FATIGUE AND FRACTURE UNDER VARIABLE-AMPLITUDE LOADING AT ULTRASONIC FREQUENCY

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ABSTRACT

Variable-amplitude loading according to a recommended standard-procedure was performed at a frequency of 20 kHz. Results for tool-steel are compared with SN curves of constant amplitude tests.

KEYWORDS

Fatigue, variable-amplitude loading, SN curves, ultrasound-loading, damage-accumulation, RMS-stresses.

INTRODUCTION

Most components of structures and machines are subjected to fatigue in service under conditions of varying amplitude and non-constant amplitude, but most fatigue tests in laboratories up until now have been performed with constant amplitudes. However, in recent times, more efforts have been made to obtain fatigue-life as well as crack growth data under more or less realistic conditions, i.e. under variable loads.

One of the main purposes of such tests is to predict fatigue life or rate of fatigue crack propagation of a certain component in service. Especially in the aircraft-, automobile- and offshore structure-industries such results are necessary, for example in designing special structures or in determining the time during which a component will work without failure. Normally these predictions are based on calculations, which assume a certain damage accumulation (fatigue life), or crack growth model (fatigue crack propagation).

The earliest and presently accepted damage accumulation model is the Palmgren-Miner rule (Palmgren, 1924, Miner, 1945) which assumes linear damage accumulation. Some of the models which predict crack growth rates under variable amplitude loading are the RMS method (Paris, 1960) which uses the random mean square value, the Wheeler-model (1970) which accounts for crack growth delay due to overloads by introducing the plastic zone size, and the Willenborg-model (1971) or the crack-closure model by Elber (1968) which take into account interaction effects. Another method for prediction fatigue life or crack growth rates is to conduct experiments under variable-amplitude conditions.

However, neither of the above mentioned methods are free from problems, because a series of more or less unrealistic assumptions or limitations have to be accepted in both cases. For example, a damage accumulation model cannot account for all unknown effects caused by previous peak or low stresses, which influence crack propagation and life time. Experimental fatigue life predictions contain other problems, in trying to simulate service loading. If service-load sequencies were used the testing times would be much too long. Therefore the applied amplitudes must be manipulated, i.e. they have to be increased (Fig. 1a) or small amplitudes have to be omitted (Fig. 1b) in order to obtain failure within reasonable time periods. So tests are carried out with a load spectrum which is only "similar" and not identical to that in service. This is often done in random tests with return periods, simulating the repeat of a fixed sequence (Schütz, 1982). For offshore structures e.g. 10^7 cycles is used, characterizing a return period of one year and 10^8 cycles would be necessary to simulate its whole life. A test with such a high number of cycles would be too long and expensive even at a high testing frequency (approximately 100 days at 10 Hz) (Schütz, 1982).

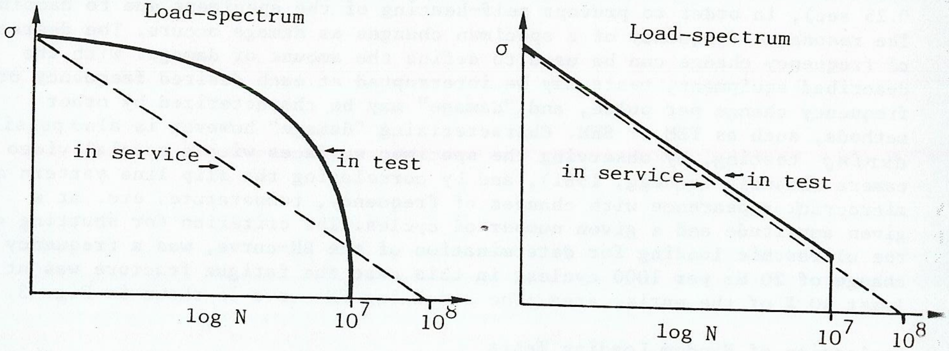

Fig. 1: Ways of simulating in service variable-amplitude sequencies (after Schütz, 1982).

a) Changed sequence in test to obtain failure within shorter

b) Omission of low amplitude in test

Therefore, it was thought useful to determine whether the ultrasound technique, which works at a frequency of about 20 000 Hz is appropriate for variable amplitude testing. In previous works it has already been shown that the testing frequency is of secondary importance (Stanzl, Tschegg, 1983), and less important than in constant amplitude tests (Schütz, 1982). So the aim of this work certainly seems promising not only from a scientific but also from an economic point of view as the ultrasound method would make it possible to conduct tests which were not possible or nearly impossible at low frequencies (10^8 cycles requires only 1.4 hour !).

The advantages are obvious; the difficulties will be discussed in this paper and it will be shown that some compromises concerning the testing technique have be to made. Essential compromises are necessary also for tests at "normal" frequencies as discussed above and it is the aim of this work to establish a testing method, which works with compromises of essentially *different* nature.

EXPERIMENTAL PROCEDURE OF ULTRASONIC FATIGUE WITH VARIABLE AMPLITUDES

Equipment consisting of an ultrasound machine working in resonance and a control unit, which yields constant or pre-determined variable amplitudes plus a computer (PDB 11/03) as described earlier (Stanzl, Tschegg, 1983) was used in this work.

Tests were conducted on tool steel with 0.45 % C, 0.3 % Si, 0.7 % Mn, max. 0.035 % P, max. 0.035 % Si. From this steel hour-glass shaped specimens with an inner diameter of 6 mm were polished and annealed in a vacuum and furnace-cooled.

In the ultrasound test, the maximum values of strain and stress are generated in the centre of the specimen. Loading is of fully reversed push-pull type (R = -1). The maximum vibration amplitude is produced at the ends of the specimens where it is measured with an electrodynamic amplitude gauge. From this, strains and stresses are calculated assuming elastic behavior of the specimens. The signal of the amplitude measurement is also used for feed-back control. Strains are also measured directly with micro-strain gauges (LY 11 Hottinger-Baldwin).

Using a computer, almost all desired amplitude-sequences can be simulated. However, the build-up of the full vibration amplitude requires approximately 150 cycles because of the resonance type of loading (Fig. 2d). This means that it is not possible to generate single vibrations; usually pulses of 1000 cycles (50 m sec) are produced.

For frequency measurement a special PLL (phase lock loop) counter is necessary, because a single vibration lasts only 50 μsec in the 20 kHz test. With the aid of this and appropriate software, it is possible to stop the test when a certain frequency change between two pulses has been reached. The unit also contains a cycle counter.

All desired measurements (displacement-amplitude, strain, frequency, number of cycles, temperature) are recorded, may be printed out and watched on a monitor during the test.

Random-Amplitude Tests

There are basically two ways of making use of the time-saving ultrasound method. One is to run sequences, which are *not* manipulated , i.e. where the amplitudes are not "scaled up" (Schütz, 1982), or where low amplitudes are omitted. Another way is to run the same test sequence, as with low frequency (i.e. manipulated), but at lower amplitudes. At such low amplitude levels, low-frequency tests would last too long.

In this work the second case was performed: a variable-amplitude program was developed, similar to the recommended standard-procedure, which simulates a random-amplitude sequence (for details refer to Fischer and co-authors, 1977). The load-range is classified into 32 levels (Fig. 2). A pseudo-random sequence of maximum amplitudes, which is essentially a Gauss series, is generated with an irregularity factor of 1 (defined as ratio of transitions through the mean value and numbers of load-reversals) and a return period of 10^6 cycles (Fig. 2). The mathematic formalism for generating the amplitude sequence is given by the Markov theory, which statistically combines one maximum value with the following one. A "transition matrix" is generated, which is axially symmetrical and symmetric around both diagonals (Fig. 2b). In this work, similar to low-frequency tests amplitudes

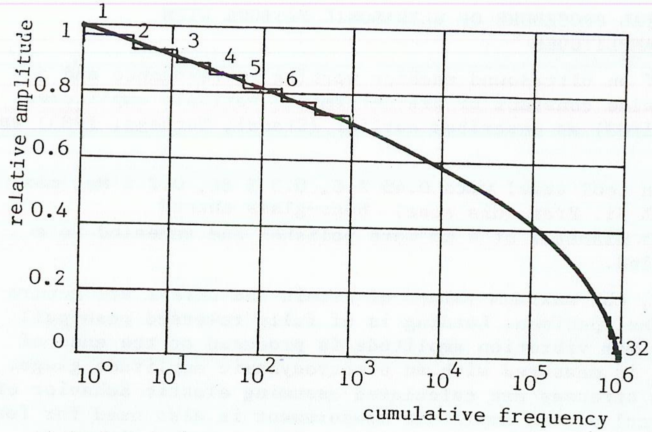

Fig. 2a

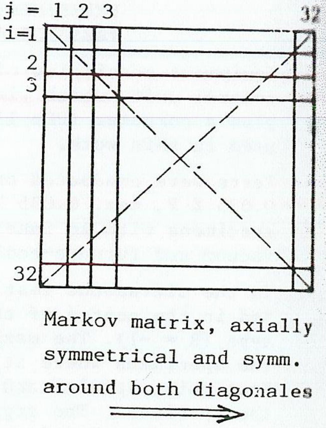

Fig. 2b

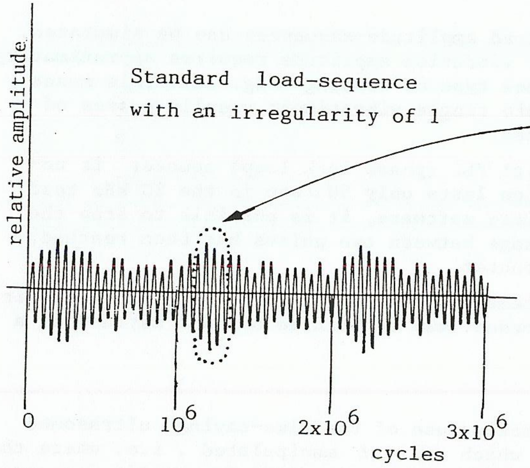

Fig. 2c

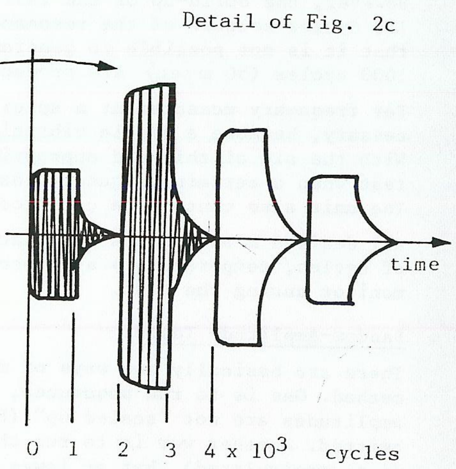

Fig. 2d

Fig 2: Load spectrum in ultrasound fatigue test (similar to procedure, recommended by Fischer and co-authors, 1977)

a) Amplitude spectrum is classified by 32 levels; highest amplitude is applied only once during one return period, lower ones more often

b) Markov matrix for generating a Gaussian type sequence; $a_{ij} = a_{ji}$

c) Part of load sequence generated with the Markov matrix procedure. Irregularity factor $(N_0/N_1) = 1$; return period: 10^6 cycles

d) Detail of Fig. 2c: One low-frequency cycle is replaced by 1000 cycles in the ultrasound test.

smaller than 10 % of the maximum value were omitted.

The random tests were performed such that one cycle of the low-frequency test was replaced by a pulse consisting of 1000 cycles (50 m sec) in the ultrasound test. In addition, periodic interruptions of 50 m sec were imposed after each pulse for cooling purposes (Fig. 2d).

RESULTS

SN-Curve and Definition of "Damage"

In determining the SN-curve, ultrasound loading was performed with periodic interruptions of 2.5 sec after pulses of 5 x 10^3 cycles (equivalent to 0.25 sec), in order to prevent self-heating of the specimens due to damping. The resonance frequency of a specimen changes as damage occurs. The degree of frequency change can be used to define the amount of damage. With the described equipment, tests may be interrupted at each desired frequency or frequency change per pulse, and "damage" may be characterized by other methods, such as TEM or SEM. Characterizing "damage" however is also possible *during* testing, by observing the specimen surfaces with a special video camera (Stanzl, Tschegg, 1981), and by correlating the slip line pattern or microcrack appearence with changes of frequency, temperature, etc. at a given amplitude and a given number of cycles. The criterion for shutting off the ultrasonic loading for determination of the SN-curve, was a frequency change of 20 Hz per 1000 cycles; in this case the fatigue fracture was at least 40 % of the entire area. The resulting SN-curve is shown in Fig. 3.

Evaluation of Random Loading Tests

There are different possibilities in evaluating the data of random tests. If the results are to be compared with constant-amplitude tests, a basis for comparing the stress-amplitudes would be interesting. One possibility is the introduction of the root-mean-square (RMS) of the variable amplitude sequence as a value, which should be equivalent to the constant amplitude in the SN-test. No interaction effect can be accounted for in this way. Therefore probably no good correlation of constant and variable amplitude results was normally found (Schijve, 1976) except by Barsom (1976). Another possibility has been proposed by Paris (1960), who abandoned any relationship to constant-amplitude data and introduced a "characteristic" stress-intensity value.

In this work the cycles to failure of the random tests are plotted versus the values of maximum stresses (σ_{max}) and strains (ε_{max}) (Fig. 3). Comparision of this curve with the SN-curve shows that the number of cycles to failure is more than an order of magnitude higher than in the constant-amplitude test. Or in other words, same fracture times are obtained at approx. 1.4 to 1.6 times the maximum stresses experienced in the finite-life regime, compared to that at constant amplitudes; the endurance limit is also approx. 1.3 times higher. This result is not surprising, as the maximum stress is reached only once during 10^6 cycles in the random test.

Life prediction based on the SN-curve (Fig. 3) using the Miner-approach results in life times which are approximately three orders of magnitude higher. This is again not surprising, as the measured SN data cover only the regime of the endurance limit, which Miner excluded from his approach.

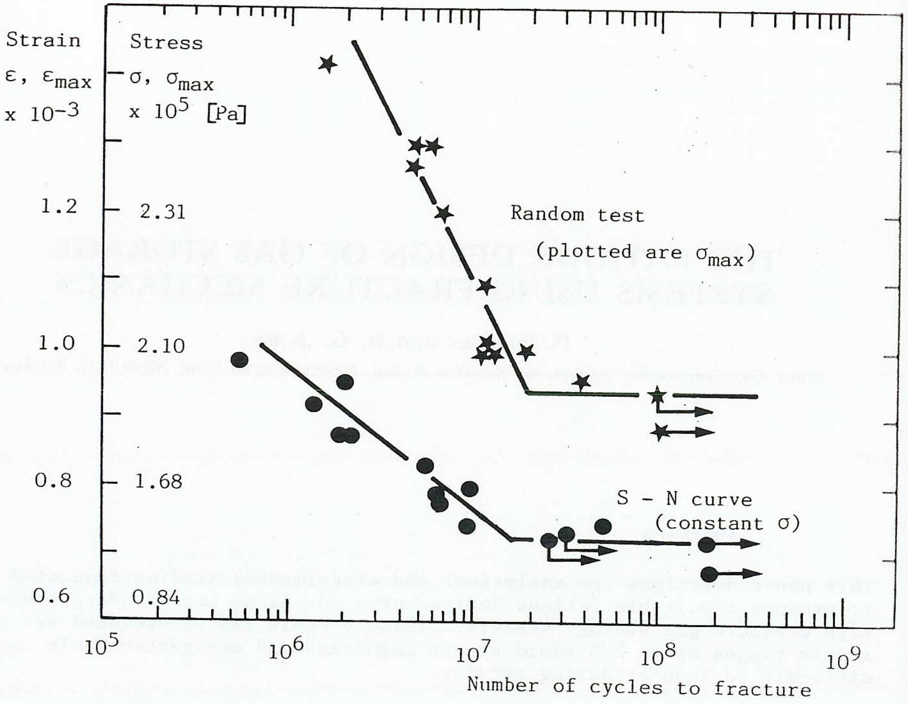

Fig. 3: SN-curve and and random-loading results of a 0.45 % tool steel measured with the ultrasound method. For the random-test results the maximum values of stresses and strain are plotted.

The RMS approach assumes that Miner's rule is valid and that the SN curve has an unrealistically high slope of two. Neither of these assumptions is valid in this work. Therefore the RMS values do not approach the constant-amplitude data; the RMS values are up to four times lower at comparative life times.

These results demonstrate that life-predictions for variable-amplitude loading based on calculations are questionable in the regime of the endurance limit. Therefore, especially in this regime, life-time predictions based on experiments seem to be necessary. As very high numbers of cycles are required in such experiments, the ultrasound method is thought to be the most appropriate for these tests.

ACKNOWLEDGEMENT

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