimating cyclic and fatigue parameters, a simple study was conducted. The blocks of load signal (Table 3) were adjusted, so the predicted life of the reference data was close to five blocks and therefore engaged both low and high cycles. The results of fatigue calculations, according to the process map from Figure 4, are collected in Table 16.

Table 16. Life results of simple case study.

Method	Life [Cycles]					
	Unalloyed Steel		Low-Alloy Steel		High-Alloy Steel	
	SB46	S35C	RHW 38	8Mn6	SUH 660-B	SUH 310-B
Four-point correlation method	3.99	5.98	9.83	12.73	6.88	7.16
Universal slope method	2.50	4.47	6.74	10.42	5.93	5.19
Modified universal slope method	3.54	4.80	9.11	11.35	5.08	6.28
Uniform material law method	2.64	4.50	8.59	13.99	6.86	5.60
Modified four-point correlation method	4.00	6.30	10.94	14.19	6.49	7.82
Median method	1.54	2.73	5.23	10.79	5.98	3.30
Roessle–Fatemi method	4.76	6.14	12.02	9.78	3.63	5.18
Reference data	4.21	5.02	5.16	7.60	6.38	6.35

Table 17 presents the percent error of the life calculations vs. reference. The best results for unalloyed steel were from MUSM, with an error value of 2.80% for S35C. The SB46 also has good correlation of 3.52% and 3.70% for MFPCM and FPCM. The large observed error was 69.75%. The low-alloy steel highlights notable differences in accuracy of both materials. The RHW 38 in MM has an error of only 0.77%, but the 8MN6 has in the best case 12.39% with the RF method. The maximum observed error was 51.43% for RHW 38 using the RF method. High-alloy steel in the best case was found for SUH 660-B, 0.99% linked with MFPCM, and SUH 310-B was only 0.56% connected with MUSM. The worst results were 35.46%, obtained for MM and SUH 310-B.

Table 17. Summary of estimation methods of error on life estimation.

Method	Error in Life [%]					
	Unalloyed Steel		Low-Alloy Steel		High-Alloy Steel	
	SB46	S35C	RHW 38	8Mn6	SUH 660-B	SUH 310-B
Four-point correlation method	3.70	10.81	39.21	25.41	4.07	6.49
Universal slope method	36.24	7.18	16.17	15.52	3.93	10.91
Modified universal slope method	11.91	2.80	34.55	19.75	12.30	0.56
Uniform material law method	32.41	6.83	31.00	30.06	3.94	6.80
Modified four-point correlation method	3.52	14.05	45.70	30.73	0.99	11.25
Median method	69.75	37.88	0.77	17.24	3.48	35.46
Roessle–Fatemi method	8.59	12.41	51.43	12.39	30.36	11.01
Reference data	0.00	0.00	0.00	0.00	0.00	0.00

5. Conclusions

The conducted study clearly shows that durability analysis requires both fatigue and cyclic material properties, which cannot be assessed separately. The final accuracy can be reduced or increased due to the combination of those properties.

This study did not find a universal method, although, for all considered materials, at least one method showed reasonably good results. Before choosing the estimation method an investigation should be undertaken to assess which of the presented methods is most suitable for the current material family.

Strain amplitude vs. reversals to failure graphs (Figures 6–11) show relatively consistent results for all methods. Most deviations can be observed on the graphs in the low cycle range; however, when taking into consideration the logarithmic scale and error calculated on the reversals' axis, it turns out that the high cycle error is larger. The largest difference was found for SUH 310-B, where $E_{\max}$ was up to 5.11, and the minimum for 8Mn6, with a value of 0.61. Looking at RMSLE shows that the error was fairly small, below 1.80 for all materials and estimation methods. The best results were 0.20 for 8Mn6 MUSM. The lines nearly perfectly match. Notice that 8Mn6 had the worst correlation in life calculations (Table 17) due to a bad correlation with the stress amplitude vs. strain amplitude relation (Table 13).

The same cannot be claimed about the stress amplitude vs. strain amplitude curves (Figures 12–17). In this case differences can easily be distinguished on graphs. Two cases can be distinguished: first, when the reference curve is the lowest one and second, where the curvature of the reference curve does not match the estimated ones but just crosses through them. Comparing the numbers from the integral of squared differences (Equation (39)) shows that large differences between materials and methods can be concluded. For SUH 660-B and 8Mn6 the minimum error was 91.20 and 93.82, which are large values. Still, overall, those materials were able to correlate with a 12.39% error for 8Mn6 and only a 0.99% error for SUH 660-B. The rest of the materials correlate better in terms of cyclic strength, with a minimum between 3.32 for RHW 38 and 12.22 for S35C.

Based on the comparative results, no single estimation method outperforms the others universally. However, certain methods (e.g., MUSM, FPCM, MFPCM) show stronger reliability for specific steel groups and can be prioritized depending on the material and expected fatigue regime. Table 18 summarizes this finding.

Table 18. Summary of the most accurate fatigue estimation methods identified for each steel material group, based on life prediction error metric.

Material Type	Best Estimation Method (Life Prediction)	Notes
Unalloyed Steel	MUSM (for S35C), FPCM (for SB46)	Good RMSLE and low $E_{\max}$; reliable for low-to-moderate cycle fatigue
Low-Alloy Steel	MM (RHW 38), RF (8Mn6)	MM highly accurate in some cases, but inconsistent
High-Alloy Steel	MFPCM (SUH 660-B), MUSM (SUH 310-B)	Strong correlation despite poor cyclic stress–strain curve fit

6. Future Directions

Further development of estimation methods requires a vast and complete database with verified material data, which then could be used in training and validating machine learning. This method of data processing might show trends, groups, or other relationships, leading to new estimation methods with improved quality.

Future work may also focus on refining the estimation of cyclic stress–strain parameters (K' and n'), for example through inverse modeling techniques or regression models based on direct cyclic test data, which could reduce the additional error introduced by relying solely on compatibility equations.

Moreover, estimation methods should not be limited to fatigue material properties. They should also include the cyclic hardening/softening material properties, such as how, in low and middle cycle ranges, plastic strains are observed and cannot be omitted. To take into account the plastic strain, the Ramberg–Osgood equation can be used. Two material constants need to be found: K' and n' . In this paper a relation between fatigue material properties was used to estimate them. The results were not accurate in some cases and therefore leave space for improvement.

While Miner's rule was used in this study to maintain comparability among estimation methods, it is recognized that nonlinear damage accumulation models could offer improved accuracy under variable amplitude loading. Future work may explore the combined impact of advanced damage models and fatigue parameter estimation techniques to better simulate real-world fatigue behavior. Also, the emerging of hybrid approaches that combine empirical estimation with machine learning techniques, as well as damage mechanics-based formulations, offer exciting opportunities for improving fatigue life prediction. An example is the work of Tao et al. [22], where the multiaxial complex load condition is analyzed based on the MCB curve. These directions, while beyond the scope of the present study, merit further investigation in future work.

It should be noted that microstructural features, such as phase composition, grain size, and inclusions, play a crucial role in fatigue behavior. Since the present study is based on historical datasets without microstructural characterization, future studies could benefit from integrating SEM-based analysis with fatigue estimation methods to enhance prediction accuracy and physical understanding.

The current study was limited to steel materials, as the analyzed estimation methods are primarily designed for this material group. Future work may focus on extending the methodology to other classes, such as aluminum or titanium alloys, to evaluate the transferability and robustness of the estimation models. There are also studies that attempt to apply strain characteristics to composites using non-linear summation of fatigue damage [23], which significantly expands the possibilities of using formulas estimating fatigue material constants.

Author Contributions: Conceptualization, S.R. and A.N.; methodology, S.R.; validation, S.R.; formal analysis, A.N. and K.K.; investigation, S.R.; resources, S.R.; data curation, S.R.; writing—original draft preparation, S.R.; writing—review and editing, S.R., A.N., K.K. and T.Ł.; visualization, S.R.; supervision, S.R. and A.N.; funding acquisition, S.R., A.N., K.K. and T.Ł. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Implementation Doctorate Program 8th edition, established by the Communication of the Polish Minister of Science and Higher Education, project number DWD/8/0311/2024.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Sebastian Raczek and Tomasz Łukasik were employed by the company Tenneco Automotive Eastern Europe Sp. z o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations and Symbols

The following abbreviations and symbols are used in this manuscript:

$2N_f$	Reversals to failure
b	Fatigue strength exponent
c	Fatigue ductility exponent
$\Delta\varepsilon$	Total strain range
$\Delta\varepsilon_p$	Plastic strain range
E	Young's modulus
$E_{\max}$	Logarithmic maximum error
$E_{\%}$	Logarithmic percent error
ε	Strain
ε_a	Strain amplitude
ε_f	Elongation at break
ε'_f	Fatigue ductility coefficient
HB	Brinell hardness
K'	Cyclic strength coefficient
K_t	Stress concentration factor
L	Integral of squared differences
n'	Cyclic strain hardening exponent
ψ	Material dependent factor
RA	Reduction in area
RMSLE	Root mean square logarithmic error
σ	Stress
σ_a	Stress amplitude
σ_f	True fracture strength
σ'_f	Fatigue strength coefficient
σ_m	Mean stress
σ_Y	Yield strength
σ_{UTS}	Ultimate tension strength
Z	Ductility

References

1. Campbell, F.C. *Fatigue and Fracture: Understanding the Basics*; ASM International: Materials Park, OH, USA, 2012; ISBN 978-1-61503-976-0.
2. Tridello, A.; Boursier Niutta, C.; Rossetto, M.; Berto, F.; Paolino, D.S. Fatigue Design Curves for Industrial Applications: A Review. *Fatigue Fract. Eng. Mater. Struct.* **2025**, *48*, ffe.14545. [\[CrossRef\]](#)
3. Fischer, A.; Izmailov, A.F.; Solodov, M.V. The Levenberg–Marquardt Method: An Overview of Modern Convergence Theories and More. *Comput. Optim. Appl.* **2024**, *89*, 33–67. [\[CrossRef\]](#)
4. Gomes, V.M.G.; Souto, C.D.S.; Correia, J.A.F.O.; De Jesus, A.M.P. Monotonic and Fatigue Behaviour of the 51CrV4 Steel with Application in Leaf Springs of Railway Rolling Stock. *Metals* **2024**, *14*, 266. [\[CrossRef\]](#)
5. Ramírez-Acevedo, D.; Ambriz, R.R.; García, C.J.; Gómora, C.M.; Jaramillo, D. Fatigue Damage Assessment in AL6XN Stainless Steel Based on the Strain-Hardening Exponent n -Value. *Metals* **2025**, *15*, 472. [\[CrossRef\]](#)
6. Lipski, A.; Mroziński, S. Approximate Determination of a Strain-Controlled Fatigue Life Curve for Aluminum Alloy Sheets. *J. Pol. CIMAC Gdań. Univ. Technol.* **2011**, *6*, 107–118.
7. Nieslony, A.; Dsoki, C.; Kaufmann, H.; Krug, P. New Method for Evaluation of the Manson–Coffin–Basquin and Ramberg–Osgood Equations with Respect to Compatibility. *Int. J. Fatigue* **2008**, *30*, 1967–1977. [\[CrossRef\]](#)
8. Roark, R.J.; Young, W.C.; Budynas, R.G. *Roark's Formulas for Stress and Strain*, 7th ed.; McGraw-Hill: New York, NY, USA, 2002; ISBN 978-0-07-072542-3.
9. Wollmann, J.; Dolny, A.; Kaszuba, M.; Gronostajski, Z.; Gude, M. Methods for Determination of Low-Cycle Properties from Monotonic Tensile Tests of 1.2344 Steel Applied for Hot Forging Dies. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 3357–3367. [\[CrossRef\]](#)
10. Harun, M.F.; Mohammad, R.; Othman, N.; Amrin, A.; Chelliapan, S.; Maarop, N. Methods for Estimating the Fatigue Properties of UNS C70600 Copper-Nickel 90/10. *Int. J. Mech. Eng. Technol.* **2017**, *8*, 413–422.

11. Basan, R.; Marohnić, T.; Marković, E. Evaluation of Fatigue Parameters Estimation Methods with Regard to Specific Ranges of Fatigue Lives and Relevant Monotonic Properties. *Procedia Struct. Integr.* **2022**, *42*, 655–662. [[CrossRef](#)]
12. Shamsaei, N.; Fatemi, A. Effect of Hardness on Multiaxial Fatigue Behaviour and Some Simple Approximations for Steels. *Fatigue Fract. Eng. Mater. Struct.* **2009**, *32*, 631–646. [[CrossRef](#)]
13. Basan, R.; Marohnić, T. A Comprehensive Evaluation of Conventional Methods for Estimation of Fatigue Parameters of Steels from Their Monotonic Properties. *Int. J. Fatigue* **2024**, *183*, 108244. [[CrossRef](#)]
14. Park, J.; Song, J. Detailed Evaluation of Methods for Estimation of Fatigue Properties. *Int. J. Fatigue* **1995**, *17*, 365–373. [[CrossRef](#)]
15. ISO 6892-1; International Standard. Metallic Materials—Tensile Testing—Part 1: Method of Test at Room Temperature. ISO: Geneva, Switzerland, 2009.
16. Colin, J.; Fatemi, A.; Taheri, S. Cyclic Hardening and Fatigue Behavior of Stainless Steel 304L. *J. Mater. Sci.* **2011**, *46*, 145–154. [[CrossRef](#)]
17. ISO 12106; International Standard. Metallic Materials—Fatigue Testing—Axial-Strain-Controlled Method. ISO: Geneva, Switzerland, 2017.
18. ISO 6506-1; International Standard. Metallic Materials—Brinell Hardness Test—Part 1: Test Method. ISO: Geneva, Switzerland, 2005.
19. ISO 18265; International Standard. Metallic Materials—Conversion of Hardness Values. ISO: Geneva, Switzerland, 2013.
20. Ince, A.; Glinka, G. A Modification of Morrow and Smith-Watson-Topper Mean Stress Correction Models. *Fatigue Fract. Eng. Mater. Struct.* **2011**, *34*, 854–867. [[CrossRef](#)]
21. Böller, C.; Seeger, T. *Materials Data for Cyclic Loading*; Elsevier Science Publishers: Amsterdam, The Netherlands, 1987; Volumes A–C.
22. Tao, Z.-Q.; Pan, X.; Zhang, Z.-L.; Chen, H.; Li, L.-X. Multiaxial Fatigue Lifetime Estimation Based on New Equivalent Strain Energy Damage Model under Variable Amplitude Loading. *Crystals* **2024**, *14*, 825. [[CrossRef](#)]
23. Batsoulas, N.D.; Giannopoulos, G.I. Cumulative Fatigue Damage of Composite Laminates: Engineering Rule and Life Prediction Aspect. *Materials* **2023**, *16*, 3271. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.