

On the estimation of cyclic material properties – Part 2: Introduction of a new estimation method

Dedicated to Professor Dr.-Ing. Harald Zenner on the occasion of his eightieth birthday

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Article Information

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In the first part of this paper, a large variety of methods for estimating cyclic material properties from quasi-static material properties were rated concerning their accuracy. For this, a massive database containing test results from quasi-static and cyclic tests has been gathered and used to compare estimated and experimental properties. In this second part of the paper, the experience of how different estimation methods work and the database itself are used to develop a new estimation method, the so-called FKM method. This new method is able to estimate cyclic material properties for steel, cast steel and wrought aluminum and thus exceeds the known estimation methods if the quality criteria from part 1 are applied.

In the first part of this paper (referred to below as Part 1), the known estimation methods, which can be found throughout the literature, have been rated with respect to their accuracy. A massive database containing cyclic and quasi-static material properties has been used for this rating.

In this second part of the paper, the same database is used to develop a new estimation method, the so called FKM method. It is valid for steel, cast steel and wrought aluminum and only requires one input-parameter: the universal tensile strength R_m .

To some extent, the contents of this part of the paper require referral to Part 1 concerning the database and criteria used for the quality rating and the basics of cyclic properties. These parts shall not be repeated here in detail, and it is suggested to read Part 1 first.

Different descriptions of cyclic material properties

The strain life and cyclic stress-strain curves are usually described by the Coffin-Manson approach [2, 3], shown in Equation (1), and the Ramberg-Osgood approach [4] shown in Equation (2).

$$\epsilon_a = \epsilon_{a,el} + \epsilon_{a,pl} = \frac{\sigma'_f}{E}(2N)^b + \epsilon'_f(2N)^c \quad (1)$$

$$\epsilon_a = \epsilon_{a,el} + \epsilon_{a,pl} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \quad (2)$$

The properties σ'_f , ϵ'_f , b , c , K' and n' are referred to as cyclic properties. N is the number of cycles until crack initiation. Equation (1) can be defined by reversals or cycles (1 reversal = 0.5 cycle), which shifts the location of the strain life curve in the direction of fatigue life if identical proper-

ties are used. It is not immediately clear which definition has been used in all sources for estimation methods or test results. We have tried to clarify each case to the best of our knowledge and belief.

If both, the Coffin-Manson and Ramberg-Osgood approach, are accepted as valid for a material, these properties are related by the compatibility Equations (3) and (4).

$$n' = \frac{b}{c} \quad (3)$$

$$K' = \frac{\sigma'_f}{(\epsilon'_f)^{n'}} \quad (4)$$

The properties of the strain life curve σ'_f/E and ϵ'_f define the intercepts of the elastic and plastic parts of the strain life with a parallel line to the ordinate at $N = 0.5$, (see Figure 1a). This definition of the cyclic properties is referred to below as conventional notation.

An alternative definition for the strain life curve using intercept points at variable numbers of cycles N_0 has been introduced by Hatcher [5], as shown in Equation (5) and Figure 1b.

$$\epsilon_a = \epsilon_{a,el} + \epsilon_{a,pl} = \frac{\sigma_0}{E} \left(\frac{N}{N_{0\sigma}} \right)^b + \epsilon_{p0} \left(\frac{N}{N_{0ep}} \right)^c \quad (5)$$

In this case, σ_0/E and ϵ_{p0} are intercepts at the corresponding number of cycles $N_{0\sigma}$ and N_{0ep} according to Hatcher. This notation is equivalent to the conventional notation of Equation (1). Nevertheless, Hatcher-notation may be useful for describing different estimation methods within the same type of properties, since not all of these methods yield estimation equations for the conventional properties at $N = 0.5$.

Since the exponents b and c are the same for both conventional and Hatcher-notation, the coefficients of Hatcher-notation can easily be transformed into conven-

tional notation, as shown by Equations (6) and (7).

$$\sigma'_f = \sigma_0 \left(\frac{0.5}{N_{0\sigma}} \right)^b \quad (6)$$

$$\epsilon'_f = \epsilon_{p0} \left(\frac{0.5}{N_{0ep}} \right)^c \quad (7)$$

For calculating the properties K' and n' of the cyclic stress-strain curve, the probability equations must be adapted (see Equation (8)).

$$K' = \frac{\sigma_0}{\epsilon_{p0}^{n'}} \left(\frac{N_{0ep}}{N_{0\sigma}} \right)^b \quad (8)$$

Development of a new estimation method

As shown in Part 1, methods are available to estimate cyclic properties for steel and aluminum materials. The uniform material

law (UML), [6], is best-suited for steel, and the modified Park-Song method, [7], for aluminum, (see Table 1). One issue with the UML is that the estimation for high-alloy steel is not provided by the authors.

When comparing the two material groups, the estimate for aluminum yields worse results than those for steel. The method of variable slopes 2006 and UML+, [8], achieve good results for thin steel sheets, which is a special case compared to the methods for non-sheet metal due to the frequently used deformation degree ϕ .

To improve the quality of the estimates for aluminum and to provide an estimation method for high-alloy steel that provides results in the range of the UML or better, a new estimation method is derived below based on the material database introduced in Part 1. Since tensile strength is one of the characteristic values most frequently known for a material, the new estimation method, hereinafter referred to as the FKM method, is intended to use tensile strength as the only input value.

Relation between cyclic properties. To derive a new estimation method, the dependencies between tensile strength and cyclic properties must be known. These will be investigated in the following paragraph. In addition, the dependencies among the cyclic properties themselves must be studied. Therefore, the properties of the strain life curve are plotted as a contrast to each other, as shown in Figure 2 for steel.

No distinct correlations can be recognized between the properties σ'_f and ϵ'_f or between the exponents b and c . In contrast, the properties σ'_f and b exhibit a weak but recognizable correlation, while a strong correlation can be determined between ϵ'_f and c . The absolute values of the exponents increase with the values of the coefficients.

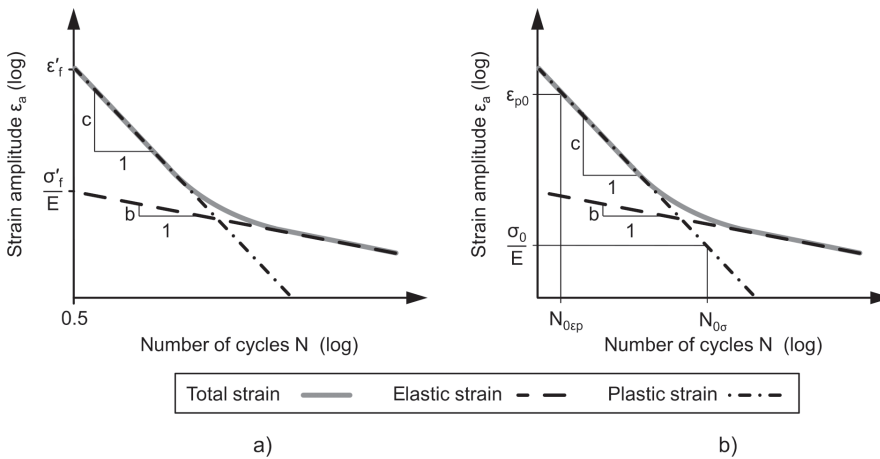


Figure 1: Description of strain-life curves according to Coffin-Manson, a) in conventional notation, b) in notation according to Hatcher

Table 1: Known estimation methods that were rated best in Part 1: uniform material law (UML) for low-alloyed steel [6] and modified Park-Song method for wrought aluminum [7]

Property	UML for low-alloyed steel	Modified Park-Song method
σ_0	$1.5 \cdot R_m$	$R_m + 335 \text{ MPa}$
$N_{0\sigma}$	0.5	1
b	-0.087	$-\frac{1}{6} \cdot \log \left(\frac{R_m + 335 \text{ MPa}}{0.446 \cdot R_m} \right)$
ϵ_{p0}	$0.59 \cdot \begin{cases} 1.0 & \text{for } \frac{R_m}{E} \leq 3 \cdot 10^{-3} \\ 1.375 - 125.0 \cdot \frac{R_m}{E} & \text{for } \frac{R_m}{E} > 3 \cdot 10^{-3} \end{cases}$	$\frac{8955 \cdot 10^{10} \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}} \right)^{-2.807} + 16460 \cdot \text{MPa}}{E}$
N_{0ep}	0.5	1
c	-0.58	-0.661
Range of validity	Low-alloyed steel $R_m = 110 \dots 2300 \text{ MPa}$	Wrought aluminum

If the intercepts at $N = 0.5$ of conventional notation are replaced by coefficients according to Hatscher at a higher number of cycles $N_{0\sigma}$ and $N_{0\epsilon_p}$, certain values for $N_{0\sigma}$ and $N_{0\epsilon_p}$ can be found where there are no recognizable correlations between coefficients and exponents anymore. However, an exact determination of these number of cycles is not possible. Instead, it is possible to determine rough ranges of one decade for $N_{0\sigma}$ and $N_{0\epsilon_p}$. For $N_{0\sigma}$ this is between 1000 and 10^4 cycles, while it is between 100 and 1000 for $N_{0\epsilon_p}$. Using the knowledge from the later paragraphs, the number of cycles are fixed at $N_{0\sigma} = 3000$ and $N_{0\epsilon_p} = 600$. The dependencies between the values at these number of cycles are plotted in Figure 3.

The correlations visible in Figure 2 disappear in Figure 3. Two scenarios might explain this effect:

- 1 There is indeed a dependency between the coefficients and exponents, and all functions fall together in a certain region of N .
- 2 This effect originates from slight errors that arise from the regression of the individual test results, leading to the curves in the elastic and plastic parts of the strain life curve. The number of cycles $N = 0.5$ of the intercept values show a rather large distance in direction of cycles from the region where there are actually individual test results. To calculate the coefficients σ'_f and ϵ'_f , an extrapolation over a long region of cycles is necessary. Slight errors in the regression lead to combinations of overestimated coefficients and steeper slopes as well as underestimated coefficients and slopes that are too flat. This effect has been observed by Hatscher, [5]. The fact that $N_{0\epsilon_p} = 600$ exhibits a lower value than that of $N_{0\sigma} = 3000$ may be explained by the fact that individual test results with low

values for plastic strain amplitude, usually 0.01 % for steel, see [9, 6], are excluded from the evaluation. Therefore, the center of the individual test results for the plastic strain parts lies at a lower number of cycles than that of the results for the elastic strain parts.

Whether Explanation 1 or 2 is correct cannot be decided with the available data, and the investigation in the following paragraphs must be taken into consideration. In principle, similar correlations to those for steel can also be found for cast steel and wrought aluminum.

Correlations between cyclic properties and universal tensile strength. As a foundation for the new estimation method, correlations between universal tensile strength and single cyclic properties must be investigated. As in the previous paragraph, the relationships found are shown for steel only; likewise, similar ones occur in the other material groups.

The logarithmic mean values for b and c are $m_b = 0.086$ and $m_c = 0.567$. These values serve as starting values for the new estimation method. Looking at the coefficients of the strain life curve, an increase in σ'_f can be seen with increasing tensile

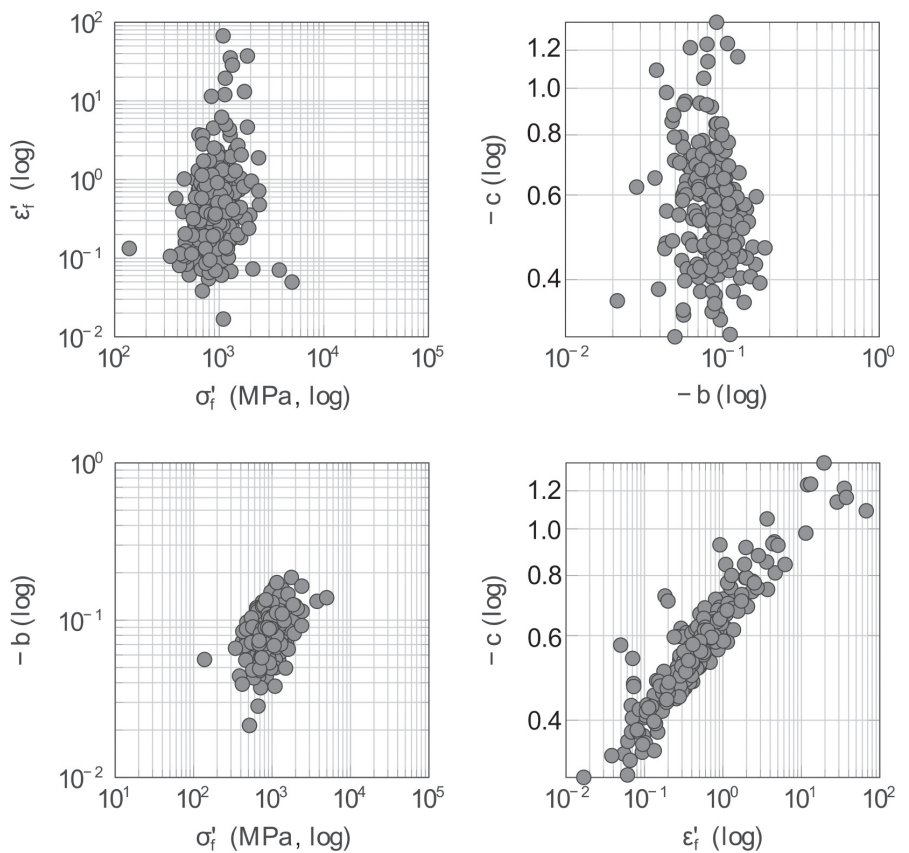


Figure 2: Correlations between the cyclic properties of steel

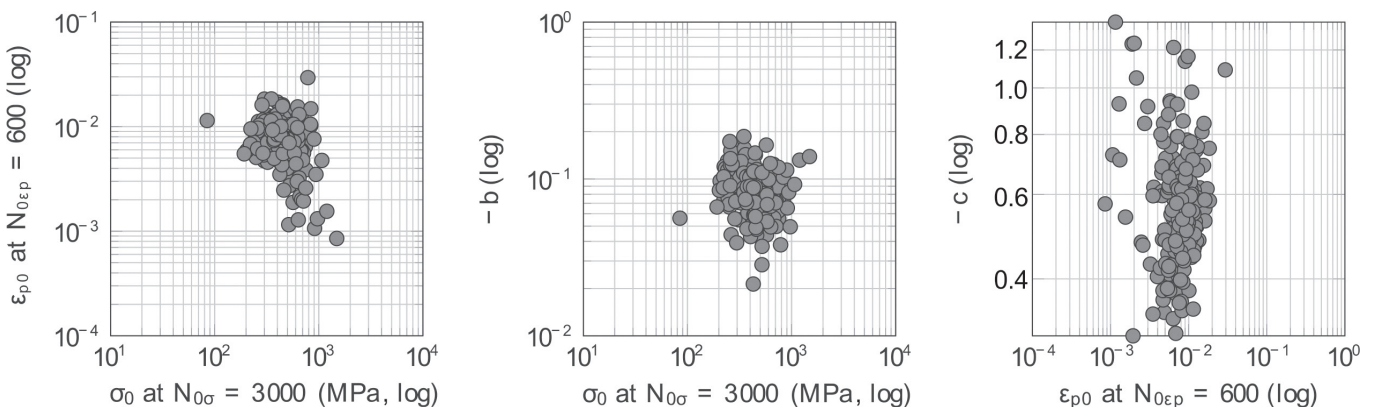


Figure 3: Correlations between the cyclic properties of steel at $N_{0\sigma} = 3000$ and $N_{0\epsilon_p} = 600$

strength. For ϵ'_f , there does not appear to be a statistical relationship to tensile strength (see Figure 4).

In the previous paragraph, it was shown that the parameters of the strain life curve manifest interdependencies when they are considered at the intercept point $N = 0.5$. But these disappear when the properties σ_0 and ϵ_{p0} are evaluated for larger numbers of cycles instead. The following attempt was made to explain this observation: the correlation between coefficients and expo-

ponents results from miscalculations of the mean curves of the two strain components, which are affected accordingly by the strong extrapolation of the curves to $N = 0.5$. If this explanation is correct, no interrelationships between the cyclic properties would have to be taken into account in an estimation method. Hatscher [5], points out that it can make sense to estimate the cyclic coefficients not at $N_0 = 0.5$, but instead at a higher number of cycles lying in the usual range of test results.

Above, it was shown that σ'_f increases with R_m . For σ_0 at $N_{0\sigma} = 3000$, an even clearer relationship can be seen, (see Figure 5). However, no relationship can be discerned between ϵ'_f and R_m , while it can for ϵ_{p0} at $N_{0ep} = 600$ and R_m . In both cases, the relationships determined are shown. For ϵ_{p0} , an approximation is chosen using a bilinear approach in a double-logarithmic representation. A similar upper limit of the coefficient ϵ'_f can be found in the UML. The scatter of the characteristic values around the found relationships was also investigated for other numbers of cycles, but it is smallest at $N_{0\sigma} = 3000$ and $N_{0ep} = 600$.

On the basis of the investigations carried out here to correlate cyclic characteristic values and tensile strength, the reason from the previous paragraph regarding the interdependencies of cyclic coefficients that change depending on the choice of the support points can be confirmed. If the relationship between the exponents and the coefficients (at $N = 0.5$) of the two strain components of the strain life curve were real and not only due to the miscalculation of the two curves, a discernible dependence would also appear between the tensile strength and the inclinations.

In principle, similar relationships to those shown for steel can also be found for cast steel and wrought aluminum. The limit for the coefficient ϵ_{p0} can only be found for steel, not however for cast steel and wrought aluminum.

Derivation of the FKM method. Based on the relationships determined in the previous chapter for steel, cast steel and wrought aluminum, estimates are made for cyclic properties. These estimates are rated according to the same quality criteria for log-average m , slope S and deviation range T for each, the elastic and plastic parts as well as for the total strain life curve as used in Part 1 for existing estimation methods. The values calculated for the quality criteria by applying quasi-static and cyclic properties from the known database to the new method can be further optimized by iterative changes in the parameters of relations found for the elastic and plastic strain components. The exponents b and c have a direct influence on the quality parameter slope S . Coefficients σ_0 and ϵ_{p0} influence the mean values m . Both can be adjusted by empirically changing the estimation formulas.

The new estimation method estimates the coefficients and exponents of the elastic and plastic strain components. The properties of the cyclic stress-strain curve are determined

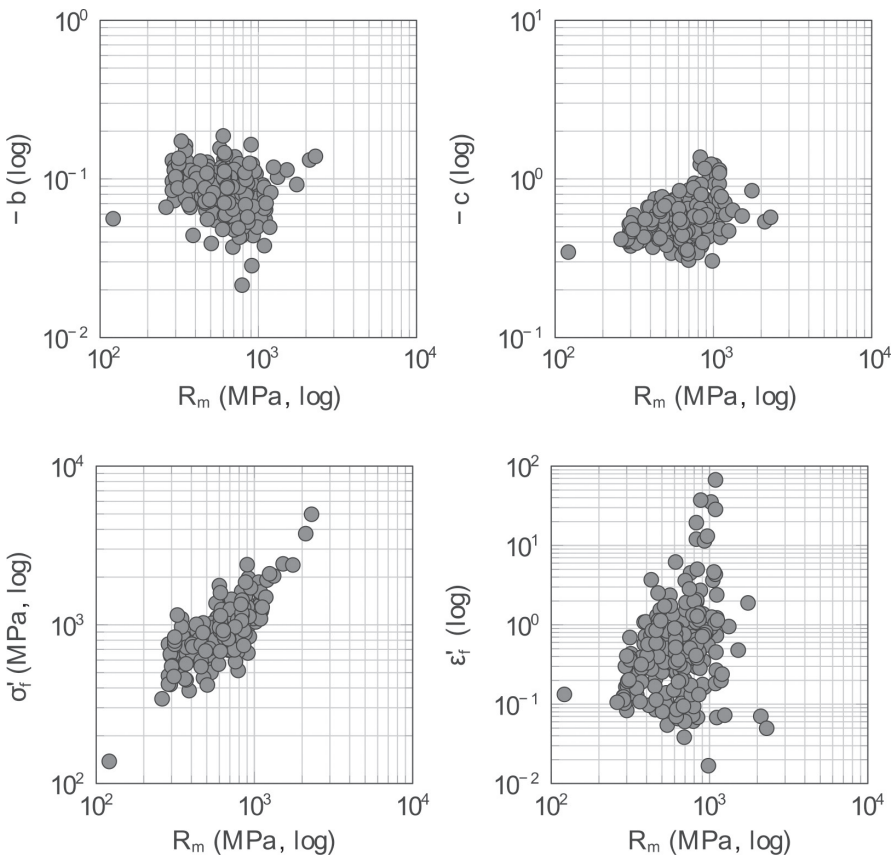


Figure 4: Correlations between the cyclic properties of steel and tensile strength

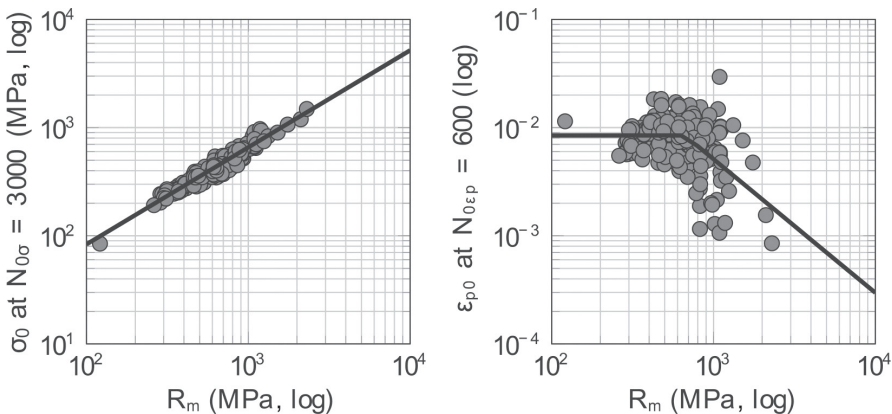


Figure 5: Correlations between the cyclic properties of steel at $N_{0\sigma} = 3000$ and $N_{0ep} = 600$ and tensile strength

via the compatibility relations, Equations (3) and (4) or (8), respectively.

The best-rated equations are adopted for the new, so-called FKM method and are listed in Table 2. FKM stands for Forschungskuratorium Maschinenbau and is a German research organization. The method was developed during a research project that was supervised by FKM, (see section "Acknowledgements").

The values pertaining to the quality criteria for this new estimation method are given in Table 3. It can be seen that the estimation for the material group steel is supported by most data sets and individual tests.

Using the new FKM method, the validity limits for the estimation of steel material are extended to the entire material group compared with that of the UML. At the same time, the deviation range is reduced. The new method also improves the estimation for wrought aluminum. For the reasons given above, elastic and plastic strain components are estimated for the two support points $N_{0\sigma}$ and $N_{0ep} \neq 0.5$. Nevertheless, because constant values were chosen for exponents b and c, the coefficients can be converted to the equivalent values for $N_{0\sigma} = N_{0ep} = 0.5$ and be displayed in conventional notation (see Table 4).

Comparison of accuracy between experimentally determined and estimated cyclic properties

As in Part 1, the accuracy between the experimentally determined and estimated cyclic properties has been compared for the FKM method. The same definitions for the deviation ranges T_N and T_σ are still valid. Both values are calculated for each of the material groups: steel, cast steel and wrought aluminum

1. For the scatter of the individual test results around the experimentally determined average curves and
2. For the scatter of the individual test results around the estimated curves using the FKM method.

These values are listed in Table 5. In addition, the scatter bands for the three material groups around the estimated mean curves using the FKM method are shown in $N_{exp}-N_{calc}$ diagrams in Figure 6. The following can be seen:

1. T_N exhibits higher values than T_σ for each material group for both the experimental and estimated results (already known from Part 1).
2. The values for T_N are approximately a factor of 2.6 larger for the estimation

Property	Steel	Cast steel	Wrought aluminum
σ_0	$1.3395 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.897}$	$0.902 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.982}$	$4.63 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.742}$
$N_{0\sigma}$	3000	300	300
b	-0.097	-0.102	-0.106
E	206 GPa	206 GPa	70 GPa
ϵ_{p0}	$\min \left(\begin{array}{c} 0.00847 \\ 25.90 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-1.235} \end{array} \right)$	$0.0392 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-0.181}$	$2.492 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-1.183}$
N_{0ep}	600	100	600
c	-0.52	-0.58	-0.83
Range of validity	$R_m = 121 \dots 2296 \text{ MPa}$	$R_m = 496 \dots 1144 \text{ MPa}$	$R_m = 216 \dots 649 \text{ MPa}$

Table 2: FKM-method for estimating cyclic properties

Material	Strain type	m	S	T	Number of	
					test series	individual tests
Steel	ϵ_{el}	1.04	0.95	14.3	240	2574
	ϵ_{pl}	0.97	1.03	8.44		
	ϵ_{tot}	1.04	1.00	5.26		
Cast steel	ϵ_{el}	0.87	1.15	20.9	6	74
	ϵ_{pl}	0.98	1.04	5.15		
	ϵ_{tot}	0.93	1.08	3.42		
Wrought aluminum	ϵ_{el}	1.00	1.01	14.3	31	404
	ϵ_{pl}	1.01	1.00	7.52		
	ϵ_{tot}	0.98	1.05	7.26		

Table 3: Values for the quality criteria and number of test data used for the FKM method

Property	Steel	Cast steel	Wrought aluminum
σ'_f	$3.1148 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.897}$	$1.732 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.982}$	$9.12 \text{ MPa} \cdot \left(\frac{R_m}{\text{MPa}}\right)^{0.742}$
b	-0.097	-0.102	-0.106
E	206 GPa	206 GPa	70 GPa
ϵ'_f	$\min \left(\begin{array}{c} 0.338 \\ 1033 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-1.235} \end{array} \right)$	$0.847 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-0.181}$	$895.9 \cdot \left(\frac{R_m}{\text{MPa}}\right)^{-0.183}$
c	-0.52	-0.58	-0.83
Range of validity	$R_m = 121 \dots 2296 \text{ MPa}$	$R_m = 496 \dots 1144 \text{ MPa}$	$R_m = 216 \dots 649 \text{ MPa}$

Table 4: FKM method for estimating cyclic properties (conventional notation)

Material group	Experimentally determined		Estimated by FKM method	
	T_N	T_σ	T_N	T_σ
Steel (no cast)	2.09	1.10	5.91	1.34
Cast steel	3.15	1.11	7.04	1.28
Steel + cast steel*	2.09	1.10	6.01	1.34
Wrought aluminum	2.34	1.12	6.34	1.26

* This row shows the values for the complete material group of steel (steel and cast steel) so that the values can be compared to Part 1

Table 5: Deviation ranges T_N and T_σ for experimentally determined and estimated (FKM method) cyclic properties

than those of the experimental results. For T_{σ} , the average factor is 1.17.

3. The deviation ranges T_N are smallest for steel, while cast steel exhibits the highest values.

Conclusions

By using the database containing experiments for quasi-static and cyclic properties

known from Part 1, a new estimation method, the so-called FKM method, has been derived for estimating cyclic properties for steel, cast steel and wrought aluminum. Comparing the calculated values of the quality criteria for the best-rated estimation methods from Part 1 to the values for the FKM method in Table 3, it can be seen that the accuracy of the estimation can be improved with the new method. The

same trend can be found comparing the deviation ranges for experimentally determined and estimated cyclic properties, as shown in Part 1 and Table 5.

For reasons of fairness, it should be noted that this database was used for the development of the FKM method as well as for its evaluation. This was not the case for the methods known from Part 1. Hence, the better performance of the FKM method is partly due to this advantage, and a direct comparison is not entirely fair. Nevertheless, in addition to better performance, the FKM method also maintains a wider range of validity compared with that of UML (material group steel) and only requires tensile strength as an input parameter.

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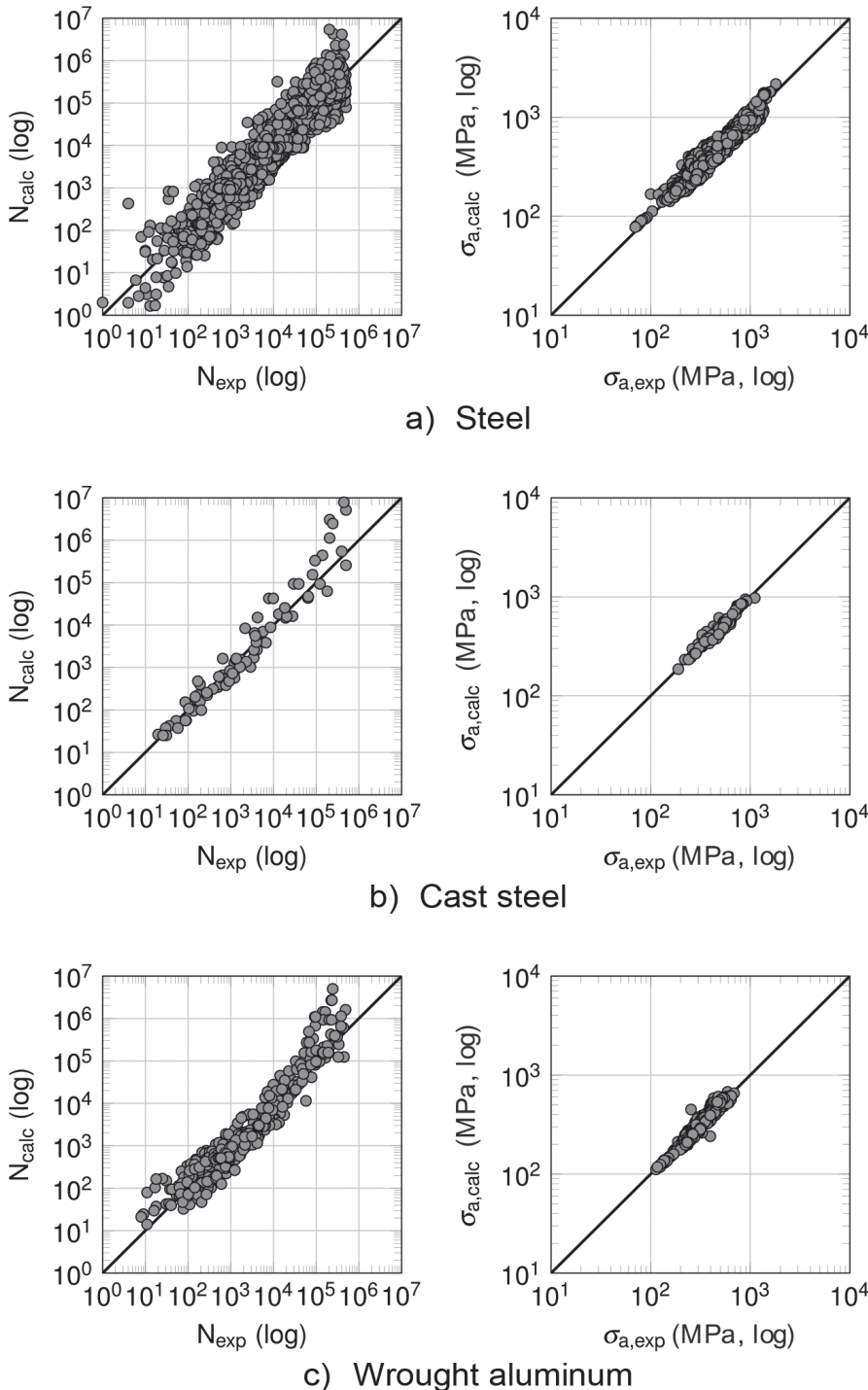


Figure 6: N_{calc} vs. N_{exp} for the three material groups (N_{calc} was calculated using the FKM method), a) steel, b) cast steel, c) wrought aluminum

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Abstract

Zur Abschätzung zyklischer Werkstoffkennwerte – Teil 2: Einführung einer neuen Abschätzmethode. Anhand einer großen Datenbasis mit Ergebnissen quasi-statischer und dehnungsgeregelter Versuche wird eine neue Methode zur Abschätzung zyklischer Werkstoffkennwerte für die Werkstoffgruppen Stahl, Stahlguss und Aluminiumknetlegierungen, die sog. FKM-Methode, abgeleitet. Die neue Methode benötigt lediglich die Zugfestigkeit als Eingabewert, weist einen größeren Gültigkeitsbereich als andere, bekannte Methoden auf und übertrifft gleichzeitig deren Schätzgüte.

ished his PhD thesis in 1995. Between 1995 and 2003 he was head of the “Fatigue Analysis” department at Deutsche Bahn AG in Minden, Germany. Since 2003 he has been a professor at TUC

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