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Computation of and testing crack growth at 20 kHz load frequency

Mohamed Sadek^{a,*}, Jens Bergström^a, Nils Hallbäck^a, Christer Burman^a

^a) *Karlstad University, Department of Engineering and Physics, SE-658 88 Karlstad*

Abstract

Fatigue properties are evaluated in a large span of fatigue lives ranging from a few load cycles to more than 10^{13} load cycles. If the interest is focused on fatigue lives above 10^7 load cycles, we speak of the very high cycle fatigue (VHCF) range. For evaluation of properties in the VHCF range one often needs to use higher load frequencies to be able to perform testing within a reasonable time. Therefore, the influence of load frequency on fatigue strength and fatigue crack growth is an important issue, both from testing and design perspectives. Within an EU-RFCS research project on the frequency influence on high strength steel fatigue properties the present study has been conducted on fatigue crack growth testing to determine threshold values and crack growth material parameters. The testing was analyzed by FE-computation to determine geometry factors for ΔK -determination.

The testing was performed in a 20 kHz ultrasound resonance instrument. In such a system the whole load train needs to be designed to run at a resonance frequency of 20 kHz, and it implies that the specimen needs to be designed and computations performed by dynamic computational methods. As the crack grows the dynamic response of the specimen will change, and hence calculation to obtain the geometry factor is made with a progressing crack length. A uniaxial tensile load at 20 kHz frequency is applied to a single edged notched side-grooved flat specimen. The specimen dimensions are calculated in order to have a resonance frequency of 20 kHz, which is the frequency used for the experiments.

Dynamic FEM computation, with a 3D-model and a quarter symmetry was used with one of the symmetry planes parallel to and in the crack growth line. To avoid crack surface interpenetration during the simulations a rigid thin sheet was introduced and used as a counter-face to the crack surface. The solution obtained was then combined with the breathing crack model proposed by Chati et. al. (1997) in order to solve for the irregularities observed when crack surface interpenetration occurs. Finally, the whole load train was considered. Thus, also the computed frequencies were very close to frequencies observed in experiments.

The computation of stress intensities was made for varying crack lengths in a series of simulations. The geometry factor relation was determined and used in 20 kHz crack growth testing to control the actual stress intensity at the advancing crack tip. Comparison of computations and experimental results were made.

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Keywords: Crack growth; High frequency; Dynamic analysis; steel; threshold testing.

* Mohamed Sadek. Tel.: +4654-700-1944; fax: +46-54-700-1829.
E-mail address: mohamed.sadek@kau.se

1. Introduction

The time consuming gathering of experimental data for VHCF properties is now possible to be reduced by the use of modern test equipment using an ultrasonic booster to generate the load pulse, with as high nominal load frequencies as 30 kHz, Mughrabi et. al. (2007), Mayer et. al. (1999) and Xue et. al. (2010). The method has been verified for a number of materials. This very high loading frequency provides an entrance to the giga cycle regime, also known as the Very High Cycle Fatigue (VHCF) – regime, where the life span is at 10^7 cycles and above.

In-service conditions of mechanical components rank from less than 1 Hz to several kHz loading frequency depending of the application. Furthermore, fatigue testing can be performed in a similar range of frequencies, but higher frequencies are usually preferable in order to reduce testing time. Thus, testing and in-service load frequencies are often not corresponding. Using equipment operating in the kHz load frequency range introduces specific local effects that may affect the material properties. This could lead to incorrect prediction of the material response, and consequently in component design. Although some researchers only find a negligible influence of testing frequency on fatigue strength and life, Bathias et. al. (2001, 2011), Kazymyrowych et. al. (2007), Stanzl-Tschegg et. al. (1999), Bergamo et. al. (2011) and Furuya et. al. (2002, 2008), the results obtained at high frequencies can sometimes differ significantly from these obtained at conventional loading conditions, Li et. al. (2011), Tsutsumi et. al. (2009), Setowaki et. al. (2011), Zhao et. al. (2011) and Guennec et. al. (2014).

Fatigue modelling approaches allow for the prediction of material behavior, based on experimental results necessary for the parameter calibration and model validation. Including the frequency effect in fracture mechanics modelling has been attempted on an empirical approach, Amirat et. al. (2003). Sakamoto et. al. (1994) studied the effect of cyclic frequency on crack growth rate for hcp metals in the low-cycle regime. Here, the growth rate was increased by a factor of two at lower frequencies. A dissimilar result was obtained by on a 0,13% carbon steel at 10 Hz and 20 kHz in VHCF, where higher fatigue strength and longer fatigue life at 20 kHz was connected to differences in crack growth, according to Sakamoto et. al. (1994). Evidently, there is scientific evidence of cases when test frequency correlates to a change in fatigue strength, and the opposite as well.

The determination of fatigue crack propagation behavior under high load frequencies as 20 kHz puts particular demands on both testing and numerical simulation of it. The testing needs to be performed under load train resonance conditions, and as the specimen compliance and thus resonance changes as the crack grows the load control needs to be calibrated for varying crack lengths. Earlier studies have presented test methods for 20 kHz crack growth testing, Bathias and Paris (2004), adapting to the ASTM E647 practice, and it has been further elaborated in by Perez-Mora et. al. (2015). However, a full dynamic numerical solution using FE methods has not been applied earlier.

The present study aims to support the use of 20 kHz testing in the determination of fatigue crack growth behavior of metallic materials. A test setup is described where a low alloyed steel single edge crack growth specimen is loaded in an ultrasonic 20 kHz equipment, the short crack growth is measured in a camera system and growth parameters in the near stress intensity threshold regime are determined according to ASTM E647 practice. The test is calibrated through numerical FE method calculations to obtain the crack geometrical correction function for stress intensities.

Nomenclature

ΔK	Stress intensity
E_d	Dynamic Elastic – modulus
ν	Poisson's ratio
a	Crack length
U_0	Displacement amplitude
ω	Angular resonance frequency.

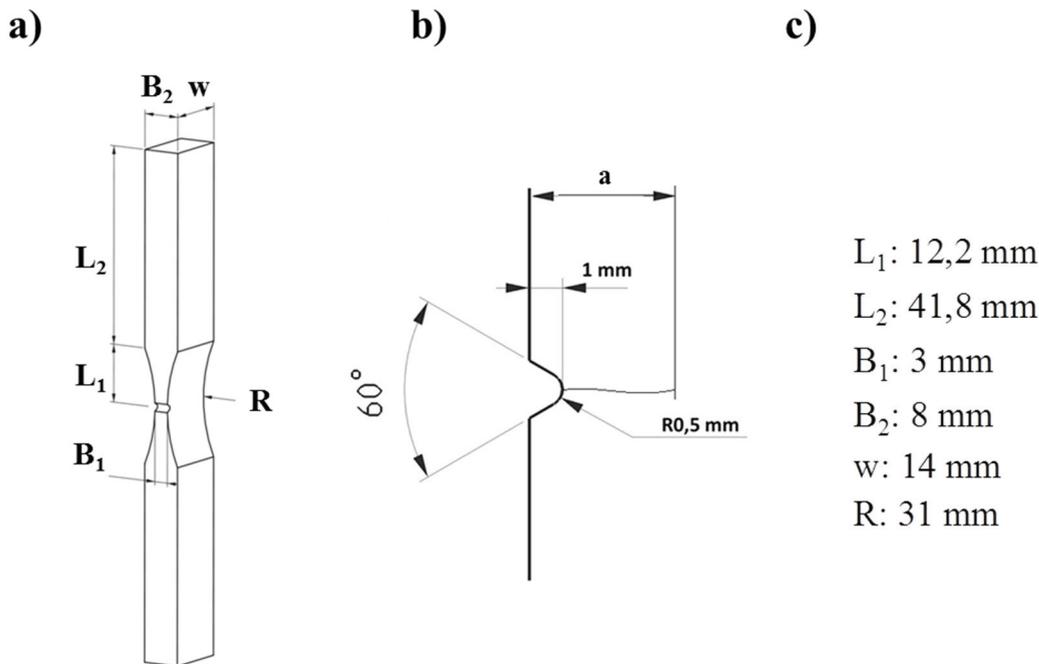


Fig. 1. (a) The FCG specimen geometry designed for 20 kHz with a) overall specimen geometry; b) notch dimensions; c) specimen dimensions.

2. Experimental procedure

2.1. FCG-specimen

A single edge notched tensile fatigue crack growth (FCG) specimen design according to [Bathias and Paris] was used in the present experiments, Fig. 1. The rectangular cross-section of the FCG-specimen, perpendicular to the applied load, provides a plane area on which the fatigue crack grows and its length is measured by a camera on the side surface. The sinusoidal shape in the middle shortens the specimen and the notch acts as a crack initiator. The dimensions of the FCG-specimen are calculated accordingly to reach the required resonance frequency 20 kHz of the ultrasonic test system. In the present case the specimen geometry, together with material density $7.8 \cdot 10^3\text{ kg/m}^3$ and Young's modulus 210 GPa, a FEM modal analysis, i.e. eigenfrequency calculations, ends in a resonance frequency of 20 038 Hz, which is well inside the $20 \pm 0.5\text{ kHz}$ requirement of the test system. In this case the full geometry of the specimen, including the notch, is considered but noting that any crack is omitted.

2.2. Resonance frequency analysis including the fatigue crack

A reliable estimate of the specimen and load line resonance frequency is required for the further analysis of stress intensities as a function of crack length. When running a crack growth test it is observed from the test system monitoring feedback how the frequency is decreasing with increasing crack length, viewed as the experimental curve in Fig. 2. To model this behavior different approaches have been employed; i) FEM modal analysis of the specimen, ii) FEM dynamic analysis of the freely vibrating system involving crack surface contact, iii) approximate semi-analytical method for the crack opening problem, and iv) inclusion of the whole load train in approach iii).

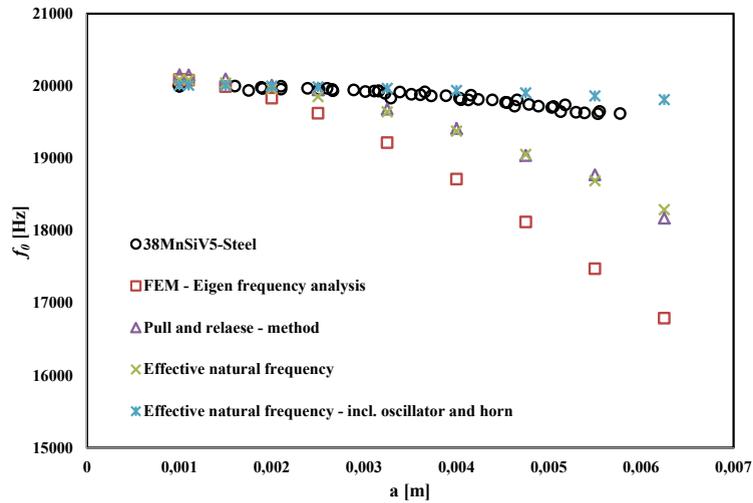


Fig. 2. Different approaches to calculate the resonance frequency dependence on the crack length plotted against a measured frequency from experimental work.

Quarter symmetry specimen, with one of the symmetry lines through the crack growth line, is used in the FEM-software ABAQUS. One problem with the FEM quarter symmetry modal analysis is that it allows crack surface interpenetration. To circumvent this problem, the freely vibrating system was analyzed as a tensile load statically applied to the specimen and then released in a dynamic step. The crack surface interpenetration was blocked by assembling a rigid body-element attached to the crack surface in the model. Upon the release the specimen will start a decaying free oscillation, and the time period of each oscillation cycle is measured and the frequency is calculated. This method will be referred to as the “Pull and release”-method.

The third attempt used was to solve the crack surface interpenetration problem applying an approximate semi-analytical method developed to define an “Effective natural frequency” (ENF) for a cracked beam, Chati et al. (1997). An analytical solution is used represented by Eq. (1), where the effective natural frequency, ω_0 , is the frequency of each individual linear system (a specimen with a specific crack length) and is supposed to account for the crack surface contact. Here are ω_1 and ω_2 the eigenfrequencies of the un-cracked and cracked specimens, respectively.

$$\omega_0 = \frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \tag{1}$$

The fourth approach to calculate the frequency dependence on the crack length was to include the whole load train; the oscillator, the horn and the specimen in the FEM-model from the third approach. The horn and specimen are modelled according to their specific dimensions while the oscillator is represented by a solid cylinder with a 20 kHz resonance frequency. A new series of modal analysis of the entire assembly of oscillator, horn and specimen, using a half symmetry model and with a progressing crack length, was made and new resonance frequencies were obtained.

2.3. Fatigue crack growth rates.

Fatigue crack growth rates were determined experimentally following the guidelines of ASTM E647, with initially a ΔK -decreasing procedure until a crack growth below the threshold growth, and then a ΔK -increasing test procedure took place. In each decreasing or increasing step the crack is allowed a growth of 0.5 mm. The load is controlled by a ΔK -value calculated from Eqs. (2) and (4).

The stress intensity range is related to the measurable quantity load displacement, U_0 , in Eq. (2), as derived by dimensional analysis, Bathias and Paris (2004).

$$\Delta K = \frac{E_d}{1-\nu^2} U_0 \sqrt{\pi/a} f(a/w) \quad (2)$$

Thus, the stress intensity range is calculated and controlled through the setting of the displacement amplitude (U_0) at the bottom of the horn (also top of the specimen), through the ultrasonic instrument voltage input calibrated for the oscillator + horn – system.

Before using the relationship in Eq. (2) for all crack lengths it is required to determine the geometry function $f(a/w)$ in Eq. (3), for all crack lengths. A series of ΔK calculations were conducted covering a group of pre-selected crack lengths using dynamic FEM analysis. The values of the calculated geometry function for these crack lengths were fitted to a 4th grade polynomial expression.

Hence, the ΔK values (calibrated ΔK) are computed for all crack lengths using Eq. (2). At the starting point before fatigue crack initiation a ΔK value is calculated using the un-cracked specimen but assuming a crack equal to the notch size $a = 1.0$ mm.

Three different approaches were tried to compute the ΔK values for the pre-selected crack lengths; static simulation, dynamic simulation with the specimen only and a constant frequency (20 038 Hz), and at last a dynamic simulation including the specimen+horn+oscillator load train system and using a crack length specific frequency. The dynamic simulations are run for 0.0005 sec and cover about 10 load cycles.

An experiment was conducted aiming to evaluate the test procedure described and to determine the crack growth rates of a high strength micro-alloyed steel 38MnSiV5. Tables 1 and 2 summarizes properties of the steel.

Table 1. Chemical composition, w%, of 38MnSiV5

C	Mn	Si	P	S	Cr	Ni	Mo	V	Cu	Al	Sn	Ti
0,37	1,46	0,68	0,011	0,05	0,12	0,1	0,03	0,1	0,12	0,014	0,009	0,014

Table 2. Mechanical properties of 38MnSiV5

Yield stress, MPa	Tensile strength, MPa	Elongation to fracture, %	Reduction of area, %
590	870	20	55

Six specimens were tested, and each specimen was tested under such procedure where the load (ΔK) is decreased during the first part of the crack growth and then increased during the last part. The da/dN vs ΔK results are then fitted to the expression in Eq. (3) and the parameters C and n are determined.

$$\frac{da}{dN} = C(\Delta K)^n \quad (3)$$

Subsequent to crack growth testing the fracture surfaces were examined to ensure proper testing conditions.

3. Results

3.1. Resonance frequency analysis.

The crack surface interpenetration occurring in the conventional modal analysis decreased the resonance frequency of the cracked specimen at a significantly higher rate than the frequencies measured during the experimental work, see Fig 2.

The results from the “Pull and release”-method confirm the approach where the effective natural frequency is calculated using Eq. (1), Chati et. al. (1997). However, the frequency still drops at a too high rate with respect to the crack length. Finally, including the whole load train (specimen+horn+oscillator) and applying a FEM half symmetry model corrected the rate under which the frequency dropped closer to the experimentally measured frequencies.

3.2. Fatigue crack growth rates

The ΔK values achieved from the different approaches are plotted in Fig. 3. The most noticeable is the difference between static and dynamic simulations. The stress intensities obtained by the static simulations are approximately 30% lower than the ones achieved by the dynamic simulations. The use of the crack length specific frequencies and including the whole load train slightly increased the ΔK values at longer crack lengths and smoothed out the curve.

Then, the dynamic ΔK vs a results including the whole load train were used to obtain the values of the calculated geometry function for the pre-selected crack lengths and fitted to a 4th grade polynomial expression. Thus, the geometry function $f(a/w)$ was derived;

$$f(a/w) = -6,0932(a/w)^4 + 7,1881(a/w)^3 - 3,0046(a/w)^2 + 1,3693(a/w) - 0,034 \tag{4}$$

By using the geometry function and the calibration parameters of the ultrasonic instrument the controlled ΔK -testing is performed. The calibrated ΔK values using Eqs. (2) and (4), are presented in Fig. 3 and includes the crack length of the un-cracked specimen ($a = 1$ mm).

The experimental crack growth results from testing the 38MnSi5V-steel are presented in Fig. 4(a). The initial ΔK -decreasing testing produces decreasing crack growth rates towards the turning point where the growth rate reached the threshold level, and when turning into the ΔK -increasing stage the cracks grow at higher rate than in the prior ΔK -decreasing stage. The results were fitted to the crack growth expression in Eq. (3), and the parameters C and n were estimated to 10^{-11} m/cycle and 2,86, respectively.

In order to underline the differences obtained using the static ΔK computation, conventionally used, and the full dynamic ΔK computation obtained in the present paper, the static and dynamic da/dN vs ΔK evaluation of the experimental results are presented in Fig. 4(b). Obviously, the selection of analysis method will significantly affect the evaluation of crack growth rates and threshold values. The vertical lines indicate the threshold value (ΔK_{th}) representing the lowest stress intensity range required for crack growth.

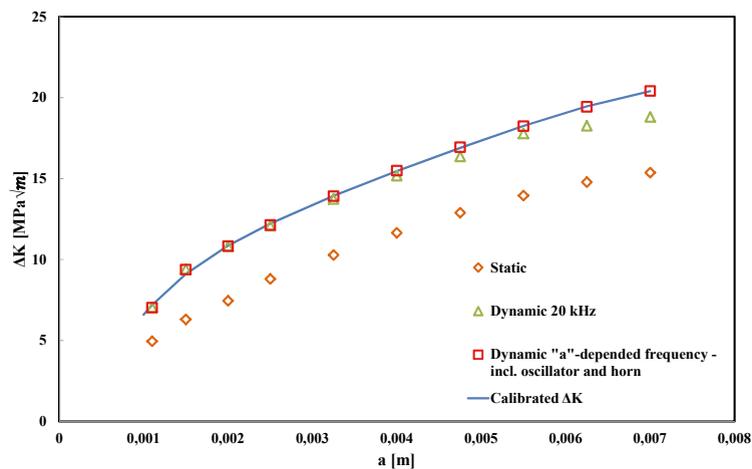


Fig. 3. Different methods of calculating the stress intensity factor dependence on the crack length numerically.

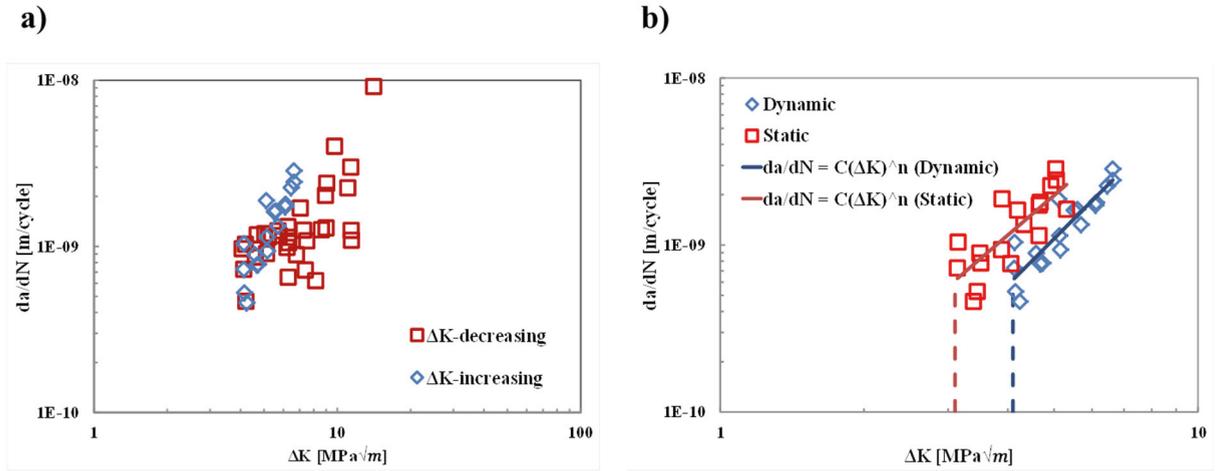


Fig. 4. a) Data from an experiment including six specimens of the 38MnSiV5 steel; b) Static vs. dynamic simulations on the crack growth rate.

3.3. Fracture surface analysis.

The fracture surface examination results display a singular initiation from the notch bottom and the crack then propagates in a straight and well-behaved manner, Fig. 5. There is no clear distinction between the ΔK -decreasing and ΔK -increasing stages. Fatigue striations were clearly observed over the fracture surface, and by measures of the striation spacing the fatigue crack growth rate was found 1-2 orders of magnitude larger than from the measured crack growth. Also, it was concluded that the striation spacing did not change in any significant way throughout the whole crack length.

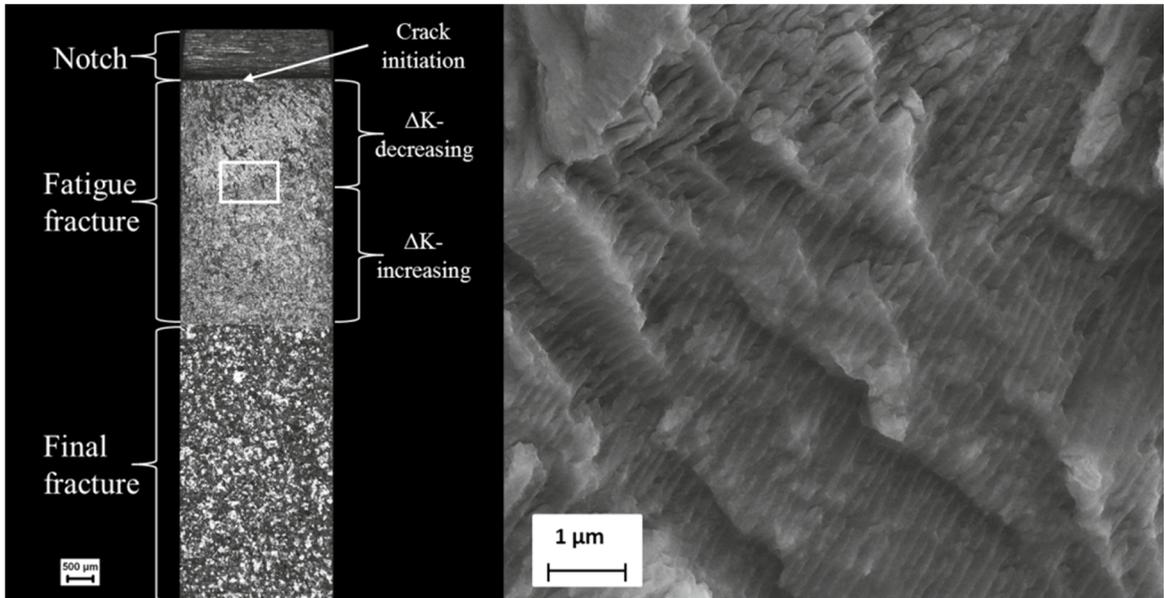


Fig. 5. Fracture surface.

4. Discussion

The present study has clearly demonstrated urgent issues to consider when analyzing the crack growth testing results derived by high load frequency testing. The implications may regard not only testing and its evaluation issues, but also regard design issues. Common procedure in testing is using static fracture mechanics solutions since most testing is performed at moderate load frequencies. With the growing possibilities to use high load frequencies to speed up testing time and to investigate long life and crack growth threshold conditions, there is a need to increase knowledge and to apply proper testing procedures.

In the present study the focus has been to analyze and determine the resonance frequency in a cracked test specimen, then to include the determined frequency in a dynamic analysis of the stress intensity of the cracked specimen, and finally to use the dynamic stress intensity to evaluate the fatigue crack growth results.

The effective natural frequency (ENF) model derived by Chati et al. (1997) was compared and found to agree well with a dynamic freely oscillating model, the “Pull and release method”. Still, applying the model to only the specimen did not result in a solution in agreement with the experimental resonance frequency feedback. Hence, it was realized that the experimental feedback signal was a system response, and it was decided to model and simulate the whole system, i.e. the whole load train. The inclusion of the whole load train in the FEM modal analysis and the combination with the ENF model led to an agreement between the theoretical analysis and experimental results. Thus, as is obvious from Fig. 2, not including the entire load train in the FEM model will lead to an overestimate of the frequency effect.

When performing crack growth testing according to a standard practice, e.g. ASTM E647, the stress intensity is calculated using geometrical corrections for specific specimen geometries and load conditions. In the present case testing at 20 kHz those do not apply but have to be derived. As the crack growth testing is controlled by setting the stress intensity, the stress intensity needs to be calculated for each crack length when testing. Once again, the dynamic response needs to be considered, and Fig. 3 displays the significant effect of the dynamic simulation compared to a static simulation. Furthermore, additional improvement is obtained when including the whole load train in the analysis. Hence, this was used for calibration of the testing and the derivation of the geometrical correction used for calculating stress intensities during testing.

Finally, the dynamic ΔK computation can be applied to the evaluation of the da/dN vs ΔK experimental results. When compared to the evaluation using the static ΔK computation, Fig. 4b), the dynamic crack growth curve and threshold are shifted towards higher ΔK . Further work will tell which procedure is the most correct. For example, crack growth testing (within the frame of the present EU-RFCS project) is undertaken at low and high frequencies to examine the frequency effect, and comparing threshold values obtained at low frequencies to the values obtained using static and dynamic computation at high test frequencies may give guidance to the selection of evaluation procedure.

The crack growth testing performed at 20 kHz was running well, the fracture surface displayed the features commonly observed also at low frequency testing. A difference in da/dN vs ΔK path between the ΔK -decreasing and the ΔK -increasing stages were found, Fig.4a), even though the locus of threshold level was the same. Any dissimilarity in crack growth features appearing on the fatigue fracture surface was looked for, but not found. It may be effects embodied in the test material, crack closure or test procedures. Further work will explore the differences. However, the experiments showed that the crack growth rates obtained from the ΔK -increasing stage were more collected and better fitted to Eq. 3, as shown in Fig. 4a).

5. Conclusions

A theoretical and experimental study on crack growth testing at 20 kHz load frequency was performed. The work is concluded by the following points.

- An acceptable estimate of the resonance frequency of a cracked specimen at 20 kHz testing was obtained by including the entire load train in the FEM modal analysis and combining this with the ENF model. Using only the test specimen in the model will overestimate the effect of the test frequency.

- The results of the stress intensity calculations for varying crack lengths show a clear difference between dynamic and static computations, where the statically computed stress intensities are approximately 30% lower. The addition of including the entire load train in the analysis will have some effect as well.
- The crack growth parameters, C and n , were determined for the ΔK -increasing procedure and using dynamic ΔK -computation, corresponding fairly well to low frequency test results.
- The present work displayed the effect of using static or dynamic ΔK computation on the evaluation of the 20 kHz crack growth test results. Further work is needed to explore a correct procedure for test evaluation.

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