A GENERALIZATION OF THE FATIGUE KOHOUT-VĚCHET MODEL FOR SEVERAL FATIGUE DAMAGE PARAMETERS

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ABSTRACT

A new proposal of generalization of the fatigue Kohout-Věchet (KV) model for different fatigue damage parameters is proposed. The purpose of this generalized model is to describe all fatigue regimes from very low-cycle fatigue (VLCF) to very high-cycle fatigue (VHCF), and accounting for several fatigue damage parameters, such as, strain parameter, Smith-Watson-Topper (SWT) parameter, Walker-like strain parameter, energy-based parameter in uniaxial loading conditions, among others. The full range of fatigue life responses for all loading regimes of materials and structural components are extremely important in the fatigue design. Engineering structures are subjected to different types of loading that cause fatigue failure. These loadings can range from quasi-static monotonic loading to long term dynamic/cyclic loading. In this paper, a proposal of generalization of the KV model for several fatigue damage parameters was verified and compared with experimental fatigue results under uniaxial loading conditions available in literature. This study validates the importance and applicability of full range fatigue life models for different damage parameters in fatigue life prediction of materials and structural components.

KEYWORDS: Fatigue; Wöhler Curve; Fatigue Damage Parameter; Kohout-Věchet Model.

1. INTRODUCTION

The engineering design of steel structures subjected to fatigue loadings is done taking into account fatigue design codes, such as the EN 1993-1-9 standard [1] developed by European Committee for Standardization that is used in design of steel structures, the BS5400 standard [2] applied in the design of steel, concrete and composite bridges and the BS7910 standard [3] used to fatigue life assessments, the latter two developed by the British Standards Institution, and the AASHTO specifications [4] recommended by the American Association of State Highway and Transportation Officials. Other standards for engineering design of offshore steel structures and shipping as DNVGL-RP-0005:2014-06 and GD-09-2013 [5,6] were proposed by DNV GL Group and China Classification Society, respectively. The American Bureau of Shipping has also proposed standards for offshore and ship structures design [7]. The European Committee for Standardization (CEN) also proposed the BS EN 13445-3:2009 standard [8] for the fatigue design of unfired pressure vessels. Many other standards have been proposed worldwide for fatigue design for various engineering applications.

In the design codes, the fatigue Wohler's or *S-N* curves have been proposed to describe the materials and structural details fatigue behaviour. The *S-N* curves originally proposed by Basquin [9,10] and adopted in the design codes [1,2,4], is given by following expression:

$$\Delta\sigma \cdot N^{m} = C \tag{1}$$

where C and m are material constants. The mean *S-N* curves may be described by a linear regression analysis using the following linear model [10,11]:

$$Y = A + B \cdot X \tag{2}$$

where Y is the dependent variable defined as $Log(N_f)$, X is the independent variable defined as $Log(\Delta\sigma)$, A and B are linear regression parameters. Equation (2) can be rewritten in the following alternative forms [10,11]:

$$\begin{cases} \log(N_f) = A + B \cdot \log(\Delta\sigma) \\ \log(\Delta\sigma) = -\dfrac{A}{B} + \dfrac{1}{B} \cdot \log(N_f) \end{cases} \tag{3}$$

where A and B are linear regression parameters related with the C and m constants:

$$\begin{cases} C = 10^{A} \\ m = -B \end{cases}. \tag{4}$$

Usually, mechanical engineering structures are designed for high- (HCF) and low-cycle fatigue (LCF) regimes. Civil engineering structures such as, railway and road bridges, offshore and onshore structures, logistics structures, among others, are designed for high-cycle fatigue (HCF) regime. Recently, a number of failures of these structures cannot be explained only with the HCF regime taking into account the extreme loading conditions to which the structural elements are subject (e.g. earthquakes). Recent studies suggest the use of *S-N* or *ε-N* curves considering both LCF and HCF regimes [12-22].

The full-range *S-N* curve based on stress damage parameter, proposed by Kohout and Věchet has been increasingly used in the fatigue life evaluation of existing bridges structures [9,23,24]. Materials and structural details representative of steel bridges may under special circumstances be subjected the different loadings from quasi-static monotonic loading (very-low-cycle and low-cycle (LCF) fatigue regimes) to high cyclic fatigue (HCF). The Kohout-Věchet (KV) fatigue model covers all fatigue regimes, LCF and HCF regimes [9,23,24]. So, this model describes the region of cycles from tensile strength to permanent fatigue limit [9,23,24], see Figure 1. The KV fatigue model is expressed by the following relation:

$$\sigma(N) = a\left[\frac{(N+B)C}{N+C}\right]^b \equiv \sigma_\infty\left(\frac{N+B}{N+C}\right)^b \equiv \sigma_1\left(\frac{1+N/B}{1+N/C}\right)^b \tag{5}$$

where, a and b are the Basquin parameters, σ_∞ is the fatigue limit, σ_1 is the ultimate tensile strength, B is the number of cycles corresponding to the intersection of the tangent line of the finite life region and the horizontal asymptote of the ultimate tensile strength, and C is the number of cycles corresponding to the intersection of the tangent line of the finite life region and the horizontal asymptote of the fatigue limit. B and C parameters are given by:

$$C = 10^7 \cdot \frac{1-\gamma}{\gamma-\beta} \tag{6}$$

$$B = \beta \cdot C \tag{7}$$

where β and γ are defined as:

$$\beta = \left(\frac{\sigma_1}{\sigma_\infty}\right)^{1/b} \ and \ \gamma = \left(\frac{\sigma_c}{\sigma_\infty}\right)^{1/b}. \tag{8}$$

σ_c is the fatigue limit for a pre-defined number of cycles (10^7).

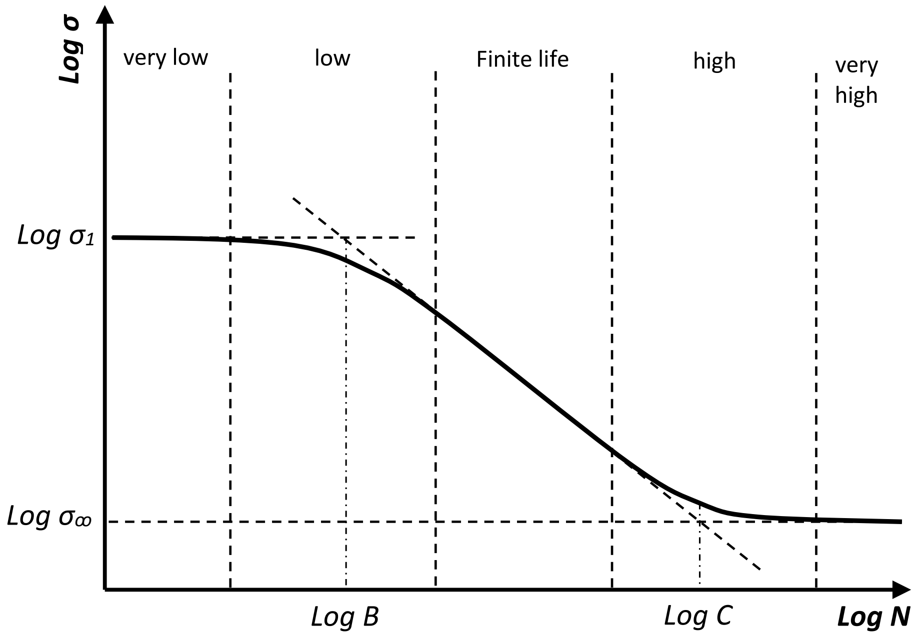


Figure 1. Schematic representation of the Kohout-Věchet stress-life curve [1].

Other authors, such as, Lemaitre and Chaboche [25] proposed an analytical expression for the *S-N* curves taking into account the mean stress effects. A new strain-life model was proposed by Karunananda et al. [14] based on the assumptions of the KV model. This model was used to estimate the fatigue life of a member bridge under regular traffic and exceptional seismic loads.

A further steep in the generalization of the Kohout-Věchet fatigue model is proposed in this study for several fatigue damage variables, including stress, strain and energy based variables. The KV fatigue model that originally was formulated according a stress damage parameter was transformed by Karunananda et al. [14] using a strain based fatigue damage parameter. In this study and following previous developments, a generalization of the fatigue model suggested by Kohout and Věchet [9] is performed using the Smith-Watson-Topper (SWT) parameter, a Walker-like strain parameter and an energy-based parameter in uniaxial loading conditions. This generalized KV fatigue model is applied to available fatigue data from stress and strain-controlled tests of smooth specimens, such as, the P355NL1 pressure vessel steel [26-31], and old steels [32-36] from the Trezói bridge. In this analysis, experimental fatigue results ranging from the short-term fatigue domain to the long-term fatigue domain are used. This study proves the importance of correctly describing the full-range KV fatigue curves, based on several fatigue damage parameters, in the fatigue life prediction of materials and notched details of engineering structures.

2. GENERALIZATION OF THE FATIGUE KOHOUT-VĚCHET MODEL

This section describes the proposal of generalization of the fatigue Kohout-Věchet (KV) model for different fatigue damage variables, such as, Smith-Watson-Topper (SWT) damage parameter [37], Walker-like strain damage parameter [38-42], and energy-based damage parameter [43-47]. All these fatigue damage parameters relate with the number of cycles to failure according a generic power law function. Figure 2 shows that characteristic power-law function as suggested by Correia et al. [48] for several fatigue damage parameters:

$$\psi = \kappa\left(2N_f\right)^{\alpha} + \psi_0 \tag{9}$$

where ψ represents a fatigue damage parameter, ψ_0 is a fatigue endurance limit, κ and α are material constants [43].

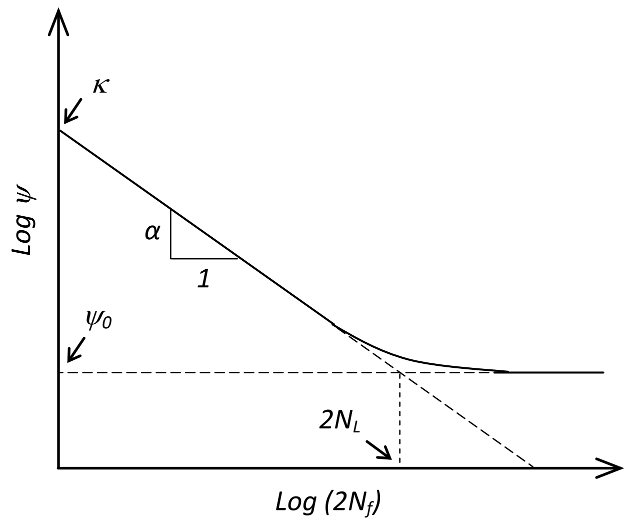


Figure 2. Schematic illustration of the deterministic power-law fatigue failure criterion.

The generalization of the KV model is based on the hypothetical ultimate strain/energy requirement for damage parameters, which was proposed by Karunananda et al. [14] taking into account the original version of the fatigue KV model [9]. The known fatigue Kohout-Věchet function is based on the stress damage parameter. The geometrical shape of the KV function covers the range of fatigue data from low-cycle fatigue region to high-cycle fatigue region. A generalization of the Kohout-Věchet fatigue model for several fatigue damage parameters (ψ), such as, stress-, strain- and energy-based parameters, in uniaxial loading conditions, can be given by the following equation (see Figure 3):

$$\psi(N) = \psi_{\mathrm{e}} \left(\frac{N + N_u}{N + N_e}\right)^{b'} \equiv \psi^{ULCF} \left[\frac{(N + N_u)N_e}{N + N_e}\right]^{b'} \equiv \psi^{UHCF} \left(\frac{1 + N/N_u}{1 + N/N_e}\right)^{b'} \tag{10}$$

where ψ_{e} is the limit fatigue damage parameter, ψ^{ULCF} is the ultimate fatigue damage parameter for the low-cycle fatigue regime, and ψ^{UHCF} is the ultimate fatigue damage parameter for the high-cycle fatigue regime. The ψ^{ULCF} parameter can be obtained by Equation (9), where $\psi^{ULCF} = \kappa$.

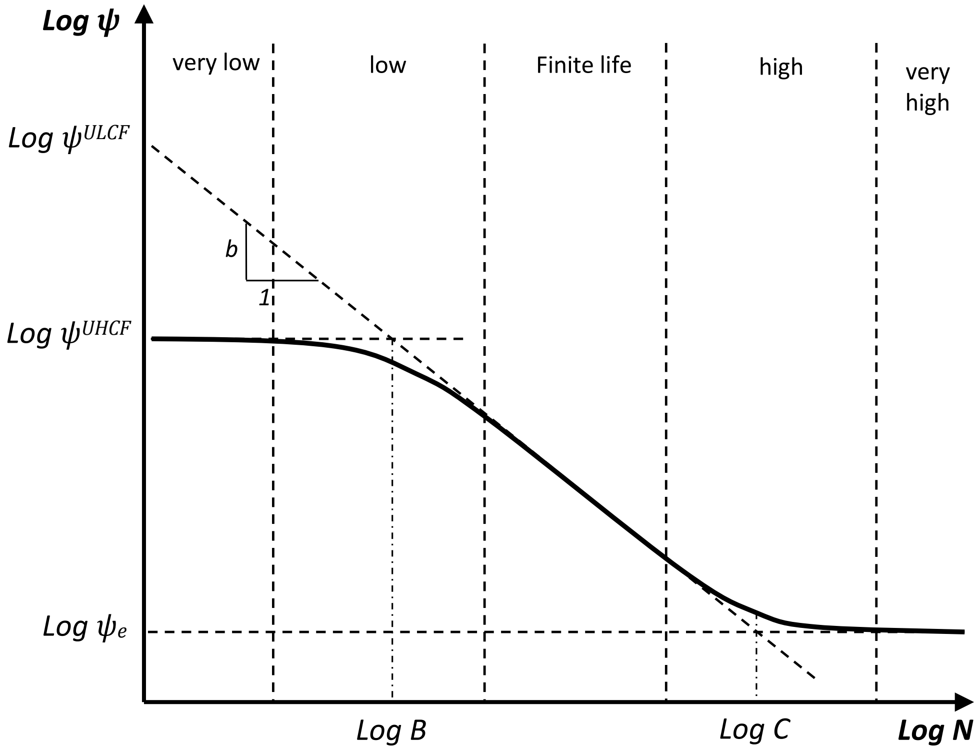


Figure 3. Schematic representation of a generalization of the Kohout-Věchet model for several fatigue damage parameters in uniaxial loading conditions.

2.1. Combined high and low-cycle fatigue model based on strain damage parameter

The combination of the HCF and LCF regimes in the KV model using the total strain range amplitude, $\Delta\varepsilon/2$, considered fatigue damage variable was proposed by Karunananda et al. [14]. This new proposed model is composed by two parts. The first part is related to the strain-life curve (see Figure 4) proposed by Coffin and Manson [49,50] for fatigue damage under elastoplastic conditions ($\varepsilon_a \geq \varepsilon_y$), as shown in the following expression:

$$\varepsilon_a = \varepsilon_a^E + \varepsilon_a^P = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c \tag{11}$$

where ε_a is the total strain amplitude, ε_a^E is the elastic strain amplitude, ε_a^P is the plastic strain amplitude, N_f is the number of cycle to failure, σ_f' is the fatigue strength coefficient, E is the elastic modulus, b is the fatigue strength exponent, ε_f' is the fatigue ductility coefficient, and c is the fatigue ductility exponent. An analysis of the ultimate strain for LCF regime can be made by considering $N_f = 0.5$, taking into account that the elastic strain amplitude is very small compared to the plastic strain amplitude. Under this conditions the ultimate strain for the low cycle fatigue regime is given by:

$$\varepsilon_a^{ULCF} = \varepsilon_f'. \tag{12}$$

The total strain amplitude, ε_a, is composed by the plastic strain amplitude, ε_a^P, which is equal to ε_a^{ULCF}. The second part of the curve presents the fatigue life for elastic strain amplitude cycles that is related to HCF regime ($\varepsilon_a < \varepsilon_y$). This part of the curve represents a hypothetical strain-life curve with the same shape of the fully stress-life curve proposed by Kohout and Věchet [9]. A new model of total strain-life curve was proposed by Karunananda et al. [14] based on the assumptions of the KV model and expressed as:

$$\varepsilon(N) = \varepsilon_e \left(\frac{N + N_u}{N + N_e}\right)^{b'} \tag{13}$$

where ε_e is the strain amplitude at the fatigue limit, N_e is the number of cycles to failure at the strain ε_e, N_u is the number of cycles corresponding to the intersection of the tangent line of the finite life region and the horizontal asymptote of the ultimate elastic strain ε^{UHCF}, and b' is the slope of the finite life region. ε_{UHCF} is the ultimate high cycle fatigue strain which is the elastic strain corresponding to an half of cycle and is expressed as:

$$\varepsilon^{UHCF} = \left(\frac{\sigma_u}{E}\right) \tag{14}$$

where σ_u is the ultimate tensile strength of the material. ε^{UHCF}can be obtained from a monotonic tension test of the material. Figure 4 shows the schematic representation of the strain-life fatigue curve that was proposed by Karunananda et al. [14].

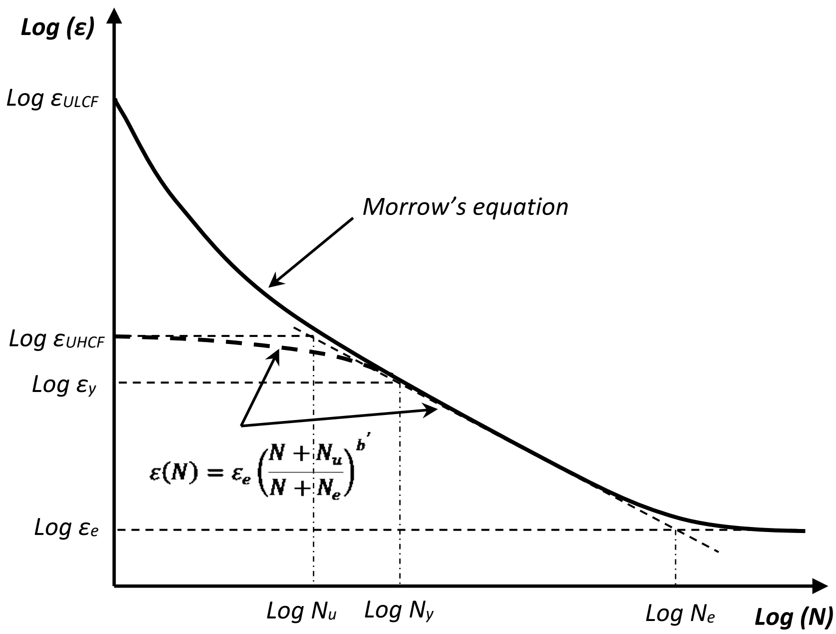


Figure 4. Schematic representation of the strain-life curve proposed by Karunananda et al. [14].

The consideration made around the parameter ε^{UHCF} by Karunananda et al. [14] can be modified based on the Ramberg-Osgood description [51] using appropriately the monotonic properties of the material:

$$\varepsilon^{UHCF} = \frac{\sigma_u}{E} + \left(\frac{\sigma_u}{K}\right)^{1/n} \tag{15}$$

where, E is the Young modulus, K and n are, respectively, the monotonic strain hardening coefficient and exponent. The combined fatigue law or KV-like fatigue model based on strain parameter can be rewritten in the following forms:

$$\varepsilon(N) = \varepsilon_e \left(\frac{N+N_u}{N+N_e}\right)^{b'} \equiv \varepsilon^{ULCF} \left[\frac{(N+N_u)N_e}{N+N_e}\right]^{b'} \equiv \varepsilon^{UHCF} \left(\frac{1+N/N_u}{1+N/N_e}\right)^{b'}. \tag{16}$$

Alternatively, the parameters of the generalized KV model can be obtained using the single power damage relation presented in Equation (9), where the b' and ε^{ULCF} parameters are respectively, $\alpha(= b')$ and $\kappa(= \varepsilon^{UHCF})$ parameters.

2.2. Generalization of the fatigue Kohout-Věchet model for several damage parameters in uniaxial loading conditions

2.2.1. Walker-like strain parameter

The combined high and low-cycle fatigue model based on strain damage parameter that was proposed by Karunananda et al. [14] can be extended for the Walker-like strain parameter 38-42] allowing for mean-stress effects. The strain-life fatigue model using this parameter is given by following relation:

$$\varepsilon_a\left(\frac{2}{1-R}\right)^{1-\gamma} = \frac{\sigma'_{fw}}{E}\left(2N_f\right)^{b_w} + \varepsilon'_{fw}\left(2N_f\right)^{c_w}\cdot\left(\frac{1-R}{2}\right)^{(c_w/b_w-1)(1-\gamma)} \quad (17)$$

where σ'_{fw}, ε'_{fw}, b_w and c_w are material parameters and γ is called the Walker fitting constant. Based on the combined HCF and LCF fatigue model proposed by Karunananda et al. [14] using the assumptions of the fatigue KV model, a new version can be presented using the Walker-like strain parameter:

$$\varepsilon_w(N) = \varepsilon_{w,e}\left(\frac{N+N_u}{N+N_e}\right)^{b'} \quad (18)$$

where the Walker-like strain damage variable, ε_w, is given by

$$\varepsilon_w = \varepsilon_a\left(\frac{2}{1-R}\right)^{1-\hat{\gamma}}. \quad (19)$$

In this sense, an adaptation of the combined HCF and LCF model proposed by Karunananda et al. [14] can be made using the same assumptions. Thus, the ultimate Walker-like plastic strain amplitude for the low cycle fatigue regime, ε_w^{ULCF} is given by following relations, respectively:

$$\varepsilon_w^{ULCF} = \varepsilon'_f\cdot\left(\frac{1-R}{2}\right)^{(c_w/b_w-1)(1-\gamma)}. \quad (20)$$

The strain-life fatigue model using Walker-life strain damage variable and taking into account the assumptions of the fatigue KV model can be rewritten as follows:

$$\varepsilon_w(N) = \varepsilon_{w,e}\left(\frac{N+N_u}{N+N_e}\right)^{b'} \equiv \varepsilon_w^{ULCF}\left[\frac{(N+N_u)N_e}{N+N_e}\right]^{b'} \equiv \varepsilon_w^{UHCF}\left(\frac{1+N/N_u}{1+N/N_e}\right)^{b'}. \quad (21)$$

The ultimate Walker-like strain for the high cycle fatigue regime, ε_w^{UHCF} takes the same value of ε^{UHCF} and is given by Equations (14) or (15).

The same assumption presented in sub-section 3.1, related to the use of the single power damage relation (Eq. 9), can be considered to estimate the b' and ε_w^{ULCF} parameters. These parameters are given in Equation (9) as $\alpha = b'$ and $\kappa = \varepsilon_w^{ULCF}$.

2.2.2. Smith-Watson-Topper (SWT) damage parameter

Smith, Watson and Topper proposed a fatigue damage parameter [37] that is known as SWT, to account for mean stress effects, updating the Morrow and Coffin-Manson strain-life fatigue model [49,50,52] which is given by the following expression:

$$\sigma_{max} \cdot \varepsilon_a = SWT = \left(\sigma_f'\right)^2 \cdot \left(2N_f\right)^{2b} / E + \sigma_f' \cdot \varepsilon_f' \cdot \left(2N_f\right)^{b+c} \quad (22)$$

where σ_{max} is the maximum stress of the stress cycle.

A generalization of the Kohout-Věchet fatigue model [9] can be done considering the SWT fatigue damage parameter and using the same assumptions that were proposed by Karunananda et al. [14]. The adapted KV fatigue model using the SWT parameter is given by following expression:

$$SWT(N) = SWT_e \left(\frac{N + N_u}{N + N_e}\right)^{b'} \equiv SWT^{ULCF} \left[\frac{(N + N_u)N_e}{N + N_e}\right]^{b'} \equiv SWT^{UHCF} \left(\frac{1 + N/N_u}{1 + N/N_e}\right)^{b'} \quad (23)$$

where SWT_e is the fatigue limit damage parameter, N_e is the number of cycles to failure for the SWT_e parameter, N_u is the number of cycles corresponding to the intersection of the tangent line of the finite life region and the horizontal asymptote of the ultimate high-cycle fatigue SWT parameter, SWT^{UHCF}, and b' is the slope of the finite life region. The ultimate low-cycle fatigue SWT parameter, SWT^{ULCF}, which corresponds to the plastic component of the Smith-Watson-Topper (SWT) relation, considering that the elastic component is very small compared to the plastic component for a half of cycle, is obtained using the following expression:

$$SWT^{ULCF} = \sigma_{max}^{ULCF} \cdot \varepsilon^{ULCF} = \sigma_f' \cdot \varepsilon_f' \quad (24)$$

SWT^{UHCF} is the ultimate high-cycle fatigue SWT parameter which corresponds to the elastic component of an half of cycle and is expressed as:

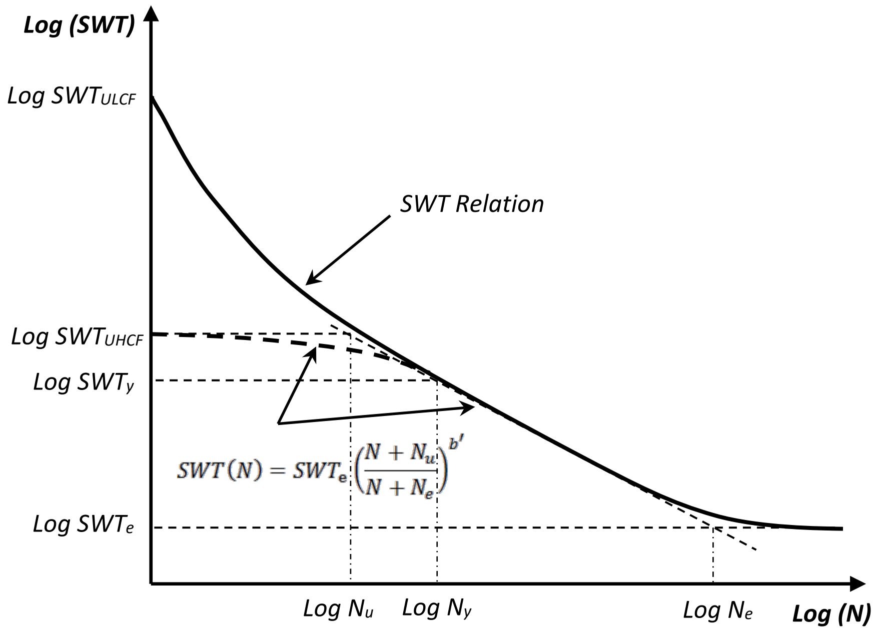
$$SWT^{UHCF} = \frac{1}{2} \cdot \sigma_{max}^{UHCF} \cdot \varepsilon^{UHCF} = \frac{1}{2} \cdot \sigma_u \cdot \left(\frac{\sigma_u}{E}\right) = \frac{(\sigma_u)^2}{2E} \quad (25)$$

where σ_u is the ultimate tensile strength of the material. The SWT^{UHCF} parameter using the Ramberg-Osgood description [51] for the monotonic $\sigma - \varepsilon$ curve, can be given by:

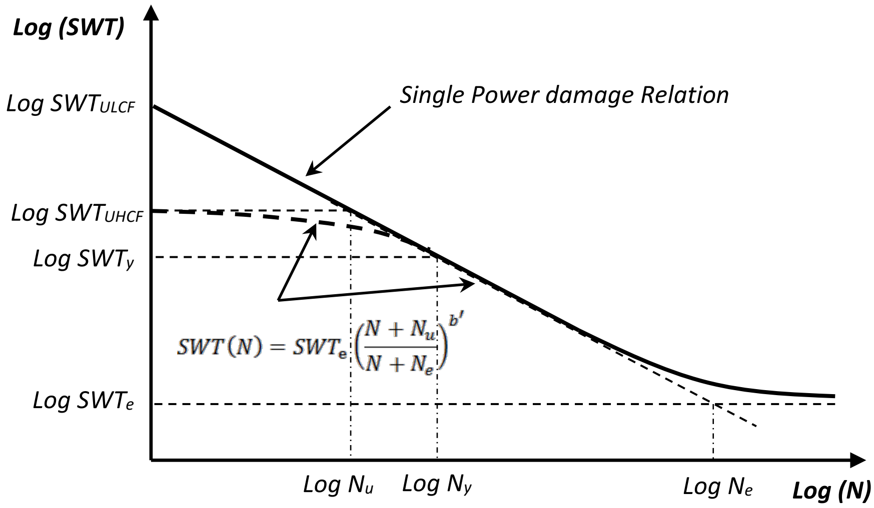
$$SWT^{UHCF} = SWT_{el}^{UHCF} + SWT_{pl}^{UHCF} = \frac{1}{2} \cdot \sigma_{max}^{UHCF} \cdot \varepsilon_{el}^{UHCF} + \frac{\sigma_{max}^{UHCF} \cdot \varepsilon_{pl}^{UHCF}}{(n + 1)} \quad (26)$$

where, SWT_{el}^{UHCF} and SWT_{pl}^{UHCF} are, respectively, elastic and plastic components of the total strain energy that corresponds to the area of the monotonic $\sigma - \varepsilon$ curve. Alternatively, the b' and SWT^{ULCF} parameters can be determined by adjusting Eq. (9) to the experimental results.

Figure 5 shows the schematic representation of the Kohout-Věchet model for SWT fatigue damage parameter based on single power damage relation (Fig. 5b) and SWT model (Fig. 5a) that is proposed in this research. This model is more complete than the combined HCF and LCF model (proposed by Karunananda et al. [14]) based on the KV model by the fact that it accounts for the mean stress effect of the materials.



a) SWT fatigue damage relation.



b) Single power damage model

Figure 5. Schematic representation of the generalised Kohout-Věchet model for *SWT* damage parameter.

2.2.3. Energy-based damage parameter

The energy-based damage parameters were developed for elastoplastic stress-strain conditions, using the strain energy associated to stress-strain hysteresis loops. Studies conducted by Halford [53] determined that for a wide variety of materials, the total absorbed energy at the moment of fracture is dependent on the numbers of cycles. In his remarks, Halford [53] assumed the hypothesis of a total fracture energy dependent of the total number of cycles. Ellyin and Kujawski [44,45] proposed the use of the total strain energy range per reversal to unify the description of the low- and high-cycle fatigue behaviours. Others authors such as Golos and Ellyin [46,47] suggested an alternative energetic parameter sensitive to the mean stress. These last authors proposed an alternative version of the total strain energy range, ΔW_t. This energetic parameter associated with the tensile stress proposed by Golos and Ellyin [46,47] results of the superposition of the plastic strain energy range, ΔW_p, computed assuming a Masing material behaviour, with the elastic strain energy range, ΔW_e^+, which is given by the following expression:

$$\Delta W_t = \Delta W_e^+ + \Delta W_p = \frac{1}{2E}\left(\frac{\Delta\sigma}{2} + \sigma_m\right)^2 + \frac{1-n'}{1+n'}\cdot\Delta\sigma\Delta\varepsilon^P \tag{27}$$

where $\Delta\sigma$ is the stress range, n' is the cyclic strain-hardening exponent, and E is the elastic modulus. For a non-Masing material, the plastic strain energy range, ΔW_p, associated to a load cycle, is given by

$$\Delta W_p = \frac{1-n^*}{1+n^*}\cdot\Delta\sigma\Delta\varepsilon^P + \frac{n^*}{1+n^*}\cdot\delta\sigma_0\Delta\varepsilon^P \tag{28}$$

where $\delta\sigma_0$ is the increase of the proportional limit stress.

An expression based on Morrow's relation using the total strain energy range, ΔW_t, as fatigue damage criteria (see Fig. 6a), was adopted by Correia et al. [48]:

$$\Delta W^t = \kappa_P\left(2N_f\right)^{\alpha_P} + \kappa_E\left(2N_f\right)^{\alpha_E} \tag{29}$$

where $\alpha_i < 0$ and $\kappa_i > 0, i = P, E$ are material constants.

Using this energetic damage parameter in Equation (10), an adaptation of the fatigue KV model is given by the following relation (see Fig. 6):

$$\Delta W_t(N) = \Delta W_e\left(\frac{N+N_u}{N+N_e}\right)^{b'} \equiv \Delta W^{ULCF}\left[\frac{(N+N_u)N_e}{N+N_e}\right]^{b'} \equiv \Delta W^{UHCF}\left(\frac{1+N/N_u}{1+N/N_e}\right)^{b'} \tag{30}$$

where, ΔW_e is the fatigue limit energetic parameter, ΔW^{ULCF} and ΔW^{UHCF} are, respectively, the low-cycle and high-cycle ultimate fatigue energetic parameters.

The ΔW^{ULCF} parameter corresponds to the plastic component of the strain energy range for a half cycle, considering that the elastic component is negligible:

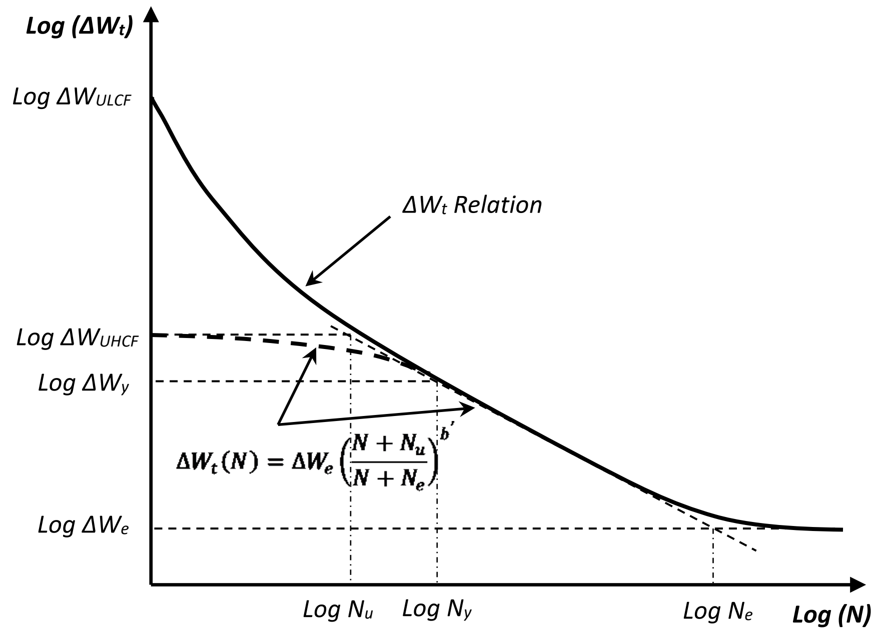
$$\Delta W^{ULCF} = \kappa_P. \tag{31}$$

The ΔW^{UHCF} parameter using the Ramberg-Osgood description [51] for the monotonic $\sigma - \varepsilon$ curve of the material, is expressed as

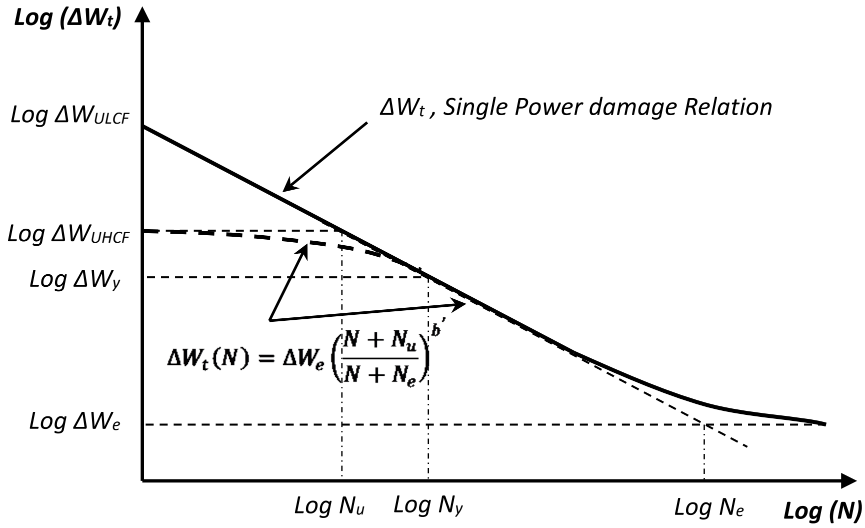
$$\Delta W^{UHCF} = \frac{1}{2} \cdot \sigma_{max}^{UHCF} \cdot \varepsilon_{el}^{UHCF} + \frac{\sigma_{max}^{UHCF} \cdot \varepsilon_{pl}^{UHCF}}{(n+1)}. \tag{32}$$

This equation is the same as Eq. (26) proposed for the SWT^{UHCF} parameter. The SWT fatigue damage parameter is an implicit energetic parameter and can be considered as a simplification of the Walker-like damage parameter when γ is equal 0.5 [41].

Instead, it can be used the single power damage relation to estimate the b' and ΔW^{ULCF} parameters. Figure 6b) presents the single power damage relation and generalized fatigue KV model for the energy-based damage parameters. The single power model can be used as alternative to the combined power damage model (energetic damage model) in evaluation of the parameters of the generalized fatigue KV model.



a) Combined power damage model



b) Single power damage model

Figure 6. Schematic representation of generalised Kohout-Věchet model for ΔW_t damage parameter.

3. RESULTS AND DISCUSSION

In this section, the generalization proposal of the fatigue KV fatigue model for several fatigue damage variables is applied to the experimental fatigue data from smooth specimens tests made of P355NL1 pressure vessel steel [26-31], and old steels [32-36] from the Trezói bridge. Several fatigue damage variables, such as, stress-, strain-, SWT- and energy-based damage parameters are used in this study. A comparison between the generalized fatigue KV model and combined HCF and LCF fatigue model proposed by Karunananda et al. [14] for strain fatigue damage parameter is presented.

3.1. Stress based fatigue damage parameter

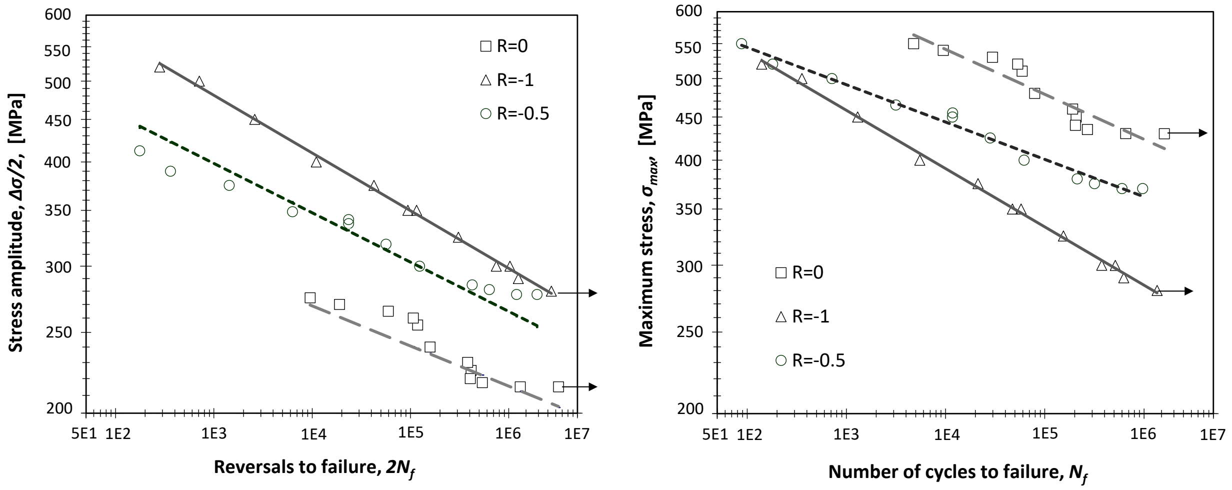
In this sub-section, an application of the Kohout-Věchet model to the P355NL1 steel under uniaxial stress is presented. The mechanical properties of the P355NL1 steel are presented in Table 1 and are used in this analysis. Three series of fatigue tests of smooth specimens covering three distinct stress ratios, namely, $\boldsymbol{R_\sigma = 0}$, $\boldsymbol{R_\sigma = -0.5}$, and $\boldsymbol{R_\sigma = -1}$, were carried out under stress-controlled conditions. Figures 7a) and 7b) show fatigue results in the form of stress amplitude vs. reversals to failure and maximum stress vs. number of cycles to failure, respectively. The mean stress effects on the fatigue resistance is not explicitly but implicitly shown in the stress ratio, $\boldsymbol{R_\sigma}$. For a constant stress amplitude, the mean stress increases with the stress ratio. This observation allows to verify the mean stress effects on the fatigue strength of the P355NL1 steel. All curves were obtained through a linear regression on the experimental data, represented in bi-logarithmic graphs. All points with infinite life were excluded from the regression. The parameters of the Basquin equation were estimated using the following relation:

$$\sigma = a \cdot N^b \tag{33}$$

where, $\boldsymbol{a}$ and $\boldsymbol{b}$ are parameters of the Basquin equation, which are respectively, the tangent in the point of inflexion for $\boldsymbol{N = 1}$, and slope of the linear regression. Table 2 presents the Basquin parameters, $\boldsymbol{a}$ and $\boldsymbol{b}$, for the various stress ratios under consideration in this study. Other important data that can be extracted from the analysis of the *S*-*N* curves are the fatigue limit stresses. In the present analysis, the fatigue stresses leading to fatigue life of $\mathbf{1 \times 10^6}$ cycles were established as fatigue limit stresses. The estimation of these stresses was made taking into consideration the *S*-*N* curves from the direct fitting to the experimental results (see Table 2). Table 3 summarizes the fatigue limit stresses obtained for the P355NL1 steel.

Table 1. Mechanical properties of the P355NL1 steel [26-31].

Ultimate tensile strength, σ_{UTS} [MPa]	568
Monotonic yield strength, σ_y [MPa]	418
Young's modulus, *E* [GPa]	205.2
Strain hardening coefficient, *K* [MPa]	611.46
Strain hardening exponent, *n* [-]	0.063
Poisson's ratio, ν [-]	0.275



a) Stress amplitude vs. reversals to failure. b) Maximum stress vs. number of cycles to failure.

Figure 7. Stress-life curves for the P355NL1 steel covering the stress ratios, R_σ=0, R_σ=-0.5 and R_σ=-1.

Table 2. Basquin parameters of the *S-N* curves of the P355NL1 steel for several stress ratios.

R_σ	*Stress*	*A=log(a)*	*B=b*	*a=10^A*	R^2
-	**MPa**	**-**	**-**	**MPa**	**-**
0.0	maximum stress, σ_{max}	2.9474	-0.0535	885.9	0.8798
	stress amplitude, $\Delta\sigma/2$	2.6464	-0.0535	443.0	
	stress range, $\Delta\sigma$	2.9474	-0.0535	885.9	
-0.5	maximum stress, σ_{max}	2.8244	-0.0443	667.4	0.9837
	stress amplitude, $\Delta\sigma/2$	2.6995	-0.0443	500.6	
	stress range, $\Delta\sigma$	3.0005	-0.0443	1001.2	
-1.0	maximum stress, σ_{max}	2.8688	-0.0692	739.3	0.9972
	stress amplitude, $\Delta\sigma/2$	2.8688	-0.0692	739.3	
	stress range, $\Delta\sigma$	3.1698	-0.0692	1478.4	

Table 3. Fatigue limits (stresses) of the P355NL1 steel for several stress ratios.

Fatigue limits – stresses	R_σ		
MPa	**0.0**	**-0.5**	**-1.0**
maximum stress, $\sigma_{max,\infty}$	432.1	361.9	284.2
stress amplitude, $\Delta\sigma_{0,\infty}$	211.5	271.5	284.2
stress range, $\Delta\sigma_\infty$	423.1	542.9	568.3

In Figure 8, the results of application of the fatigue Kohout-Věchet model based on stress fatigue damage parameter are plotted. The results are presented using the maximum stress and the number of cycles to failure. The constants of the fatigue Kohout-Věchet model based on stress fatigue damage parameter are presented in Table 4. The $\boldsymbol{\psi}^{ULCF}$ and $\boldsymbol{b}'$ parameters (Eq. 10) of the generalization proposal of the fatigue Kohout-Věchet model were estimated using the Basquin relation (Equation (33)), which corresponds to the $\boldsymbol{a}$ and $\boldsymbol{b}$ parameters, respectively. The $\boldsymbol{B}$ and $\boldsymbol{C}$ parameters were obtained using the ultimate stress, $\boldsymbol{\sigma_1}$, and fatigue limit stress, $\boldsymbol{\sigma_\infty}$, in the Basquin equation, see Equation (33) and Table 2 ($\boldsymbol{B} = \boldsymbol{N_u}$, $\boldsymbol{C} = \boldsymbol{N_e}$, $\boldsymbol{\sigma_1} = \boldsymbol{\psi}^{UHCF}$, and $\boldsymbol{\sigma_\infty} = \boldsymbol{\psi_e}$ are parameters of the generalized fatigue KV model).

The analytical relations, which describe the generalized KV model for the stress fatigue damage parameter of the P355NL1 steel for several stress ratios, are given by,

$$\sigma(N, R = 0) = 885.9\left[\frac{(N+4059)\cdot 673490}{N+673490}\right]^{-0.0535}, \quad (34)$$

$$\sigma(N, R = -0.5) = 667.4\left[\frac{(N+38)\cdot 1000594}{N+1000594}\right]^{-0.0443}, \quad (35)$$

$$\sigma(N, R = -1) = 739.3\left[\frac{(N+45)\cdot 999199}{N+999199}\right]^{-0.0692}. \quad (36)$$

Table 4. Constants of the fatigue Kohout-Věchet model based on stress fatigue damage parameter for the P355NL1 steel.

R_σ	$a = \psi^{ULCF}$	$b = b'$	$B = N_u$	$C = N_e$	$\sigma_1 = \psi^{UHCF}$	$\sigma_\infty = \psi_e$
-	MPa	-	-	-	MPa	MPa
0.0	885.9	-0.0535	4059	673490		211.5
-0.5	667.4	-0.0443	38	1000594	568.0	271.5
-1.0	739.3	-0.0692	45	999199		284.2

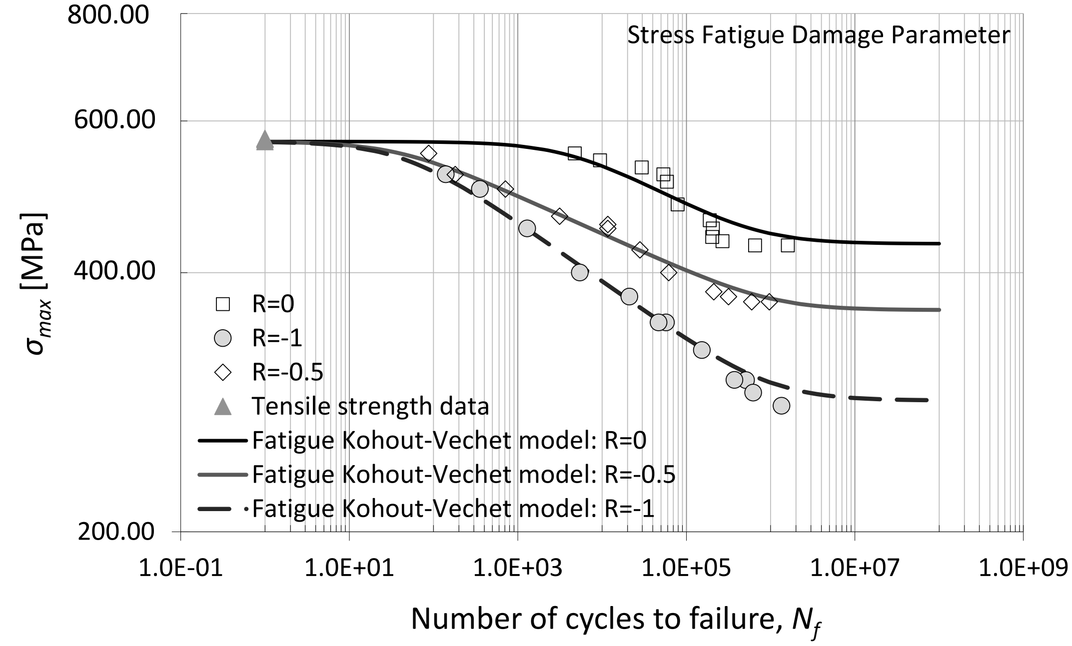


Figure 8. Fatigue KV model using the stress fatigue damage parameter for the P355NL1 steel covering the stress ratios, R_σ=0, R_σ=-0.5 and R_σ=-1.

3.2. Strain fatigue damage parameter

In this sub-section, the strain fatigue damage parameter is used in the generalized KV model aiming the validation and the applicability of the assumptions of the fatigue Kohout-Věchet model. The evaluation of parameters of the generalized KV model are made based on single and combined power damage models. Thereby, the materials used in this study are the P355NL1 pressure vessel steel and material from Trezói bridge, a puddle iron.

3.2.1. P355NL1 steel

The strain-life behaviour for the P355NL1 steel used in this study was collected in references [26-31]. Fatigue tests of smooth specimens of this material were performed according to the ASTM E606 standard [54]. These fatigue tests for two series of specimens were carried out under strain control conditions ($\boldsymbol{R_\varepsilon = 0}$: 19 specimens; $\boldsymbol{R_\varepsilon = -1}$: 24 specimens). Figure 9 shows the experimental strain-life fatigue data with the fit of the Morrow's relation, for the conjunction of the both strain ratios [26-31]. Table 5 summarizes the fatigue properties, constants of the cyclic curve (Ramberg-Osgood description [51]) and strain-life curve [26-31].

Table 5. Fatigue and cyclic properties of the P355NL1 steel [26-31].

Parameter	R_ε=0	R_ε=-1	R_ε=0 + R_ε=-1
σ'_f *(MPa)*	1087.6	932.4	1005.5
B	-0.1090	-0.0955	-0.1013
R^2	0.9641	0.8611	0.9140
ε'_f	0.4108	0.2933	0.3678
c	-0.5547	-0.5311	-0.5475
R^2	0.9918	0.9695	0.9795
K' (MPa)	913.6	1022.3	948.4
n'	0.1459	0.1682	0.1533
R^2	0.9675	0.9765	0.9662

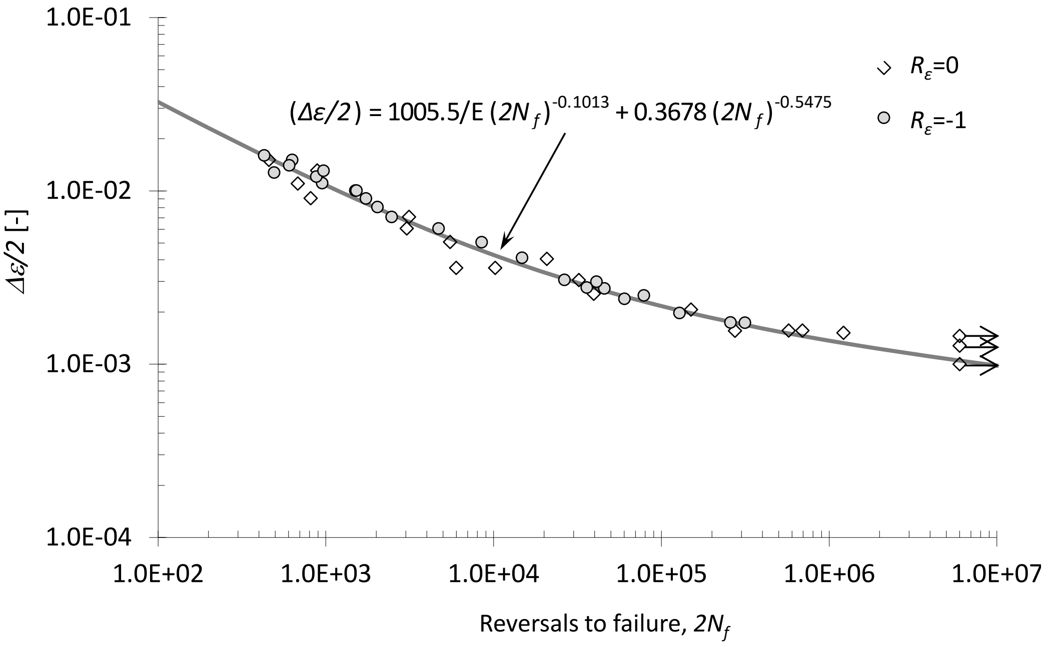


Figure 9. Strain-life curves for the P355NL1 steel, R_ε=-1+R_ε=0.

In Table 6, the constants of the generalized fatigue KV model using the strain fatigue damage parameter based on single and combined power damage models for the P355NL1 steel for the combination of the strain ratios, $\boldsymbol{R_\varepsilon = 0 + R_\varepsilon = -1}$, are shown.

The single power damage model presented in Equation (9) was used to estimate the $\boldsymbol{\varepsilon^{ULCF}}$ and $\boldsymbol{b'}$ parameters of the generalized KV model using the strain-life data. This relation was obtained through of a linear regression to the experimental strain-life data leading the following expression:

$$\varepsilon = 0.13216 \cdot \left(N_f\right)^{-0.4025}, \tag{37a}$$

$$\varepsilon = 0.13216 \cdot \left(N_f\right)^{-0.4025} + \varepsilon_e, \tag{37b}$$

where, $\boldsymbol{\varepsilon_e}$ is the fatigue limit strain that corresponds to the strain of the experimental strain-life data with infinite life ($\boldsymbol{\varepsilon_e = 8 \times 10^{-4}}$). The $\boldsymbol{\varepsilon^{ULCF}}$ parameter using the Equation (37a)) for $\boldsymbol{N = 1}$ and $\boldsymbol{N = 0.5}$ is equal to $\boldsymbol{0.13216}$ and $\boldsymbol{0.17549}$, respectively. The $\boldsymbol{N_u}$ and $\boldsymbol{N_e}$ parameters were obtained using the ultimate strain from the monotonic tests, $\boldsymbol{\varepsilon^{UHCF}}$, and fatigue limit strain, $\boldsymbol{\varepsilon_e}$, in the Equation (37a)).

The combined high and low-cycle fatigue model proposed by Karunananda et al. [14] presented in sub-section 3.1 is based on strain-life relation proposed by Morrow [52] commonly called as Coffin-Manson equation [49,50] and Kohout-Věchet model [9]. Additionally, Karunananda et al. [14] proposed to evaluate the $\boldsymbol{\varepsilon^{UHCF}}$ parameter based on the $\boldsymbol{\sigma_u/E}$ ratio. In this study, it was used the Ramberg-Osgood description [51] to determine the $\boldsymbol{\varepsilon^{UHCF}}$ parameter. As an alternative, it can be used the values of $\boldsymbol{\varepsilon^{UHCF}}$ obtained directly from the experimental monotonic results. Table 6 shows the parameters that were determined for the combined power damage model (Morrow's relation). The criterion for obtaining the $\boldsymbol{\varepsilon^{ULCF}}$ parameter was based on $\boldsymbol{N = 1}$ or $\boldsymbol{N = 0.5}$ ($\boldsymbol{\varepsilon^{ULCF} = \varepsilon'_f}$).

The difference between the use of single and combined power damage relations is in the estimation of the slope $\boldsymbol{b'}$ required in the generalized fatigue KV model. This parameter can be obtained using the single power damage relation excluding the experimental strain-life data of the HCF region. Alternatively, the slope $\boldsymbol{b'}$, may be estimated using the generalized fatigue KV model and experimental fatigue data, since that other parameters are previously obtained based on the Morrow's relation. In this sense, the model proposed by Karunananda et al [14] is based on assumption of an iterative evaluation process of the slope using the expression of the generalized fatigue KV model. In this paper, it is proposed the use of the simple power damage relation to estimate the slope $\boldsymbol{b'}$. This parameter is used directly in the generalized KV model.

Figure 10 shows the generalized fatigue KV model using the strain fatigue damage parameter taking into account the single power relation based on ultimate strain for low-cycle fatigue, ε^{ULCF}, evaluated to $N = 1$ and $N = 0.5$. For the $\varepsilon^{ULCF} = 0.13216$ ($N = 1$) leads to a good agreement between the generalized fatigue KV model and the experimental fatigue data.

Figure 11 presents the generalized fatigue KV model using the strain fatigue damage parameter taking into account the combined high and low-cycle relation. A good agreement between the generalized fatigue KV model and experimental fatigue data is exhibited. However, in this latter application, the slope b' is considered an adjustment parameter.

Table 6. Constants of the generalized fatigue Kohout-Věchet model using the strain fatigue damage parameter based on single and combined power damage models for the P355NL1 steel.

Model	*N to ULCF*	$\varepsilon^{ULCF} = \psi^{ULCF}$	b'	N_u	N_e	$\varepsilon^{UHCF} = \psi^{UHCF}$	$\varepsilon_e = \psi_e \varepsilon_e$
-	cycles	-	-	-	-	-	-
single power damage model	0.5	0.17549	-0.4025	1	324029	0.14560	0.00080
	1	0.13216					
combined HCF and LCF model	0.5	0.36780	-0.5475	5	72955	0.14560	0.00080
	1	0.25621	-0.4900				

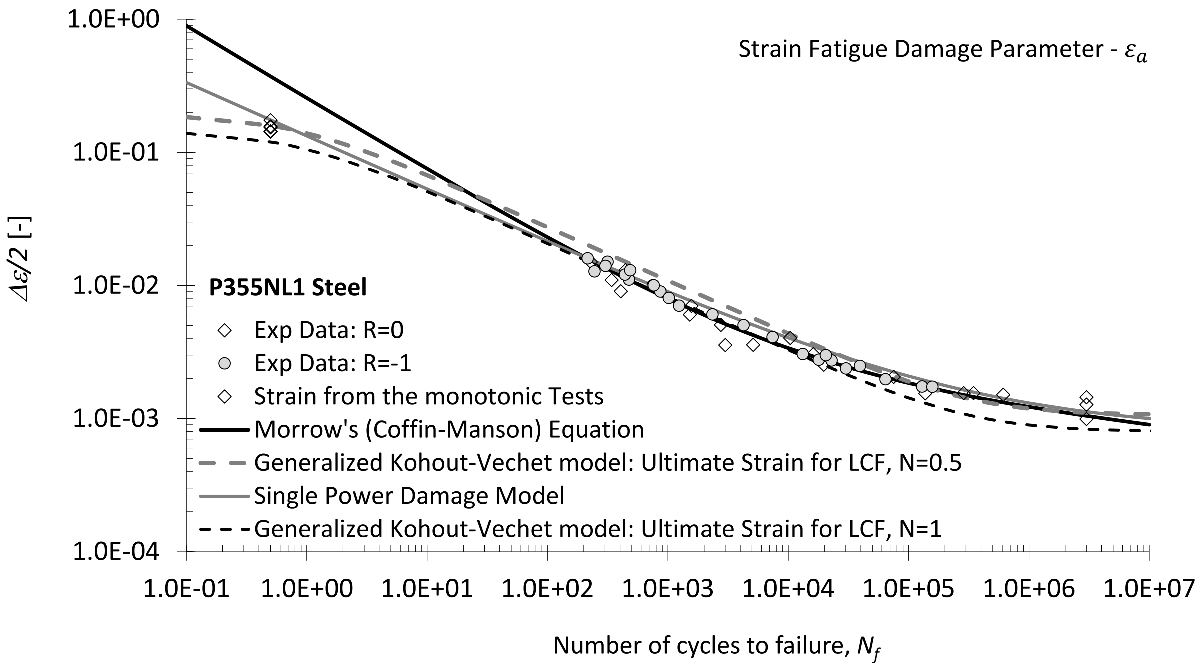


Figure 10. Generalized fatigue KV model using the strain fatigue damage parameters taking into account the single power relation for the P355NL1 steel.

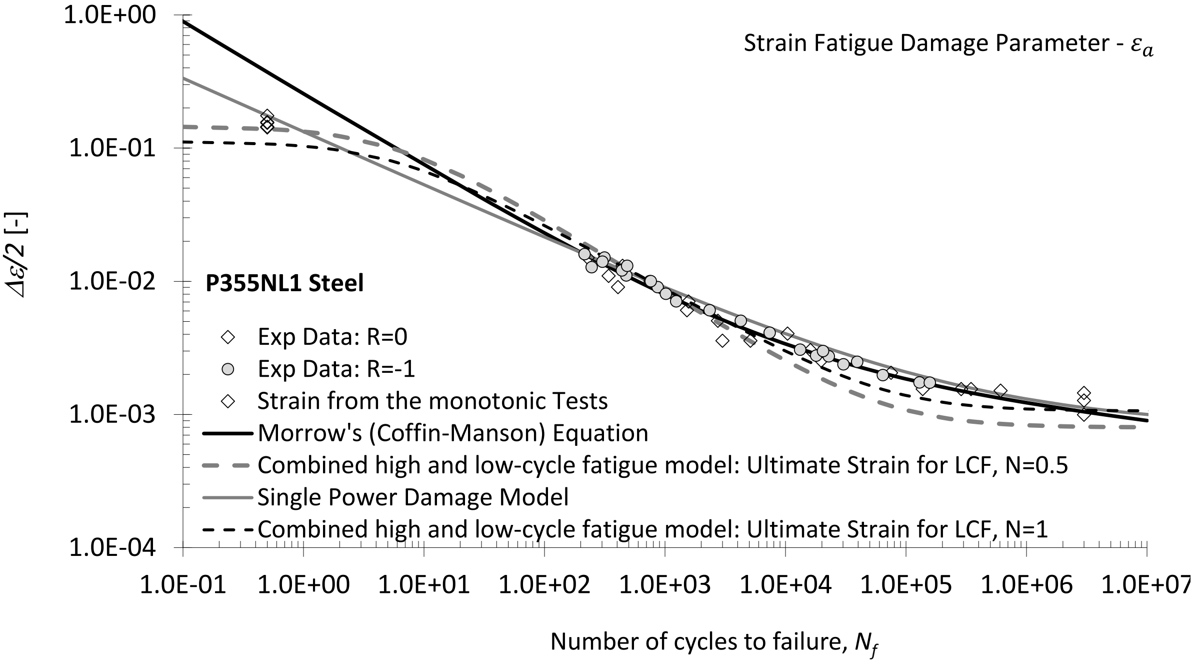


Figure 11. Generalized fatigue KV model using the strain fatigue damage parameter taking into account the combined high and low-cycle relation for the P355NL1 steel.

3.2.2. Material from the Trezói bridge

This sub-section presents the application of the generalized fatigue KV model to the experimental fatigue strain-life data of the material from the Trezói bridge, which is a Puddle iron produced latter in the XIV century. Table 7 shows the mechanical properties of the material from the Trezói bridge, which are required in this study. Figure 12 presents the strain-life data for the material from the Trezói bridge. The total strain, i.e. elastic strain plus plastic strain, versus life relations is considered. The data are correlated based on the Coffin-Manson, Basquin and Morrow models. The strain-life parameters are presented in Figure 12.

Table 7. Mechanical properties of the material from the Trezói bridge.

Ultimate tensile strength, σ_{UTS} [MPa]	473.3
Monotonic yield strength, σ_y [MPa]	398.3
Young's modulus, E [GPa]	198.5
Ultimate strain, ε_u [-]	0.10799
Strain hardening coefficient, K [MPa]	586.86
Strain hardening exponent, n [-]	0.09567
Poisson's ratio, ν [-]	0.320

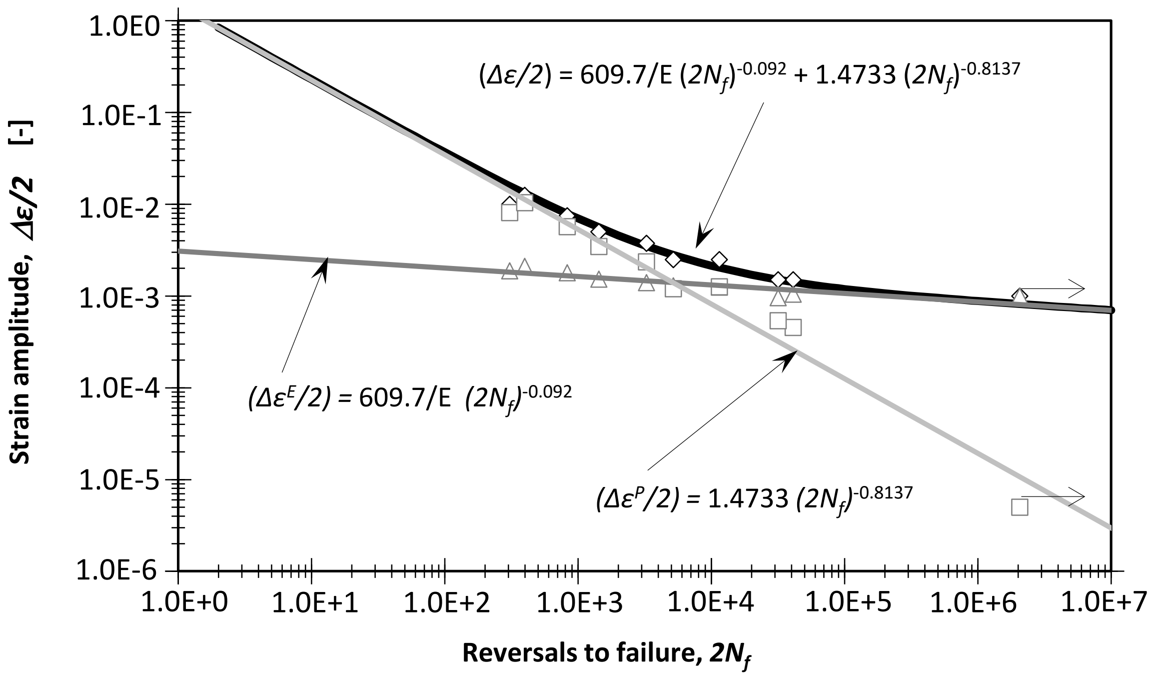


Figure 12. Strain-life curves for the material from the Trezói bridge, R_{ε}=-1.

In Table 8, the constants of the generalized fatigue KV model using the strain fatigue damage parameter based on single power damage model for the material from the Trezói bridge are presented.

In this sub-section only the single power damage model is used to evaluate the $\boldsymbol{\varepsilon^{ULCF}}$ and $\boldsymbol{b'}$ parameters that are required in the application of the generalized KV model, using the strain-life data. The single power damage relation was determined taking into account the experimental strain-life data. This relation is given by:

$$\varepsilon = 0.0941 \cdot \left(N_f\right)^{-0.429} \text{ or} \tag{38a}$$

$$\varepsilon = 0.0941 \cdot \left(N_f\right)^{-0.429} + 6.5 \times 10^{-4}. \tag{38b}$$

The $\boldsymbol{\varepsilon^{ULCF}}$ parameter was evaluated using the Equation (38a)) for $\boldsymbol{N = 1}$. The ultimate strain from the monotonic tests, $\boldsymbol{\varepsilon^{UHCF}}$ was determined using the Ramberg-Osgood description with the monotonic parameters shown in Table 7. The $\boldsymbol{N_u}$ and $\boldsymbol{N_e}$ parameters were estimated using the Equation (38a)) for the ultimate strain from the monotonic tests, $\boldsymbol{\varepsilon^{UHCF}}$, and fatigue limit strain, $\boldsymbol{\varepsilon_e}$, respectively.

In Figure 13, the generalized fatigue KV model using the strain fatigue damage parameter taking into account the single power relation based on ultimate strain for low-cycle fatigue, ε^{ULCF}, evaluated to $N = 1$, is presented. A good agreement between the generalized fatigue KV model and the experimental fatigue data is verified. The Morrow's equation can be used by LCF and HCF regimes, however, it is not advised for ultra-low-cycle fatigue (ULCF) regime because it does not take into account the quasi-static behaviour of the material.

Table 8. Constants of the generalized fatigue Kohout-Věchet model using the strain fatigue damage parameter based on single power damage model for the material from the Trezói bridge.

$\varepsilon^{ULCF} = \psi^{ULCF}$	b'	N_u	N_e	$\varepsilon^{UHCF} = \psi^{UHCF}$	$\varepsilon_e = \psi_e$
-	-	-	-	-	-
0.09410	-0.4290	1	108778	0.10799	0.00065

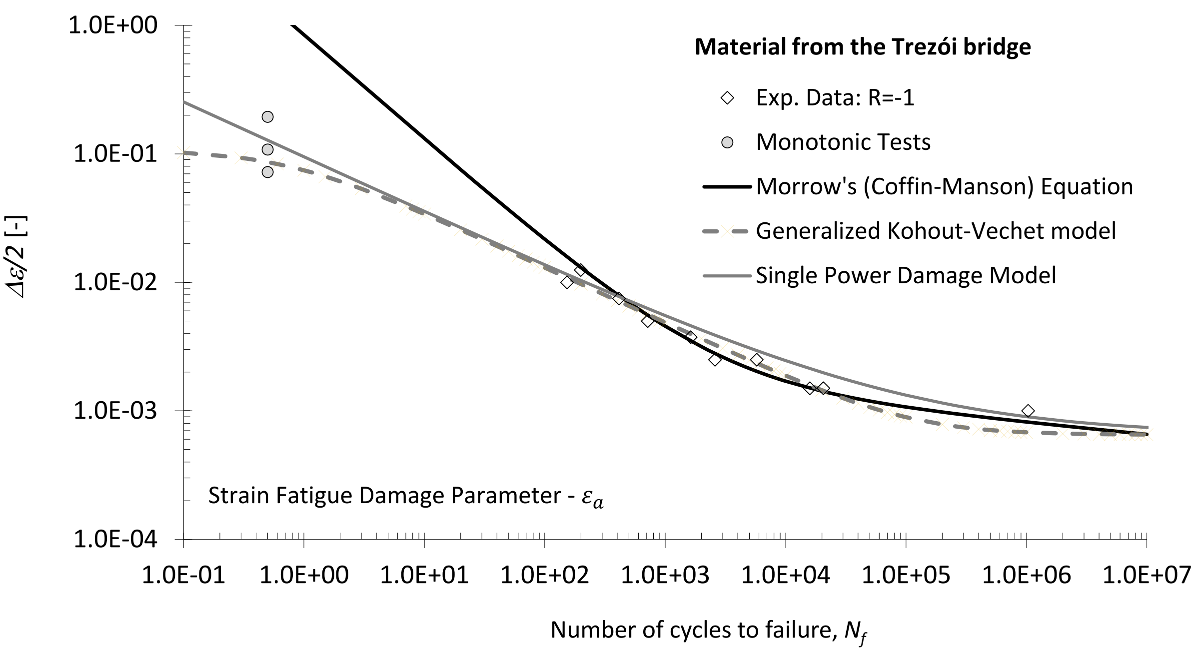


Figure 13. Generalized fatigue KV model using the strain fatigue damage parameter taking into account the single power relation for the material from the Trezói bridge.

3.3. SWT fatigue damage parameter

3.3.1. P355NL1 steel

In this sub-section, the parameters of the generalized fatigue KV model using SWT damage parameter are presented for the P355NL1 pressure vessel steel. In the sub-section 3.2.1 the fatigue and cyclic properties (see Table 5) that are used in this study were presented. The monotonic properties of the P355NL1 steel are shown in Table 1 of the sub-section 3.1.

Table 9 shows the parameters of the generalized fatigue KV model using as damage criteria the SWT fatigue parameter, taking into account single and combined power damage relations. Figures 14 and 15 present the SWT fatigue KV model based on single and combined power damage relations, respectively. The SWT based KV models plotted in Figure 14, using the single power damage relation to estimate the values of the KV parameters, show the best fit considering the SWT^{ULCF} parameter determined for $N = 1$. The same conclusion is obtained when the Figure 15 is analyzed. This last figure shows the generalized fatigue KV model using SWT parameter where the KV parameters were obtained taking into account the combined power damage relation (relation proposed by Smith-Watson-Topper [37]). The simple power damage model proves to be more effective compared to the combined power damage model for the determination of Kohout-Věchet constants.

Table 9. Constants of the generalized fatigue Kohout-Věchet model using the SWT fatigue damage parameter based on single and combined power damage models for the P355NL1 steel.

Model	*N to ULCF*	$SWT^{ULCF} = \psi^{ULCF}$	b'	N_u	N_e	$SWT^{UHCF} = \psi^{UHCF}$	$SWT_e = \psi_e$
-	cycles	-	-	-	-	-	-
single power damage model	0.5	156.53	-0.4993	2	129728	87.33	0.31
	1	110.74					
combined power damage model	0.5	369.82	-0.6508	9	52290	87.33	0.31
	1	235.55	-0.6050				

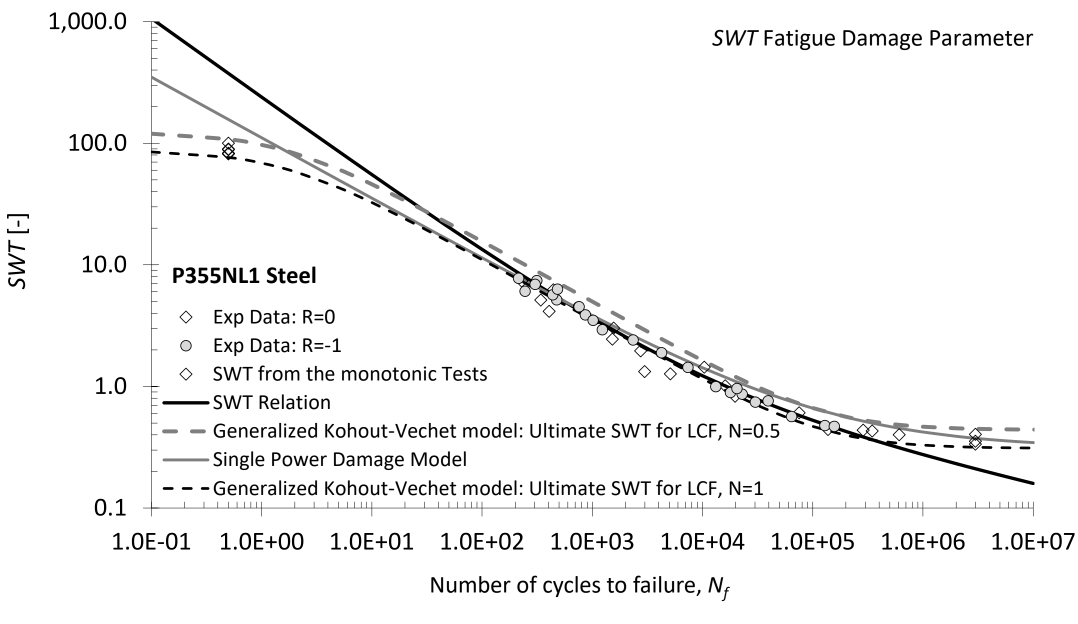


Figure 14. Generalized fatigue KV model using the SWT fatigue damage parameter taking into account the single power relation for the P355NL1 steel.

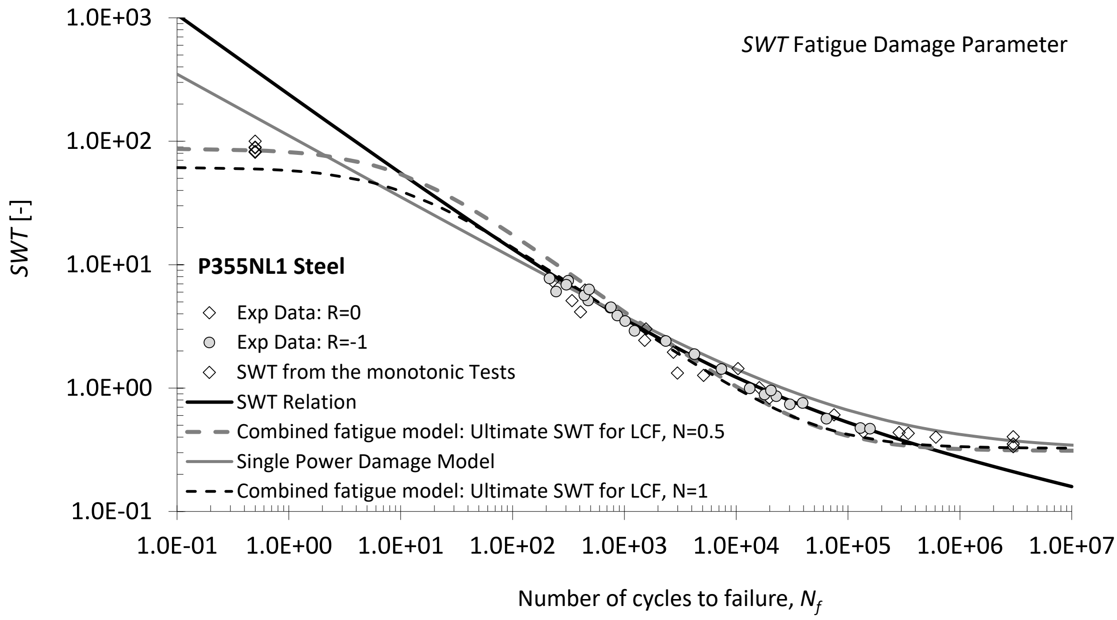


Figure 15. Generalized fatigue KV model using the SWT fatigue damage parameter taking into account the combined fatigue relation (SWT model) for the P355NL1 steel.

3.3.2. Material from the Trezói bridge

In this sub-section, the generalized fatigue KV model using the SWT fatigue damage parameter based on single power damage model is applied to the fatigue experimental results for the material from the Trezói bridge. The single power damage relation used to estimate the $\boldsymbol{SWT^{ULCF}}$ and $\boldsymbol{b'}$ parameters is given by:

$$SWT = 75.42 \cdot \left(N_f\right)^{-0.5771}, \tag{39a}$$

$$SWT = 75.42 \cdot \left(N_f\right)^{-0.5771} + 0.075. \tag{39b}$$

Based on this approach, the $\boldsymbol{SWT^{ULCF}}$ and $\boldsymbol{b'}$ parameters of were determined. The $\boldsymbol{SWT^{ULCF}}$ parameter was evaluated using the Equation (39a)) for $\boldsymbol{N = 1}$. The same equation was used to obtain the $\boldsymbol{N_u}$ and $\boldsymbol{N_e}$ parameters for the ultimate SWT from the monotonic tests, $\boldsymbol{SWT^{UHCF}}$, and SWT fatigue limit, $\boldsymbol{SWT_e}$, respectively. The ultimate SWT from the monotonic tests, $\boldsymbol{SWT^{UHCF}}$ was determined using the Ramberg-Osgood description with the monotonic parameters shown in Table 7 and applying the Equation (26).

In Figure 16, the generalized fatigue KV model using the SWT fatigue damage parameter taking into account the single power relation, is shown. For the SWT parameter, a good agreement between the generalized fatigue KV model and the experimental fatigue data is verified.

Table 10. Constants of the generalized fatigue Kohout-Věchet model using the SWT fatigue damage parameter based on single power damage model for the material from the Trezói bridge.

$SWT^{ULCF} = \psi^{ULCF}$	b'	N_u	N_e	$SWT^{UHCF} = \psi^{UHCF}$	$SWT_e = \psi_e$
-	-	-	-	-	-
75.42	-0.5771	1.47	159453	60.37	0.075

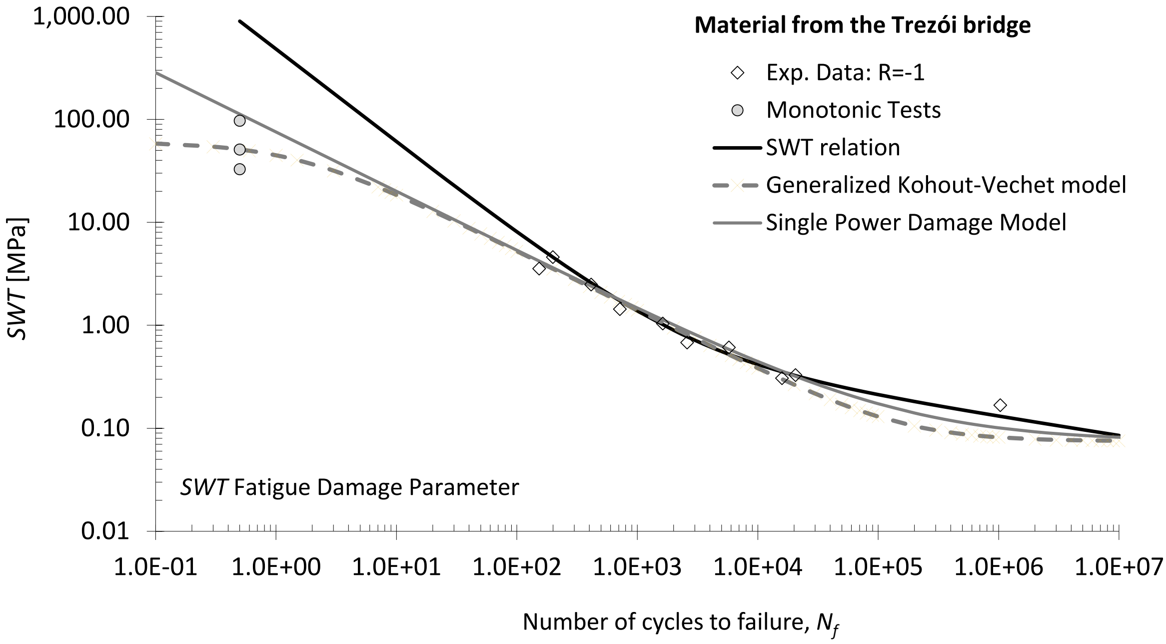


Figure 16. Generalized fatigue KV model using the SWT fatigue damage parameter taking into account the single power relation for the material from the Trezói bridge.

4. CONCLUSIONS

In this paper, a generalization of the fatigue Kohout-Věchet (KV) model for several fatigue damage variables, such as, stress-, strain-, and energy-based damage parameters, was proposed. The Kohout-Věchet constants (ψ^{ULCF}, b', N_u, N_e) of the generalization proposal of the KV model can be estimated taking into account single and combined power damage models. The single power damage relation proved to be more efficient in the estimation of the KV constants than the combined power damage relation.

The combined HCF and LCF strain fatigue model proposed by Karunananda et al. [14] is a particular case of strain fatigue damage parameter of the generalized fatigue KV model proposed in this paper. This research also proposed the use of the Ramberg-Osgood description for the monotonic $\sigma - \varepsilon$ curve with the aim to evaluate the ultimate fatigue damage parameter for the high-cycle fatigue regime (ψ^{UHCF}). In the strain fatigue model proposed by Karunananda et al. [14], the slope b' is obtained using a combined power damage relation based on assumption of an iterative evaluation process, which is required in the generalized fatigue KV model. This parameter can be obtained directly using the single power relation excluding the experimental strain-life data of the HCF region.

The generalized KV model for several fatigue damage variables could be considered a significant enhancement towards the fatigue assessment of structural details covering all fatigue regimes of the fatigue data (quasi-static regime to high-cycle fatigue regime). However, a probabilistic modelling counterpart for the fatigue design needs to be developed.

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