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Evaluation of Methods for Estimation of Cyclic Stress-Strain Parameters from Monotonic Properties of Steels

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Abstract: Most existing methods for estimation of cyclic yield stress and cyclic Ramberg-Osgood stress-strain parameters of steels from their monotonic properties were developed on relatively modest number of material datasets and without considerations of the particularities of different steel subgroups formed according to their chemical composition (unalloyed, low-alloy, and high-alloy steels) or delivery, i.e., testing condition. Furthermore, some methods were evaluated using the same datasets that were used for their development. In this paper, a comprehensive statistical analysis and evaluation of existing estimation methods were performed using an independent set of experimental material data compriseding 116 steels. Results of performed statistical analyses reveal that statistically significant differences exist among unalloyed, low-alloy, and high-alloy steels regarding their cyclic yield stress and cyclic Ramberg-Osgood stress-strain parameters. Therefore, estimation methods were evaluated separately for mentioned steel subgroups in order to more precisely determine their applicability for the estimation of cyclic behavior of steels belonging to individual subgroups. Evaluations revealed that considering all steels as a single group results in averaging and that subgroups should be treated independently. Based on results of performed statistical analysis, guidelines are provided for identification and selection of suitable methods to be applied for the estimation of cyclic stress-strain parameters of steels.

Keywords: estimation methods; monotonic properties; cyclic stress-strain parameters; Ramberg-Osgood; steel grouping; statistical analysis

1. Introduction

Development of computer technology and CAE software solutions have enabled performing complex simulations of material and product behavior under cyclic loading and fatigue life determination already during early stages of product development process. In recent years, rapid increases in computing power and availability of distributed and cloud-based resources have been seen. Within short time frame, complex simulations can be run for multiple materials. An example of these are strain-based, i.e., local strain-life fatigue, analyses which have been widely adopted in automotive, aeronautic, and power industry for fatigue life predictions of highly-loaded steel and aluminium components [1,2]. In order to perform these analyses, both cyclic stress-strain and strain-life fatigue curves and parameters that define them must be known. Well-accepted and widely used representation of stress-strain response of the majority of metallic materials is the cyclic Ramberg-Osgood (R-O) equation [3,4]:

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

For determination of lifetime in both low-cycle and high-cycle regime, Coffin-Manson-Basquin (C-M-B) [4,5] approach is applied:

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

In Equations (1) and (2) $\Delta\varepsilon$, $\Delta\varepsilon_e$ and $\Delta\varepsilon_p$ are true total, elastic and plastic strain ranges, respectively, $\Delta\sigma$ is true stress range, E is Young's modulus, K' is cyclic strength coefficient, and n' is cyclic strain hardening exponent. Furthermore, σ_f', ε_f', b and c are fatigue strength and ductility parameters obtained from fully reversed tension-compression fatigue tests.

Cyclic R-O and C-M-B parameters obtained through material testing are most accurate, but are very often unavailable due to long time and high costs associated with experimental characterization. Existing test results which are available in literature and materials databases often do not sufficiently correspond to the actual material under consideration. Hence, it has become common practice to estimate cyclic R-O and C-M-B parameters of the material from its monotonic properties early during product development. For estimation of C-M-B fatigue parameters from monotonic properties of materials, many methods have been developed [5–8] and evaluated in literature [9]. To the contrary, for estimation of cyclic R-O parameters of materials, only a limited number of methods are proposed [10–13]. For estimations of cyclic yield stress R_e' and R-O parameters (K' and n') various monotonic properties and their combinations are used, with ultimate strength R_m and yield stress R_e being the most common since they are readily available. Detailed overview of monotonic properties used for estimation of cyclic parameters of metallic materials and systematic study of their relevance for estimation purposes is provided in [14].

No independent and systematic evaluations of these methods can be found in the literature, the only ones available being those performed in respective papers where methods were proposed.

The main aim of this paper is to provide detailed analysis and evaluation of existing methods for estimation of cyclic yield stress R_e' and cyclic stress-strain parameters K' and n' from monotonic properties. For this purpose, a large and independent set of material data was collected from relevant sources. Since previous investigations [15–17] confirmed that dividing steels into different subgroups might improve estimation accuracy, this will also be taken into consideration. One-way Analysis of Variance (one-way ANOVA) and post hoc Tukey's test will be performed in order to check whether individual steel groups are statistically different regarding their cyclic parameters R_e', K' and n'. If such differences are confirmed to exist, in addition to evaluation of existing methods for all steels together, partial evaluations for each steel subgroup will be performed as well.

2. Overview of Existing Methods for Estimation of Cyclic Stress-Strain Parameters

2.1. Methods for Estimation of Cyclic Yield Stress R_e'

Li et al. [11] originally proposed estimation of cyclic yield stress R_e' of steels from ultimate strength R_m and reduction of area at fracture RA. Equation (3) was developed using monotonic and cyclic properties of 27, mostly unalloyed and low-alloy steels:

$$R_e' = (1 + RA)R_m\left(-\frac{0.002}{\ln(1 - RA)}\right)^{0.16} \quad (3)$$

Evaluation of proposed expression is performed on the same data used for developing the method, and is reported that estimated values of R_e' deviate at most 14% from their experimental counterparts.

Lopez and Fatemi [12] developed a number of relationships between Brinell hardness *(HB* or monotonic properties and cyclic yield stress R_e' of steels. These were developed and validated on a relatively large number of steels consisting mostly of unalloyed and low-alloy steels, covering a wide variation of chemical composition and mechanical properties, with ultimate stress R_m ranging from 279 to 2450 MPa and hardness from 80 to 595 HB. Materials were divided according to ultimate strength to yield stress ratio R_m/R_e, since it was shown that such division improves the accuracy of cyclic parameters estimation. Ratio R_m/R_e was originally proposed by Smith et al. [18] to be used for prediction of cyclic behavior (hardening, softening, stable behavior) of materials. Correspondingly, authors proposed a number of separate expressions for estimation of R_e' depending on value of R_m/R_e of which the most successful ones are:

$$R_e' = 0.75R_e + 82 \text{ for } R_m/R_e > 1.2 \tag{4a}$$

$$R_e' = 3.0 \times 10^{-4}R_e^2 - 0.15R_e + 526 \text{ for } R_m/R_e \leq 1.2 \tag{4b}$$

Additionally, single expression for all steels, regardless of the value of R_m/R_e is also proposed:

$$R_e' = 8.0 \times 10^{-5}R_m^2 + 0.54R_m. \tag{5}$$

Values of coefficient of determination R^2 for expressions (4a), (4b) and (5) were 0.88, 0.99, and 0.94 respectively. Evaluation was performed on a single dataset comprising data used for developing expressions and additional data (all together 121 materials, mostly unalloyed and low-alloy steels). It was established that 84% of estimated values of R_e' from yield stress R_e (Equations (4a) and (4b)) deviate up to ±20% from experimental values while 79% of values of R_e' estimated from ultimate strength R_m (Equation (5)) deviated up to ±20% from experimental values.

Motivated by findings from [12] that Equation (3) always underestimates cyclic yield stress R_e' when experimental value of R_e' exceeds 900 MPa, Li et al. [13] recently modified Equation (3) to:

$$R_e' = 0.089(1 + RA)^{1.35}{R_m}^{1.35} \times \left(-\frac{0.002}{\ln(1 - RA)}\right)^{0.216} + 120 \tag{6}$$

resulting in rather high coefficient of determination $R^2 = 0.961$. Analysis was performed on the majority of data used in [12]. For evaluation, data used for developing Equation (6) was complemented with additional data. Results showed that most values of R_e' estimated from Equation (6) deviate up to 20% from their experiment-based counterparts. It must be noted that [11] and [13] suggest that values of true fracture strength σ_f can be calculated using the expression:

$$\sigma_f = R_m(1 + RA) \tag{7}$$

which is recognizable as first part of Equations (3) and (6). However, a well-known approximation of the relationship between ultimate strength R_m and true fracture stress σ_f, recommended by Manson [5,9] is:

$$\sigma_f = R_m(1 + \varepsilon_f) \tag{8}$$

Therefore, caution is advised when applying expressions (3) and (6) for estimation of not only cyclic yield stress R_e', but also cyclic parameters K' and n' that will be discussed later in Section 2.2.

2.2. Methods for Estimation of Cyclic Parameters $K'$and n'

Zhang et al. [10] proposed several equations for estimation of K' and n' based on 22 steels, aluminium (Al), and titanium (Ti) alloys. For this purpose, materials were divided by value of so-called new fracture ductility parameter α:

$$\alpha_f = RA \times \varepsilon_f = -RA\ln(1 - RA) \tag{9}$$

proposed in [19]. Expressions were proposed for estimation of K' and n', Equation (10) through Equation (11c), when strength coefficient K and strain hardening exponent n are available:

$$K' = 57K^{0.545} - 1220 \tag{10}$$

$$n' = 1.06n\left(1+\beta\left|1-\frac{R_{\mathrm{m}}}{R_{\mathrm{p0.2}}}\right|\right) \text{ for } \alpha < 5\% \text{ or } 10\% \le \alpha < 20\% \tag{11a}$$

$$n' = 1.06n\left(1+\beta\left|1-\frac{\sigma_{\mathrm{f}}}{R_{\mathrm{m}}}\right|\right) \text{ for } 5\% < \alpha < 10\% \tag{11b}$$

$$n' = \frac{R_{\mathrm{p0.2}}}{\sigma_{\mathrm{f}}-R_{\mathrm{m}}}n \text{ for } \alpha > 20\% \tag{11c}$$

and Equation (12a) through Equation (13c) when K and n are not available:

$$K' = 57\left(\sigma_{\mathrm{f}}\varepsilon_{\mathrm{f}}^{-\frac{\log\left(\frac{R_{\mathrm{m}}{}^{2}\sigma_{\mathrm{f}}{}^{3}}{R_{p0.2}{}^{5}}\right)}{3\log(500\varepsilon_{\mathrm{f}})}}\right)^{0.545} - 1220 \text{ for } \alpha < 5\% \text{ or } 10\% \le \alpha < 20\% \tag{12a}$$

$$K' = 57\left(\frac{\sigma_{\mathrm{f}}R_{\mathrm{p0.2}}}{R_{\mathrm{m}}}\varepsilon_{\mathrm{f}}^{-\frac{\log\left(\frac{\sigma_{\mathrm{f}}{}^{2}}{R_{\mathrm{p0.2}}R_{\mathrm{m}}}\right)}{2\log(500\varepsilon_{\mathrm{f}})}}\right)^{0.545} - 1220 \text{ for } 5\% < \alpha < 10\% \text{ or } \alpha > 20\% \tag{12b}$$

$$n' = 1.06\left(1+\beta\left|1-\frac{R_{\mathrm{m}}}{R_{\mathrm{p0.2}}}\right|\right)\frac{\log\left(\frac{R_{\mathrm{m}}{}^{2}\sigma_{\mathrm{f}}{}^{3}}{R_{\mathrm{p0.2}}{}^{5}}\right)}{3\log(500\varepsilon_{\mathrm{f}})} \text{ for } \alpha < 5\% \text{ or } 10\% \le \alpha < 20\% \tag{13a}$$

$$n' = 1.06\left(1+\beta\left|1-\frac{\sigma_{\mathrm{f}}}{R_{\mathrm{m}}}\right|\right)\frac{\log\left(\frac{\sigma_{\mathrm{f}}{}^{2}}{R_{\mathrm{p0.2}}R_{\mathrm{m}}}\right)}{2\log(500\varepsilon_{\mathrm{f}})} \text{ for } 5\% < \alpha < 10\% \tag{13b}$$

$$n' = \frac{R_{\mathrm{p0.2}}}{\sigma_{\mathrm{f}}-R_{\mathrm{m}}}\frac{\log\left(\frac{\sigma_{\mathrm{f}}{}^{2}}{R_{\mathrm{p0.2}}R_{\mathrm{m}}}\right)}{2\log(500\varepsilon_{\mathrm{f}})} \text{ for } \alpha > 20\% \tag{13c}$$

For both methods, parameter $\beta = 1$ for $\sigma_{\mathrm{f}}/R_{\mathrm{p0.2}} < 1.6$ and $\beta = -1$ for $\sigma_{\mathrm{f}}/R_{\mathrm{p0.2}} > 1.6$. As most successful expressions authors proposed estimation of K' based on strength coefficient K (Equation (10)) and estimation of n' based on ultimate strength R_{m}, yield stress R_{e}, true fracture stress σ_{f} and strain hardening exponent n (Equation (13a) through Equation (13c), depending on value of α). For steels, values of K' and n' estimated in such a way deviated up to 27% and 34%, respectively, from their experiment-based counterparts. Data tables with percentage deviation for aluminium and titanium alloys suggest even larger deviations of estimates of n' (up to 65%). They also suggested that, for stress amplitudes $\Delta\sigma/2$ calculated from estimated values of K' and n', besides percentage deviation of particular parameter, sign of deviation is also significant. If sign of deviations of K' and n' is the same, calculated and experimental cyclic stress-strain curves are in good agreement.

In [12], besides expressions for estimation of R_{e}', Lopez and Fatemi developed several relationships between Brinell hardness *HB* or monotonic properties and cyclic parameters K' and n' of steels. Steels are divided into two subgroups according to the value of the $R_{\mathrm{m}}/R_{\mathrm{e}}$ ratio (as was the case for estimation of cyclic yield stress R_{e}') and different expressions are proposed accordingly. Equations (14a) and (14b) are denoted as most successful:

$$K' = 1.16R_{\mathrm{m}} + 593 \text{ for } R_{\mathrm{m}}/R_{\mathrm{e}} > 1.2 \tag{14a}$$

$$K' = 3.0\cdot10^{-4}R_{\mathrm{m}}^{2} + 0.23R_{\mathrm{m}} + 619 \text{ for } R_{\mathrm{m}}/R_{\mathrm{e}} \le 1.2 \tag{14b}$$

$$n' = -0.37\log\left(\frac{0.75\mathrm{R}_{e}+82}{1.16R_{\mathrm{m}}+593}\right) \text{ for } R_{\mathrm{m}}/R_{\mathrm{e}} > 1.2 \tag{15a}$$

$$n' = -0.37\log\left(\frac{3.0\times10^{-4}R_{\mathrm{e}}^{2}-0.15R_{\mathrm{e}}+526}{3.0\times10^{-4}R_{\mathrm{m}}^{2}+0.23R_{\mathrm{m}}+619}\right) \text{ for } R_{\mathrm{m}}/R_{\mathrm{e}} \le 1.2 \tag{15b}$$

Authors provided coefficients of determination R^2 only for expressions (14a) and (14b). It is worth noting that R^2 of expressions proposed for estimation of K' for steels with $R_m/R_e > 1.2$ is 0.75 which is significantly lower than 0.90 obtained for steels with $R_m/R_e \leq 1.2$. About 73% values of K' estimated using Equations (14a) and (14b) deviate less than ±20% from their experimental values. As for n', percentage of values estimated from Equations (15a) and (15b) that deviate less than ±20% from their experiment-based counterparts is around 60%.

Lopez and Fatemi [12] proposed additional expression for estimation of n' valid for all steels:

$$n' = -0.33(R_e/R_m) + 0.40 \tag{16}$$

for which R^2 obtained was 0.79. Percentage of values of n' estimated from Equation (16) that deviated up to ±20% from experimental values was 68%.

Both methods proposed in [12] for estimation of n' provide reasonably good results, so in further evaluations in this paper, both methods will be taken into account: first using Equation (14a) through Equation (15b), and second using Equations (14a), (14b) and (16).

Li et al. [13] proposed expressions for estimation of cyclic parameters K' and n':

$$K' = 500^{n'} R'_e \tag{17}$$

$$n' = \frac{\log(K') - \log(R'_e)}{\log 500} \tag{18}$$

where $R_e{}'$ is estimated using Equation (6). However, Equations (17) and (18) can be used only when either K' or n' are available, so in the same paper an alternative method for estimation of these parameters was proposed. Cyclic strength coefficient K' should be estimated using Equations (19a), (19b) or (19c) first, then cyclic strain hardening n' exponent is calculated from estimated values of K'.

$$K' = 2.16 \cdot 10^{-4} (R_m)^{2.1} + 738 \text{ for } R_m/R_e \leq 1.2 \tag{19a}$$

$$K' = 3.63 \cdot 10^{-4} (R_m)^2 + 0.68 R_m + 570 \text{ for } 1.2 < R_m/R_e < 1.4 \tag{19b}$$

$$K' = 1.21 R_m + 555 \text{ for } R_m/R_e \geq 1.4 \tag{19c}$$

Equation (19a) through Equation (19c), when used in combination with Equation (18), yielded reasonable results with most of estimated values of K' deviating up to ±20% from experimental values. Obtained coefficients of determination R^2 for Equation (19a) through Equation (19c) decrease with higher values of R_m/R_e, which is in accordance with findings from [12]. R^2 obtained for steels with $R_m/R_e \leq 1.2$ is 0.921, while for steels with $1.2 < R_m/R_e < 1.4$ and $R_m/R_e \geq 1.4$ coefficients of determination are R^2 = 0.813 and R^2 = 0.712, respectively. Again, caution is advised when using Equation (18) due to the suggested way of estimating $R_e{}'$ that was already discussed at the end of Section 2.1.

2.3. Conclusions

A review of methods for estimation cyclic parameters shows that sets of material data on which most of them were developed and evaluated differ significantly regarding their size and material groups included. In this sense, they can still be considered adequate with the exception of expressions for estimation of K' and n' proposed in [10] which were developed using a quite small and heterogeneous set of material data (22 datasets for steels, aluminium and titanium alloys) and expression for estimation of $R_e{}'$ proposed in [10] which was developed using only 27 steel datasets.

In an attempt to further improve estimation accuracy, most methods address steels separately from other kinds of metallic materials [11–13] and all methods divide materials into separate subgroups using different criteria [10,12,13]. For this purpose, Zhang et al. [10] used new fracture ductility parameter α that was originally developed to predict materials' cyclic behavior [10,19]. Lopez and

Fatemi [12] and Li et al. [13] divided steels into two, i.e., three subgroups according to the ratio of ultimate strength to yield stress R_m/R_e.

Lack of general consensus regarding the treatment of individual material subgroups as well as different methodologies for evaluation of estimation methods implemented in their respective papers makes comparison of their performance quite difficult. In order to determine which estimation method is most suitable for estimation of cyclic parameters of steels, systematic and consistent evaluation of presented methods will be performed on an independent set of material data.

Different delivery, i.e., testing conditions of material, can be obtained for example through different processing method or heat treatment and this can strongly impact both monotonic and cyclic/fatigue material properties and behavior [5,20]. This is an important aspect which none of the discussed methods takes into account directly. One of the possible reasons is a multitude of conditions of steel materials which were used for development of these methods, particularly in [12,13]. For certain materials, such information, even if available, was of a rather general nature (for example heat treated, modified, etc.).

In practice, steels are commonly divided according to the content of alloying elements into unalloyed, low-alloy and high-alloy steels. Already Baümel and Seeger [6] considered unalloyed and low-alloy steels separately from other metallic materials when they developed Uniform Material Law for estimation of C-M-B parameters. Hatscher et al. [8] also mentioned the prospect of such division for estimation of fatigue C-M-B parameters. Results of detailed analysis performed on a large number of material data done by Basan et al. [15] showed that there is statistically significant difference among individual C-M-B fatigue parameters as well as strain-life behavior ($\Delta\varepsilon$–$2N_f$ relationships) of unalloyed, low-alloy and high-alloy steels. Also, preliminary investigations on cyclic parameters in [16,17] showed that dividing steels by alloying content could result in more accurate estimations of cyclic parameters and hence, more accurate estimations of cyclic stress-strain curves of materials.

For that reason, statistical analysis of steel subgroups (unalloyed, low-alloy and high-alloy steels) will be performed in order to determine if their cyclic parameters differ significantly. If confirmed, individual steel subgroups will be taken into account during evaluation and comparison of estimation methods.

3. Methods and Data

3.1. Methods for Statistical Analysis

To test whether statistically significant differences exist among experimental data for cyclic yield stress R_e' and cyclic stress-strain parameters K' and n' of unalloyed, low-alloy and high-alloy steels, one-way Analysis of Variance (one-way ANOVA) is performed. One-way ANOVA is a technique that provides a statistical test of whether or not means of several (typically three or more) groups are all equal. If results obtained by one-way ANOVA show that statistically significant difference exists between cyclic parameters of analyzed groups, post hoc analysis by Tukey's multiple comparison method will be performed in order to determine pairwise differences between groups. Significance level α for one-way ANOVA is set to 0.05, while overall significance (family error rate) in Tukey's multiple comparison test is set to 0.05 to counter type I error for a series of comparisons. Procedure for both one-way ANOVA and Tukey's multiple comparison test are given in [21]. Statistical analyses were performed in statistical package MINITAB [22].

To evaluate predictive accuracy of estimation methods and to facilitate their comparison, deviations of estimated values from their experimentally obtained counterparts were used as relevant indicators. Deviations up to ±10, ±20 and $\pm30\%$ were used as in [12,13] to facilitate comparison with results reported there. Instead of directly comparing estimated Ramberg-Osgood parameters K' and n' to their experiment-based counterparts as in [12,13], much more useful information regarding the predictive accuracy of these methods can be obtained by comparing values of stress amplitudes $\Delta\sigma/2$, i.e., points on cyclic stress-strain curves as in [10,16,17]. Therefore, values of stress amplitudes $\Delta\sigma/2$

were calculated using experimental values of K' and n' and their estimations for series of total strain amplitudes $\Delta\varepsilon/2$: 0.1, 0.2, 1 and 2%.

3.2. Data to Be Analyzed

Experimental data for three representative groups of steels: unalloyed (UA), low-alloy (LA) and high-alloy (HA) steels from [6] and [23] were obtained through the MATDAT Materials Properties Database [24]. Only results of strain-controlled, fully reversed ($R = -1$) axial cyclic tests performed in the air at room temperature were considered. Furthermore, only data for materials tested at more than four different strain amplitudes and at range of total strain amplitudes larger than 0.4% were used in the analysis.

Only datasets that contained all experimental values of monotonic properties needed for estimation of cyclic parameters by each method were used. An exception was made with the high-alloy steel group. Since most datasets did not contain values of true fracture stress σ_f which is necessary for calculation of parameters by Zhang et al. method [10], values were calculated by their relationship between ultimate strength R_m and true fracture strain ε_f, according to Equation (8). Also, if a dataset contained only reduction of area at fracture RA, true fracture strain ε_f was calculated by the relationship between these two properties:

$$\varepsilon_f = -\ln(1 - RA) \tag{20}$$

In total, 34 unalloyed steels, 47 low-alloy steels and 35 high-alloy steel datasets were available for analysis. Wide variety of conditions resulting from different processing and heat treatment were present in materials used for statistical analysis and evaluation of existing methods. This is consistent with datasets used for development of methods in their respective papers.

Detailed material data are given in Appendix A in Tables A1–A3. Data used for statistical analysis in [14] were complemented with values of true fracture strain ε_f. Additionally, data for high-alloy steels were complemented with values of true fracture stress σ_f, strength coefficient K and strain hardening exponent n since those are required so that evaluations of particular existing methods could be performed.

4. Analysis and Results

4.1. Results of One-Way ANOVA and Tukey's Multiple Comparison Test

Performing one-way ANOVA for three cyclic parameters (R_e', K' and n') of unalloyed, low- and high-alloy steel subgroups showed that statistically significant differences exist between steel subgroups regarding cyclic yield stress R_e' ($F(2, 113) = 32.25$; $p < 0.05$), cyclic strength coefficient K' ($F(2, 113) = 22.61$; $p < 0.05$), and cyclic strain hardening exponent n' ($F(2, 113) = 72.00$; $p < 0.05$).

Since steel subgroups were confirmed to be significantly different regarding their cyclic parameters R_e', K' and n', post hoc Tukey's test was performed to determine which subgroups are mutually different. Results showed that unalloyed and low-alloy steels as well as low-alloy and high-alloy steels differ significantly regarding the cyclic yield stress R_e'. No such difference was determined between unalloyed and high-alloy steels. Statistically significant difference was also found for cyclic strength coefficient K' of unalloyed and high-alloy steels, as well as low-alloy and high-alloy steels, while no such difference was found between unalloyed and low-alloy steels. Cyclic strain hardening exponent n' differs between pairs of all three groups.

4.2. Evaluation of Methods for Estimation of Cyclic Yield Stress R_e' and Ramberg-Osgood Parameters K' and n' of Steels

Since unalloyed, low-alloy and high-alloy steels subgroups were proved to be significantly different, steel subgroups will be considered separately for evaluation of estimation methods. Evaluation will also be made for all steels as a single group to check for differences between results of analyses performed on individual subgroups and to enable comparison and determination of potential discrepancies with results reported in original papers.

Methods for estimation of cyclic yield stress R_e' and R-O parameters K' and n' of steels whose predictive accuracy will be evaluated are listed in Table 1. For every material, expressions for estimation of cyclic yield stress R_e' and R-O parameters K' and n' will be used according to ranges defining the applicability of the models regarding criteria for grouping of materials in original papers (new fracture ductility coefficient α, ultimate strength to yield stress ratio R_m/R_e).

4.2.1. Evaluation of Methods for Estimation of Cyclic Yield Stress R_e'

Percentages of values of R_e' estimated according to selected methods (Table 1) that deviate up to 10%, 20% and up to 30% from experiment-based values were calculated and are given in diagrams on Figure 1.

Table 1. Methods for estimation of R_e' and K' and n' which will be evaluated.

Evaluated Value	Method	Estimated Parameters	Originally Proposed for	Equation Number
R_e'	Lopez and Fatemi 1 [12]	R_e'	steels divided by R_m/R_e	(4a,b)
	Lopez and Fatemi 2 [12]	R_e'	all steels	(5)
	Li et al. [13]	R_e'	all steels	(6)
$\Delta\sigma/2$	Zhang et al. 1 [10]	K'	steels, Al and Ti alloys	(10)
	(K and n available)	n'	steels, Al and Ti alloys divided by α	(11a,b,c)
	Zhang et al. 2 [10]	K'	steels, Al and Ti alloys divided by α	(12a,b)
	(K and n not available)	n'	steels, Al and Ti alloys divided by α	(13a,b,c)
	Lopez and Fatemi 1 [12]	K'	steels divided by R_m/R_e	(14a,b)
		n'	steels divided by R_m/R_e	(15a,b)
	Lopez and Fatemi 2 [12]	K'	steels divided by R_m/R_e	(14a,b)
		n'	all steels	(16)
	Li et al. [13]	K'	steels divided by R_m/R_e	(19a,b,c)
		n'	steels divided by R_m/R_e	(18)

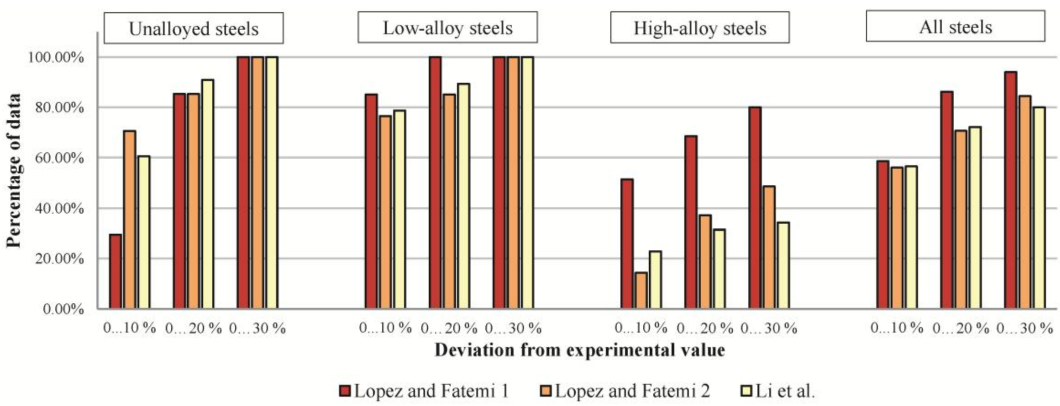

Figure 1. Percentage of R_e' values estimated by selected methods that deviate up to 10%, 20% and 30% from experiment-based values.

Reasonable results are obtained for All steels group with about 70%–80% of data deviating up to 20% from their experimental counterparts for each method.

For unalloyed steels, for each method about 80%–90% of estimates of cyclic yield stress R_e' deviate up to 20%, while all estimates fall within ±30% deviation from corresponding experimental values. Highest percentage of data that deviate only up to 10% is obtained by Lopez and Fatemi 2 (about 70%).

For low-alloy steels, results obtained using any of the three selected methods were even more accurate than for unalloyed steels. Best results for estimation of R_e' of low-alloy steels are obtained using Lopez and Fatemi 1 method, for which all estimates deviate 20% or less from their experiment-based counterparts.

As for high-alloy steels, no method proved to be sufficiently accurate. Lopez and Fatemi 1 provides reasonable results with about 70% of estimated data deviating up to 20%, although 20% of data deviate more than 30% from experimental values. Estimations made by other two methods result with less than 50% of estimates deviating below 30% from experimental values (below 40% by Li et al.).

4.2.2. Evaluation of Methods for Estimation of Ramberg-Osgood Parameters K' and n' of Steels

As was explained in Section 3.1, accuracy of estimates of Ramberg-Osgood parameters K' and n' will be determined by evaluating values of stress amplitudes $\Delta\sigma/2$ calculated using estimated K' and n' opposed to those obtained using experimental values of those parameters.

Percentages of estimated values of $\Delta\sigma/2$ as calculated by selected methods (Table 1) that deviate up to 10%, 20% and up to 30% from experiment-based values are given in Figure 2.

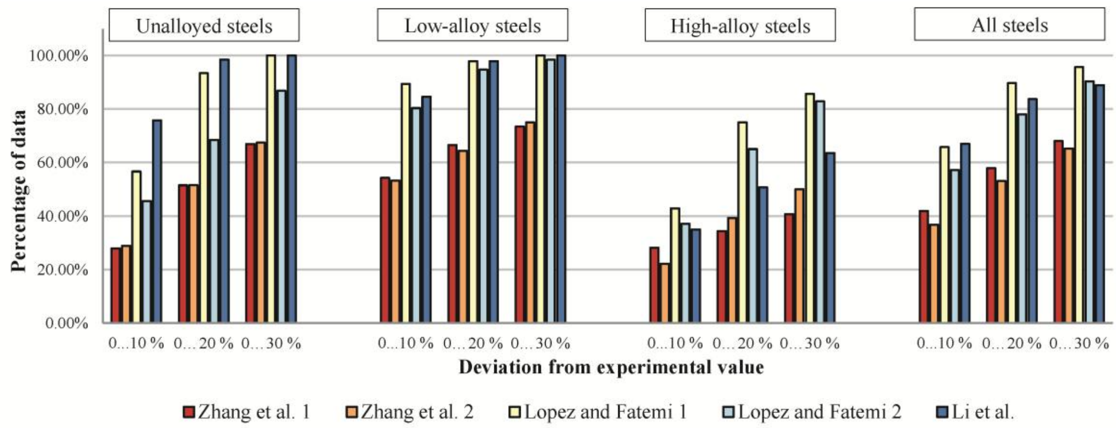

Figure 2. Percentage of $\Delta\sigma/2$ values estimated by selected methods that deviate up to 10%, 20% and 30% from experiment-based values.

Results obtained using Lopez and Fatemi 1 and Li et al. method for estimation of K' and n' both provide very good results for estimation of stress amplitudes $\Delta\sigma/2$ of unalloyed steels, with over 90% of data deviating 20% or less from experimental values. For both methods, all estimates of $\Delta\sigma/2$ for unalloyed steels fall within $\pm$30% deviation from experimental values, with Li et al. method providing as much as 75% of data within $\pm$10% deviation.

The same methods yield even better results for low-alloy steels, with more than 80% of data deviating up to 10% from experiment-based counterparts. Although somewhat less accurate than previous two, Lopez and Fatemi 2 method also provides very good results for estimation of $\Delta\sigma/2$ of low-alloy steels.

Both methods by Zhang et al. gave significantly inferior results for both unalloyed and low-alloy steel subgroups. For unalloyed steels, by either method, only about 50% of data deviate 20% or less from experimental values, while about one-third of data deviate more than 30% from corresponding experimental values. Results are somewhat better for low-alloy steels, with a higher percentage of data deviating 20% or less from experimental values (about 65%). Still, only 75% of estimates obtained using both methods by Zhang et al. deviate less than 30% from experimental values.

As for high-alloy steels, no method provided estimates on the level of accuracy observed for unalloyed and low-alloy steels. Results obtained using either method by Lopez and Fatemi are the most acceptable, with around 75% of values estimated using Lopez and Fatemi 1 deviating less than 20%. Estimations by Li et al. resulted in more than 35% of data deviating more than 30% from experimental values, while the most inaccurate results were obtained by either of Zhang et al. methods. More than half of the estimates obtained by these methods deviate at least 30% from corresponding experimental values.

Overall evaluation for all steels provided averaged results as was the case for estimates of R_e'. Lopez and Fatemi 1 method is the most accurate while both Zhang et al. methods are least successful, as was the case for individual steel subgroups.

5. Discussion

Estimation methods investigated in this paper were developed on datasets comprising all steels [11–13], and even some other groups of metallic materials (steels, aluminium and titanium alloys) [10]. However, in order to improve accuracy of estimations, most methods propose some criterion for grouping of materials. In [12,13] authors divided steels by rather easily available R_m/R_e ratio. In [10], grouping criteria used was the new fracture ductility parameter α, which is cumbersome to use since true fracture stress ε_f or reduction of area *RA* needed for its calculation are often unavailable.

Much more usable, and often encountered in practice, is division of steels by their alloying content into unalloyed, low-alloy and high-alloy steels. It was shown in [6,8,15–17] that dividing steels in this manner contributes to improvement of estimations of steel behavior from monotonic properties of steels. Results of analysis performed in Section 4.1 confirmed that statistically significant differences exist between cyclic yield stress R_e' and cyclic parameters K' and n' of mentioned group of steels. According to these findings, authors propose evaluation of existing methods for estimation of R_e', K' and n' to be performed for each group individually, in addition to all steels together.

For estimation of R_e', K' and n' of both unalloyed and low-alloy steels, methods by Lopez and Fatemi [12], and by Li et al. [13] provide very good results. However, estimations for high-alloy steels are notably worse, especially those obtained using the Li et al. method which is not surprising since both methods are developed on the same set of data, consisting mostly of unalloyed and low-alloy steels.

Values of K' and n' estimated with two methods developed by Zhang et al. [10], are generally unsatisfactory and provide poor results for all steel subgroups, especially high-alloy steels. This can be attributed to the fact that methods were developed on a modest number (22) of heterogeneous data (steels, aluminium and titanium alloys). Another drawback of methods proposed by Zhang et al. are intricate expressions requiring monotonic properties which are often unavailable, especially during the early stages of product development.

Evaluations of existing methods in original references are performed for all materials together. Also, in some cases, evaluation of existing methods is performed on the same sets of data that were used for development of the method—a practice which can be considered less than objective.

Results of evaluations strongly depend on structure and amount of data available. Proposed consideration of individual subgroups provides valuable additional information. Figure 3 shows that, although methods by Lopez and Fatemi and Li et al. are suitable for all steels, individual results for unalloyed and low-alloy steels are even better.

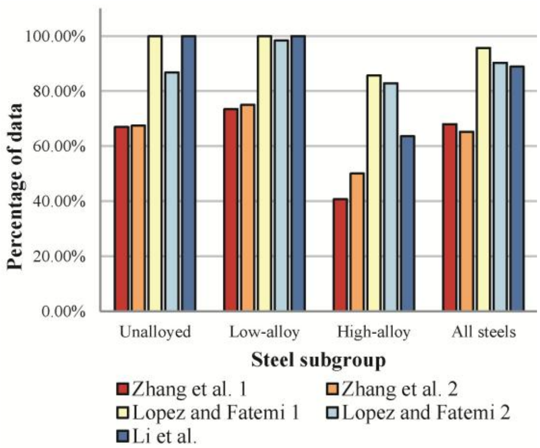

Figure 3. Percentage of estimates of $\Delta\sigma/2$ deviating up to 30% from experimental values.

As mentioned earlier, this was expected since the similar set of data, consisting of mostly unalloyed and low-alloy steels, was used in both papers. If only results for all steels group were observed, information about lower accuracy for high-alloy steels would go unnoticed, particularly for the method by Li et al. This example shows how evaluations of estimation methods performed for all steels together could be misinterpreted due to averaging.

Table 2 provides recommended methods for estimation of cyclic parameters of each group of steels, noting that great care is advised when estimating cyclic parameters of high-alloy steels. Ordinal number preceding the method indicates suggested selection priority. In cases where multiple methods are given without order simpler methods requiring a smaller number of monotonic properties (such as methods by Lopez and Fatemi) might be preferred.

Table 2. Recommended methods for estimation of cyclic yield stress $R_e{'}$ and cyclic parameters K' and n' of steels.

Steel Subgroup	Estimation of $R_e{'}$	Estimation of $\Delta\sigma/2$ (K', n')
Unalloyed steels	Li et al. Lopez and Fatemi 2	1. Li et al. 2. Lopez and Fatemi 1
Low-alloy steels	1. Lopez and Fatemi 1 2. Li et al. 3. Lopez and Fatemi 2	Lopez and Fatemi 1 Lopez and Fatemi 2 Li et al.
High-alloy steels	Lopez and Fatemi 1	Lopez and Fatemi 1

6. Conclusions

Available methods for estimation of cyclic yield stress $R_e{'}$ and cyclic stress-strain parameters K' and n' of steels and their applicability to individual steel subgroups and to steels as a general group were studied. A large, independent set of steel data was collected in order to perform the study as it was shown that number and type of materials used for development of estimation methods have significant influence on their performance and evaluation results.

Statistically significant differences were determined to exist among unalloyed, low-alloy and high-alloy steels regarding their cyclic stress-strain behavior and parameters. Such division of steels based on their content of alloying elements is also commonly encountered in practice, so it was used for performed evaluation of studied estimation methods.

Comparison of values of stress amplitudes $\Delta\sigma/2$ calculated using experimental and estimated cyclic parameters (K' and n') is proposed as a more suitable criterion for evaluation instead of direct comparison of corresponding individual cyclic parameters $R_e{'}$, K' and n'.

Having all steels in a single group for evaluation purposes causes significant averaging of the results so unalloyed, low-alloy and high-alloy steels were treated separately. Considerable differences were determined in accuracy and applicability of different methods for different steel subgroups.

For estimations of $R_e{'}$ of unalloyed and low-alloy steels methods proposed by Li et al. and Lopez and Fatemi were found to provide very good results, while for high-alloy steels, only the method dividing steels by R_e/R_m ratio proposed by Lopez and Fatemi provides reasonably accurate estimates. The method for estimations of K' and n' of unalloyed steels proposed by Li et al. gives the best estimates followed closely by the Lopez and Fatemi method which considers the R_e/R_m ratio. For low-alloy steels, both methods by Lopez and Fatemi and the method by Li et al. provide excellent results. Of all methods, only the method proposed by Lopez and Fatemi considering the R_e/R_m ratio can be considered for use with the high-alloy steels group.

Estimation accuracy of all studied methods for $R_e{'}$, K' and n' was notably lower for high-alloy steels in comparison to other two subgroups, which can be attributed to the fact that high-alloy steels were found to be underrepresented in material datasets used for development of estimation methods.

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Appendix A

Detailed material data used for analysis in this paper are given in Tables A1–A3.

Table A1. Monotonic and cyclic properties for unalloyed steels [6,23,24].

Material Designation	Monotonic Properties									Cyclic Parameters		
DIN or SAE/other	E (MPa)	R_e or $R_{p0.2}$ (MPa)	R_m (MPa)	R_m/R_e (-)	RA (%)	K (MPa)	n (-)	σ_f (MPa)	ε_f (-)	$R_e{}'$ (MPa)	K' (MPa)	n' (-)
1038 (SAE)	207,000	347	610	1.758	55.5	511	0.071	956	0.590	332	1207	0.208
Armco (other)	210,000	207	359	1.734	64	675	0.285	653	1.030	280	858	0.18
C 20	190,000	224	414	1.848	70	330	0.061	953	1.190	239	1050	0.238
C 10	217,510	435	566	1.301	68	659	0.073	1205	1.130	463	1381	0.176
Ck 15	196,793	263	392	1.490	55	711	0.224	746	0.806	249	824	0.193
Ck 15	204,500	320	434	1.356	67.5	394	0.067	848.7	1.126	269	813	0.178
Ck 15	202,000	431.3	615.2	1.426	54	598	0.045	1011.7	0.776	492	1296	0.156
Ck 15	203,000	660	828	1.255	2.6	863	0.042	850.5	0.026	687	1165	0.085
Ck 25	210,000	346	507	1.465	63	926	0.264	1027	0.994	280	1345	0.252
Ck 25	210,000	307	464	1.511	65	924	0.276	982	1.050	278	1111	0.223
Ck 25	210,000	366	527	1.440	60	1033	0.264	997	0.916	303	1217	0.224
Ck 35	210,000	414	617	1.490	58	1216	0.258	1150	0.868	328	1355	0.229
Ck 35	210,000	394	593	1.505	62	1168	0.257	1169	0.968	333	1460	0.238
Ck 35	210,000	396	565	1.427	63	1134	0.264	1134	0.994	316	1534	0.254
Ck 35	210,000	587	780	1.329	67	1356	0.186	1514	1.109	463	1106	0.14
Ck 35	210,000	480	656	1.367	74	1196	0.207	1468	1.347	393	1033	0.156
Ck 35	210,000	596	733	1.230	71	1170	0.152	1541	1.238	447	1027	0.134
Ck 35	210,000	542	730	1.347	68	1311	0.2	1473	1.139	430	1087	0.149
Ck 35	210,000	513	669	1.304	70	1121	0.18	1417	1.204	387	1081	0.165
Ck 45	206,000	540	790	1.463	60	730	0.047	1400	0.916	481	980	0.115
Ck 45	210,500	531	790	1.488	60	1219	0.0151	1271	0.777	462	1078	0.133
Ck 45	199,700	622	915	1.471	59	1606	0.18	1784	0.900	591	2407	0.226
Ck 45	199,700	622	915	1.471	59	1606	0.18	1784	0.900	538	1762	0.191
Ck 45	201,500	380	684	1.800	36.8	735	0.092	987	0.460	336	1414	0.231
Ck 45	205,000	760	1018	1.339	0	1141	0.059	1018	0.000	722	2075	0.17
Ck 45	199,000	466	737	1.582	54	1469	0.248	1296	0.777	368	1486	0.225
Ck 45	207,000	462	672	1.455	61	1288	0.235	1298	0.942	354	1391	0.22
Ck 45	208,000	588	730	1.241	70	1154	0.148	1540	1.204	420	1194	0.168
Ck 45	207,000	551	774	1.405	68	1297	0.166	1559	1.139	464	1235	0.158
Ck 45	206,000	728	844	1.159	64	1208	0.108	1582	1.022	516	1217	0.138
Ck 45	210,000	652	787	1.207	68	1200	0.129	1568	1.139	472	1285	0.161
Ck 45	204,000	702	863	1.229	66	1268	0.118	1651	1.079	526	1243	0.138
St 37	210,000	295	435	1.475	64	829	0.275	835	1.020	273	988	0.207
St 52-3	210,000	400	597	1.493	63	1061	0.225	1083	0.980	389	1228	0.185

Note: Shaded values are calculated by Equation (20).

Table A2. Monotonic and cyclic properties for low-alloy steels [6,23,24].

Material Designation	Monotonic Properties									Cyclic Parameters		
DIN	E (MPa)	R_e or $R_{p0.2}$ (MPa)	R_m (MPa)	R_m/R_e (-)	RA (%)	K (MPa)	n (-)	σ_f (MPa)	ε_f (-)	$R_e{}'$ (MPa)	K' (MPa)	n' (-)
100 Cr 6	207,000	1927	2016	1.046	12	2281	0.031	2230	0.120	1341	3328	0.146
11 NiMnCrMo 55	210,000	745	852	1.144	57	1277	0.124	1327	0.834	663	1145	0.088
14 Mn 5	206,000	580	697	1.202	68	858	0.067	1222	1.150	537	1436	0.158
16 NiCrMo 3 2	209,000	891	939	1.054	63	963	0.011	1491	0.994	617	1080	0.09
17 MnCrMo 33	214,000	833	929	1.115	58	1285	0.099	1446	0.867	663	1252	0.102
20 Mn 3	206,000	910	960	1.055	43	1190	0.06	1090	0.561	675	1313	0.107
22 MnCrNi 3	198,000	1200	1510	1.258	42	2447	0.114	2034	0.549	1046	2149	0.112
22 MnCrNi 3	195,000	1200	1586	1.322	3	2586	0.115	1669	0.026	1193	2759	0.135
23 Mn 4	207,000	1008	1091	1.082	61	1185	0.026	1616	0.950	656	1616	0.145
23 NiCr 4	208,531	725	808	1.114	66	762	0.007	1215	1.080	541	1221	0.131
25 Mn 3	200,000	351	540	1.538	67	992	0.236	1173	1.100	322	1219	0.214
25 Mn 5	207,000	904	1008	1.115	49	1138	0.033	1284	0.680	608	1900	0.183
28 MnCu 6	204,000	330	580	1.758	64	938	0.19	950	1.030	347	1151	0.193
30 CrMo 2	221,000	780	898	1.151	67	1117	0.063	1692	1.120	579	1366	0.138
30 CrMo 2	200,250	1360	1429	1.051	55	1661	0.033	2085	0.790	814	1758	0.124
30 CrMoNiV 5 11	212,000	605	773	1.278	62	717	0.027	1332	0.968	497	894	0.094
30 CrNiMo 8	206,000	700	910	1.300	66	1128	0.079	1168	0.708	573	972	0.085
30 CrNiMo 8	206,000	700	910	1.300	66	1128	0.079	1168	0.708	522	995	0.095
30 MnCr 5	206,000	820	950	1.159	64	1250	0.097	1445	1.068	576	1618	0.166
34 CrMo 4	193,000	1017	1088	1.070	65	1344	0.056	1903	1.050	692	1310	0.103
34 CrMo 4	188,000	847	939	1.109	69	1215	0.074	1795	1.171	624	1008	0.077
34 CrMo 4	190,000	893	978	1.095	67	1338	0.089	1787	1.109	650	987	0.067
34 CrMo 4	197,000	980	1078	1.100	61	1382	0.07	1818	0.942	711	1373	0.106
34 CrMo 4	194,000	780	881	1.129	71	1299	0.116	1740	1.238	556	1198	0.124
4 NiCrMn 4	206,000	454	623	1.372	76	753	0.081	1229	1.450	505	1111	0.127
40 CrMo 4	208,780	840	940	1.119	64	1300	0.094	1440	1.035	583	1307	0.13
40 NiCrMo 6	201,000	1084	1146	1.057	59	1549	0.083	1857	0.890	758	1550	0.115
40 NiCrMo 6	190,000	910	1015	1.115	62	1372	0.089	1808	0.970	660	1392	0.12
40 NiCrMo 6	202,000	953	1029	1.080	62	1448	0.1	1724	0.970	659	1628	0.145
40 NiCrMo 6	193,000	998	1067	1.069	62	1474	0.092	1761	0.970	716	1292	0.095
40 NiCrMo 6	205,000	810	884	1.091	67	1378	0.142	1680	1.110	586	1303	0.129
40 NiCrMo 7	193,500	1374	1471	1.071	38	1796	0.04	1920	0.480	905	1890	0.118
40 NiCrMo 7	193,500	635	829	1.306	43	1175	0.098	1201	0.570	474	1332	0.167
41 MnCr 3 4	207,280	800	930	1.163	62	1350	0.112	1390	0.960	551	1340	0.143
42 Cr 4	195,000	903	1006	1.114	62	1293	0.068	1716	0.968	679	1153	0.085
42 Cr 4	194,000	813	921	1.133	65	1249	0.086	1674	1.050	613	1147	0.101
42 Cr 4	194,000	845	952	1.127	62	1288	0.086	1689	0.968	619	1207	0.107
42 Cr 4	192,000	833	943	1.132	65	1289	0.09	1690	1.050	621	1192	0.105
42 Cr 4	193,000	717	840	1.172	69	1240	0.118	1617	1.171	543	1161	0.122
42 CrMo 4	211,400	998	1111	1.113	60	1469	0.069	1525	0.496	716	1367	0.104
49 MnVS 3	210,200	566	840	1.484	19	1428	0.194	1152	0.380	520	1396	0.159
50 CrMo 4	205,000	970	1086	1.120	48.6	1132	0.026	1609	0.665	700	1568	0.13
50 CrMo 4	205,000	947	983	1.038	14.6	1042	0.018	926	0.157	774	1754	0.132
8 Mn 6	198,000	862	965	1.119	57	1227	0.054	1579	0.850	580	1256	0.125
8 Mn 6	198,000	821	869	1.058	53	1085	0.046	1434	0.750	674	1258	0.101
80 Mn 4	187,500	502	931	1.855	16	1100	0.127	1060	0.174	459	1859	0.225
WStE 460	210,000	560	667	1.191	61	1096	0.153	1171	0.932	514	1194	0.128

Table A3. Monotonic and cyclic properties for high-alloy steels [6,23,24].

Material Designation	Monotonic Properties									Cyclic Parameters		
DIN	E (MPa)	R_e or $R_{p0.2}$ (MPa)	R_m (MPa)	R_m/R_e (-)	RA (%])	K (MPa)	n (-)	σ_f (MPa)	ε_f (-)	$R_e{}'$ (MPa)	K' (MPa)	n' (-)
X 10 CrNi 18 8	204,000	245	635	2.592	79	1416	0.362	1908	1.563	307	2397	0.331
X 10 CrNiNb 18 9	210,000	237	615	2.595	72			1398	1.273	271	1967	0.319
X 10 CrNiNb 18 9	210,000	237	615	2.595	72			1398	1.273	276	1667	0.289
X 10 CrNiTi 18 9	210,000	211	677	3.209	67			1428	1.109	455	8384	0.469
X 10 CrNiTi 18 9	210,000	182	668	3.670	68			1429	1.139	414	6179	0.435
X 10 CrNiTi 18 9	210,000	211	677	3.209	69			1470	1.171	496	3647	0.321
X 10 CrNiTi 18 9	210,000	177	516	2.915	74			1211	1.347	220	2264	0.375
X 10 CrNiTi 18 9	210,000	177	516	2.915	74			1211	1.347	250	1535	0.292
X 10 CrNiTi 18 9	210,000	214	529	2.472	74			1242	1.347	228	2086	0.357
X 10 CrNiTi 18 9	210,000	214	529	2.472	74			1242	1.347	251	1682	0.306
X 10 CrNiTi 18 9	210,000	177	535	3.023	77			1321	1.470	220	3080	0.424
X 10 CrNiTi 18 9	210,000	177	535	3.023	77			1321	1.470	241	2097	0.348
X 15 Cr 13	210,000	598	736	1.231	70			1622	1.204	475	1056	0.128
X 15 Cr 13	210,000	598	736	1.231	70			1622	1.204	497	987	0.11
X 15 CrNiSi 25 20	210,000	271	630	2.325	69			1368	1.171	289	2302	0.334
X 15 CrNiSi 25 20	210,000	271	630	2.325	69			1368	1.171	284	2242	0.332
X 2 CrNi 18 9	192,000	280	601	2.146	46	455	0.097	971	0.616	207	2807	0.419
X 20 CrMo 12 1	210,000	795	1013	1.274	47			1656	0.635	716	1325	0.099
X 20 CrMo 12 1	210,000	795	1013	1.274	47			1656	0.635	730	1301	0.093
X 25 CrNiMn 25 20	193,340	220	642	2.918	63	754	0.228	1360	1.010	421	2267	0.271
X 3 CrNi 19 9	172,625	746	953	1.277	69	1114	0.063	2037	1.160	882	2313	0.155
X 3 CrNi 19 9	186,435	255	746	2.925	74	548	0.136	1920	1.370	678	4634	0.309
X 5 CrNi 18 9	210,000	207	611	2.952	75			1458	1.386	197	3331	0.455
X 5 CrNi 18 9	210,000	207	611	2.952	83			1694	1.772	203	3001	0.434
X 5 CrNiMo 18 10	210,000	230	587	2.552	78			1476	1.514	256	1644	0.299
X 5 CrNiMo 18 10	210,000	231	587	2.541	78			1476	1.514	247	2755	0.388
X 5 CrNiMo 18 10	210,000	257	606	2.358	79			1830	1.561	313	2000	0.298
X 5 CrNiMo 18 10	210,000	228	665	2.917	81			1769	1.661	259	2081	0.336
X 5 CrNiMo 18 10	210,000	228	665	2.917	81			1769	1.661	259	2674	0.376
X 5 NiCrTi 26 15	210,000	777	1158	1.490	52			2008	0.734	713	1617	0.132
X 5 NiCrTi 26 15	210,000	777	1158	1.490	52			2008	0.734	711	1543	0.125
X 6 CrNi 19 11	183,000	325	650	2.000	80	1210	0.193	1400	1.610	267	1628	0.291
X 8 CrNiTi 18 10	204,000	222	569	2.563	76	349	0.062	1381	1.427	383	5234	0.421
X2 CrNiMo 18 10	210,000	373	700	1.877	75			1670	1.386	295	1232	0.23
X5 CrNi 18 9	198,000	242	666	2.752	82	484	0.113	2407	1.715	275	2872	0.378

Note: Shaded values are calculated by Equations (8) and (20).

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