Two Approaches to Identify Inherent Damage in Steel Structures

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ABSTRACT

An adequate service life prediction of existing structures is of major economical interest. The condition of steel structures is commonly determined by visual inspection and a calculated estimation of fatigue damage. For this calculation, modeling load histories and an accumulation of damage is a widely used approach. Unfortunately load recordings (e.g. train schedules, traffic counts) are seldom available, so this method is relatively inaccurate. Two approaches are presented here to directly determine inherent fatigue damage in structural steel. Inherent damages are those, that accumulate before a macro crack occurs.

The first method is based on the idea of a reduced ductility at the zone of inherent damage. Notched specimens of S355J2, a widely used construction steel, are subjected to cyclic loading on different load levels and different numbers of load cycles. Once a short crack of predefined length occurred in the root of one notch, the specimen is defined as damaged and the associated number of load cycles is retained. Partial amounts of this number are applied to a series of specimens to produce an evolution of damage. Afterwards all specimens are cut into Charpy-type samples and their impact energy is determined at different temperatures. Parameters, e.g. heat of steel and radius of the notches are varied between the individual series. The results show a correlation between rising inherent damage and loss of ductility.

The second method exploits acoustic effects that occur in inherently damaged material. Defects in the material, caused by fatigue, distort the waveform of a signal travelling through the material. This leads to additional harmonics with decreasing amplitudes in the spectrum. The distortion of a fatigue damaged steel specimen is investigated experimentally, therefore a sinusoidal signal is created and recorded by piezoelements applied on the specimen that is subjected to cyclic loading.

Aim of this research is a direct assessment of the service life of a structure to avoid the commonly used error-prone modeling of load histories and damage accumulation.

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INTRODUCTION

In most cases the remaining life time of a steel structure and its actual fatigue condition is unknown. A conventional calculation of the service life can differ in the order of one magnitude [1]. The state of fatigue itself is one essential input value for the exact evaluation of the remaining life time of a structure [2]. This important parameter currently is almost not achievable with practical on-site methods. Historical load data up to the time of the investigation can improve the accuracy of damage calculation if they are available or can be determined with reasonable effort [3]. Two approaches to directly determine the inherent fatigue damage in construction steels are presented in this paper.

The occurrence of micro cracks in the microstructure of metallic materials is an indicator for inherent damage. Micro cracks are commonly considered to occur early in a microstructure, that is subjected to cyclic loading [4]. The correlation between micro-structural effects and physical quantities, for example the change of ultrasound waves or magnetic fields, were examined by numerous research projects providing a wide range of results. The procedures presented in the following aim to measure fatigue damage before a macro crack grows by impact-tests and by nonlinear acoustic effects.

APPROACH 1 - REDUCTION OF DUCTILITY

The first approach investigates if there is a physical influence of inherent damage on ductility. This material property is described by the resulting Charpy impact work KV or characteristic values of fracture-mechanical K_{Ic} or J_{Ic}. The entire procedure is designed as a concept, which compares each measured value of toughness to an initial value from undamaged material.

Initial values can be determined experimentally from tests of samples, which can be taken out of low stressed regions of a building at any time. To obtain measured values of possibly damaged material, samples have to be taken out of a region with higher stresses. The samples, that have to be taken directly out of the structure are nevertheless small enough to classify the process presented in the following as an NDT-method [5].

Procedure of the investigation

A series of specimen is cyclically loaded in a servo-hydraulic testing machine. The method is intended to fracture the specimen, in the following assigned as N, as well as to complete up to five pre-defined partial amounts of N. The damage D of those is defined by the Palmgren-Miner-law $D = n / N$. The final state is considered to be reached under occurrence of a small macro crack.

The geometry shown in Figure 1 contains 12 notches of the same type which are assumed to carry the the same stress state under cyclic loading. The fatigue failure of the total sample is revealed by separation of the crack detection wire in one of the notches. The wire is applied to both sides of the specimen and stops the testing rig after occurrence of a crack with a length of $a = 0.5$ mm. This state was defined as technical macro crack initiation over the whole test program.

After completion of the fatigue tests 12 equally notched Charpy-type impact samples were machined out of the specimen, all of them being theoretically damaged equally. Their ductility is determined in an impact test.

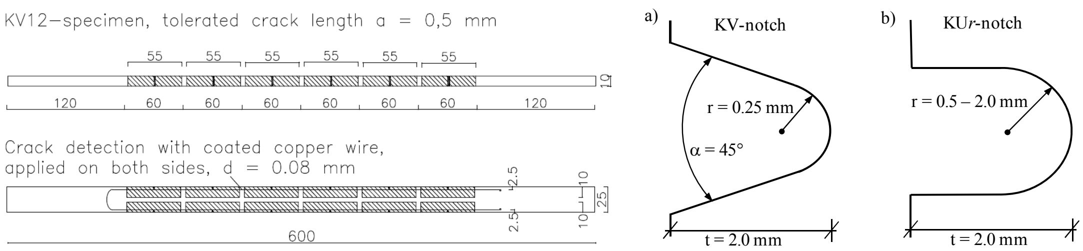


Figure 1. Fatigue testing specimen with 12 KV-notches (left); detail of notch geometry (right).

A geometry of a notch was developed, that differs from current standards because it has to meet requirements, which partly contradict each other. The stress concentration K_I in the root of the notch has to be high enough, to allow a crack to occur inside HCF-region of N. The notch also has to be sharp enough to allow an impact test according to DIN EN ISO 148-1.

On the other hand, the high gradient of stress amplitudes σ_a behind a very sharp notch relates to fatigue damage in a very small region, so that the surrounding material is exposed to minor fatigue damage only. Two basic geometries were defined, the standard KV Charpy sample with $r = 0.25$ mm and two KU-sample types with a wider radius r. The KV-notch was chosen for early testing, assigned as a) in Figure 1. The KUr-notch, assigned as b) is derived from the KU-notch and was used with wider radii $r = 1.0$ mm and 2.0 mm with a stress concentration closer to real structures.

Definition of stress level

The damage parameter P_{SWT} defines the grade of fatigue damage in the root of the notch at each load stage following Equation 1

$$P_{SWT} = \sqrt{(\sigma_a + \sigma_m) \cdot \varepsilon_a \cdot E} \tag{1}$$

where P_{SWT} = damage parameter; σ_a = elastic-plastic stress amplitude; σ_m = mean stress; ε_a = elastio-plastic strain amplitude and E = modulus of elasticity [6].

The linear stress amplitude σ_a in the notch and in the cross section behind was determined from a finite-element-model with a linear material law. The mean stress σ_m and the stain amplitude ε_a were calculated by an iterative process, using the Neuber-hyperbola in Equation 2 and the Ramberg-Osgood-law which is printed in Equation 3 in the complete form for unalloyed steels. The ultimate tensile strength R_m has to be determined from tensile tests for each sort of steel.

$$\sigma \cdot \varepsilon = \frac{\sigma_{linear}^2}{E} \tag{2}$$

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{1.65 \cdot R_m} \right)^{\frac{1}{0.15}} \tag{3}$$

Material characterization

Four representative heats of structural steel S355J2 were selected for the experimental investigations. The mechanical properties of those and their composition were determined by tensile tests on round tensile specimen ($d = 5.0$ mm, $l_0 = 25$ mm) and a chemical analysis (Figure 2). In Table 1, the material parameters are shown as mean values out of 5 samples, together with the requirements of DIN EN 10025-2:2005-2.

The impact energy-temperature curves were so far determined for two of the four materials at specified temperatures T_P in the upper and lower shelf and the steep drop. In Figure 3 the curve for undamaged material No. 4 is drawn in black diamonds with 0.9/0.1-fractiles. The greater variation of values in the transition zone is evident. The absorbed energy from pre-damaged samples is shown by white diamonds.

Material No. 6, was tested by the same method. The 27 J-horizon was reached at a temperature of T_P = -18°C, compared to -58°C of material No. 4, so it can be determined, that this alloy is significantly less ductile in the undamaged state compared to material No. 4. Small differences were found between damaged and undamaged specimens.

Table 1. Mechanical properties of tested materials and code requirements.

Material No. -	Grade -	R_e MPa	R_m MPa	A %	T_{27} °C
4	S355J2	399.5	559.1	32.6	-58
6	S355J2	354.6	541.5	28.9	-18
7	S355J2	371.4	548.2	28.6	n.n.
9	S355J2	388.0	551.9	29.0	n.n.
DIN EN 10025-2	S355J2	≥ 355.0	470.0 - 630.0	≥ 22.0	-20

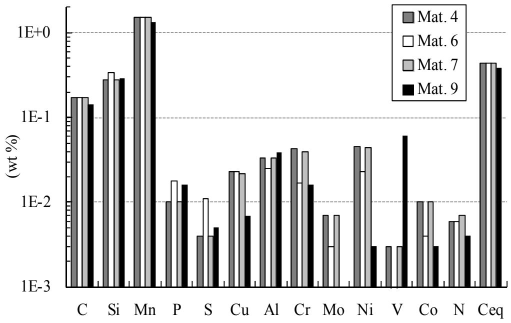


Figure 2. Chemical analysis of heates S355J2.

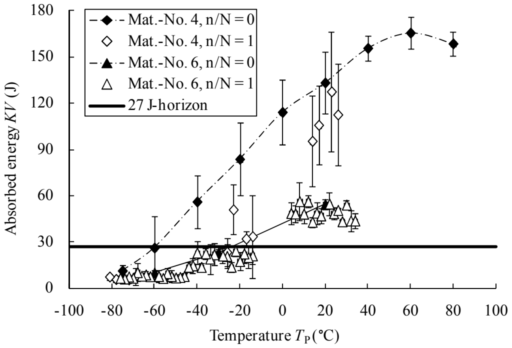


Figure 3. Impact energy temperature curves, undamaged /after crack initiation, 0.9/0.1-quantiles.

Fatigue testing and partial damage

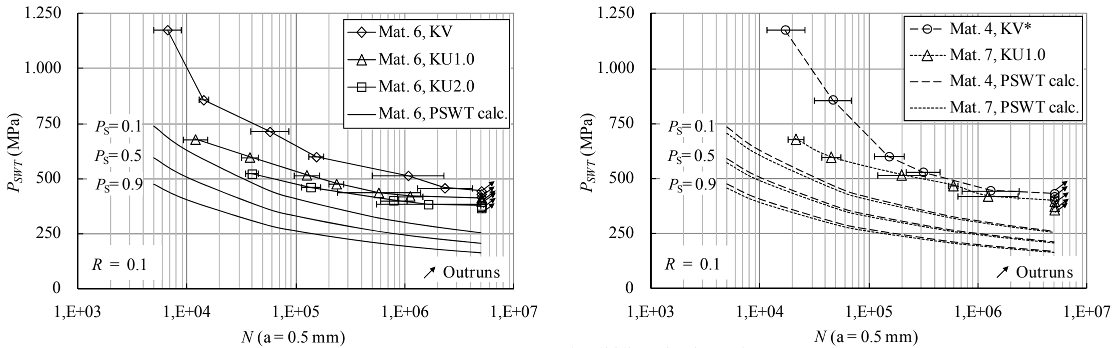
S-N curves were determined for five series. Specimens of the type shown in Figure 1 were cyclically loaded with a stress ratio of $R = 0.1$ on up to six load levels for each series. Five specimens were tested per load level, each test stopped by transection of the detection wire at a crack length of $a = 0.5$ mm. The stress level is defined by the damage parameter P_{SWT} following Equation 1. Results of the fatigue tests are shown in Figure 4. Equation 4 is used to calculate mean values of N to avoid overestimation of outliers. For comparison, calculated P_{SWT}-S-N curves basing on Equation 5 are shown in Figure 4. Equation 5 also incooperates values for the structural steels used in the experiments [7].

$$\log N_{50\%} = \frac{1}{n}\sum_{i=1}^{n} \log N_i \tag{4}$$

$$P_{SWT} = \left[\left(1.5 \cdot R_m\right)^2 \cdot \left(2N\right)^{-0.174} + \left(0.885 \cdot E \cdot R_m \cdot 1.0\right) \cdot \left(2N\right)^{-0.667} \right]^{1/2} \tag{5}$$

From Figure 4 it can be concluded, that the radius r of the notch has a major influence on the gradient of the associated S-N curve. As stresses were defined by the damage parameter P_{SWT} in the root of the notch (Equation 1), the number of cycles to failure N of the sharp notched specimens is up to one power of ten larger in contrast to the slightly notched variants.

Also micro-support of the surrounding material is a reason for this occurrence. In order to investigate also partial damage levels, five additional samples per series and per load level were tested in up to five partial amounts of N. For the following investigations damaged specimens with $D = 1$ and partially damaged specimens $D < 1$ are now available with a sufficing statistical coverage.



*until failure of entire specimen

Figure 4. Results of fatigue testing and calculated P_{SWT} S-N curves; 0.9/0.1-quantiles of P_S.

Reduction of ductility

All pre-damaged specimen were processed to 12 individual Charpy-type samples. Four of them at a time were tested for their impact energy KV (J) at specified temperatures in the upper shelf, the lower shelf and the steep drop. The number of cycles N from the fatigue-series were classified from N1 to N8 according to Table 2.

In Figure 5 the experimental results of material No. 6 are shown over two classes of *N*. The type of notch is KU1.0, the testing temperature was $T = +20°C$. On the ordinate the fatigue damage *D* according to Equation 6 is applied.

Table 2. Classes of N.

Class No.	min. N No. of cycles	max. N No. of cycles
N1	1	10,000
N2	10,001	20,000
N3	20,001	100,000
N4	100,001	200,000
N5	200,001	500,000
N6	500,001	1,000,000
N7	1,000,001	2,000,000
N8	2,000,001	5,000,000*

* defined as the limit of endurance

The tracers in both axes show 0.1/0.9-quantiles. The abscissa shows the normalized impact energy KV' defined by Equation 6 where KV' = normalized ductility reduction, KV_D = notch energy of damaged material, KV_0 = initial notch energy. Figure 5 shows that the increase of damage under stress levels according to N2 and N3 is starting at $D = 0.4$. A non-linear increase of material damage can occur at the beginning and the end of a degradation process [8].

$$KV' = 1 - \frac{KV_D}{KV_0} \tag{6}$$

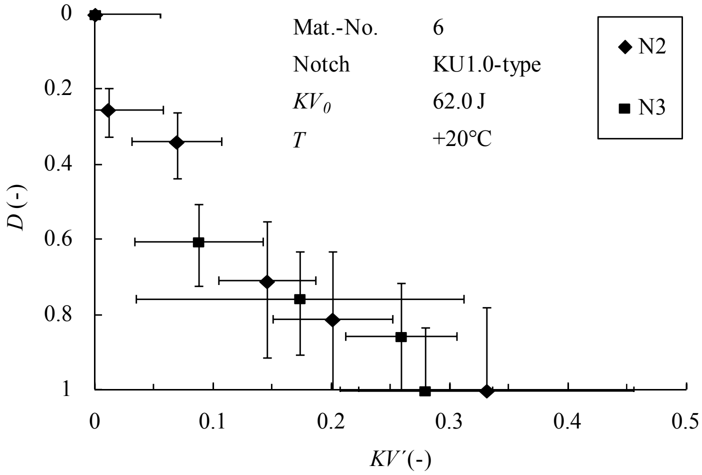


Figure 5. Fatigue damage D, normalized ductility KV′; 0.1/0.9-quantiles.

Derivation of a damage model from the experimental results

Assuming there is a damage model according to Equation 7, the following conditions are required. First, there exists a specific material S-N curve $P_{SWT} = f(N)$, which can be determined experimentally or can be taken from literature.

$$D = f\left(KV', P_{SWT}, KV_0\right) \tag{7}$$

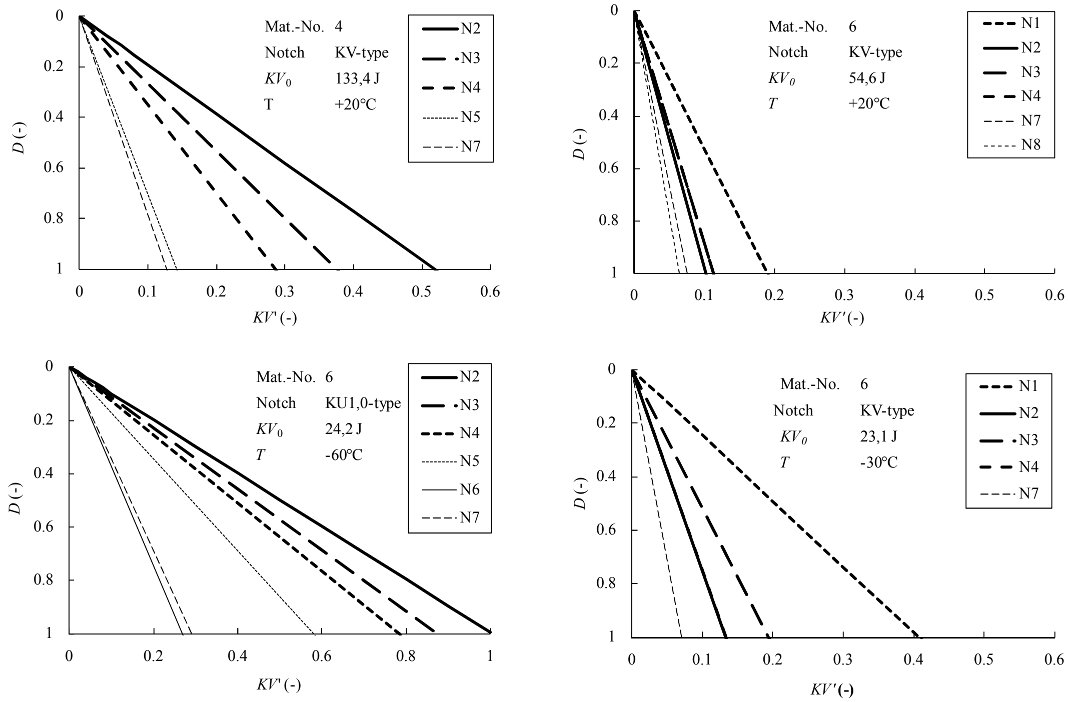


Figure 6. Approximations of KV' over load levels Ni for different materials and temperatures .

Second, the impact energy-temperature curve $KV_0 = \mathrm{f}(T_{\mathrm{KV}},\ \mathrm{r})$ is required where T_{KV} = test temperature of impact test and r = radius of the notch. It can be determined experimentally and used after a regression calculation e.g. as shown above.

The characteristic properties of P_{SWT} and KV_0 are examined in the following. The empirical relationship between N and the damage parameter P_{SWT} according to Equation 2 is defined by the *S-N* curve of each material and notch- type. A rough linear approximation of curves N_{i} is shown in Figure 6.

It shows clearly that the number of load cycles to failure N has an influence on the degradation of impact energy with increasing damage. All experiments show, that specimen under LCF-loading have substantially larger values of *KV'* with increasing damage *D*. Basically all experimental data show substantial results in the load stages N1 to N4 with the highest values at the lower end of the LCF-region (N1 and N2) and a border to lower values behind N4; e.g. $N > 200.000$ cycles according to Table 2.

From Figure 6 is apparent, that the brittle material No. 6, provides lower total values of *KV'*. The values *KV'* of notch-type KU1.0 are approximately 0.2 higher over the entire temperature-range, compared to the sharper KV-type. From that result is derived, that a slight notch with a larger radius *r* improves the height of the result. A ductile material with a high default ductility KV_0 will also have a positive effect. Since the investigations are in progress currently, more precise statements can be made after completion of the experiments. Currently, the effects of the notch-radius and the height of the achievable results are of particular interest.

APPROACH 2 - NONLINEAR ACOUSTIC EFFECTS

The second approach applied to examine the feasibility of inherent damage detection is the vibro-modulation method. It is a non-destructive testing method that exploits nonlinear acoustic effects for crack detection. The modulation of high frequency signals passing contact-type defects by low frequency oscillation indicate material damages. Contact-type defects are for example, cracks and delaminations. Due to the nonlinear behavior of these defects, the modulation leads to additional frequencies as sideband components in the spectrum at the combined frequencies. In reality the mechanism is more complex and cannot simply be described by considering quasi one-dimensional, nonlinear effect on the propagating signal. A discussion on this aspect is given in [9].

The vibro-modulation method is an established approach beside other modulation techniques such as impact-modulation using nonlinear acoustic effects. They are used for a variety of materials [10, 11, 12]. A major advantage of modulation techniques is that they are sensitive to nonlinear effects of defects and relatively insensitive to signal scatter from edges and other geometric features. Furthermore, the change in nonlinear responses from undamaged to damaged material is significantly higher than in case of linear responses [13]. An advantage of the vibro-modulation method is that the low frequency vibration cause stress concentration exactly in those parts of the specimen, where the fatigue damage occurs. Consequently, it increases the nonlinear interaction of both signals in these areas and therefore improves the detection of damages. An overview on nonlinear acoustic methods and more details on their fields of application are given by Donskoy [13]. Donsky presented a virbo-modulation study on aluminium specimens under fatigue loading. A damage index based on changes in modulation characteristics is used as a measure of fatigue damage in the material. The index indicates damages already in the early stage of fatigue. Therefore, this method is examined for comparison to the first approach.

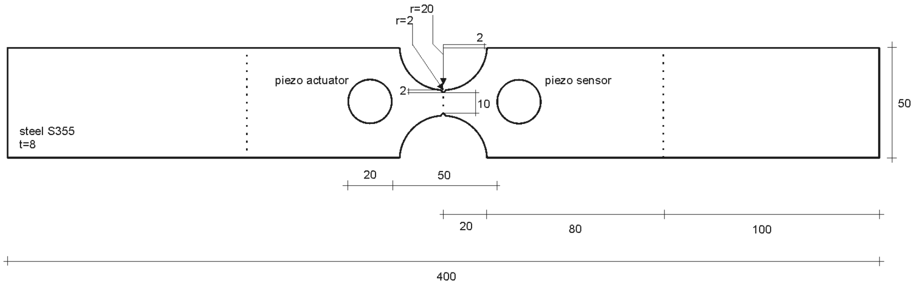


Figure 7. Steel specimen attached with piezo actuator and sensor.

Figure 7 shows the design of the steel specimen attached with a piezo actuator and a sensor. The signals for the measurement are generated by the piezo actuator and the fatigue testing machine. The latter provides the low frequency signal of 4 Hz. In order to diminish effects of the structure by choosing a certain frequency, the high frequency signal is swept in the range of 70-100 kHz. The specimens are subjected to cyclic loading, leading to low cycle fatigue failure at around 30,000 cycles. The response signals are analyzed following Donskoy [13], which means that first the frequency is averaged with the modulation index and then the computation of the damage index is done.

CONCLUSIONS

In this paper the inherent damage in structural steel is examined using two approaches. The first approach shows, that the grade of fatigue damage in notched steel samples is correlated to a normalized reduction of impact energy KV'. A variety of four structural steels S355J2 was tested to determine influences of the material characteristics (initial ductility), notch geometry (radius) and type of loading (HCF/LCF), which have been identified as key parameters that affect the impact energy. From the results can be seen, that larger notch radii lead to clearer results, as well as a high initial ductility. In the HCF-region the results values become smaller and less distinctive. A low initial ductility apparently leads to a significant reduction in ductility, one reason for this is the calculation method, the scatter in this region is also far above the average.

The second approach exploits nonlinear acoustic effects to detect material defects. The experiments are running and results will be presented at the conference.

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