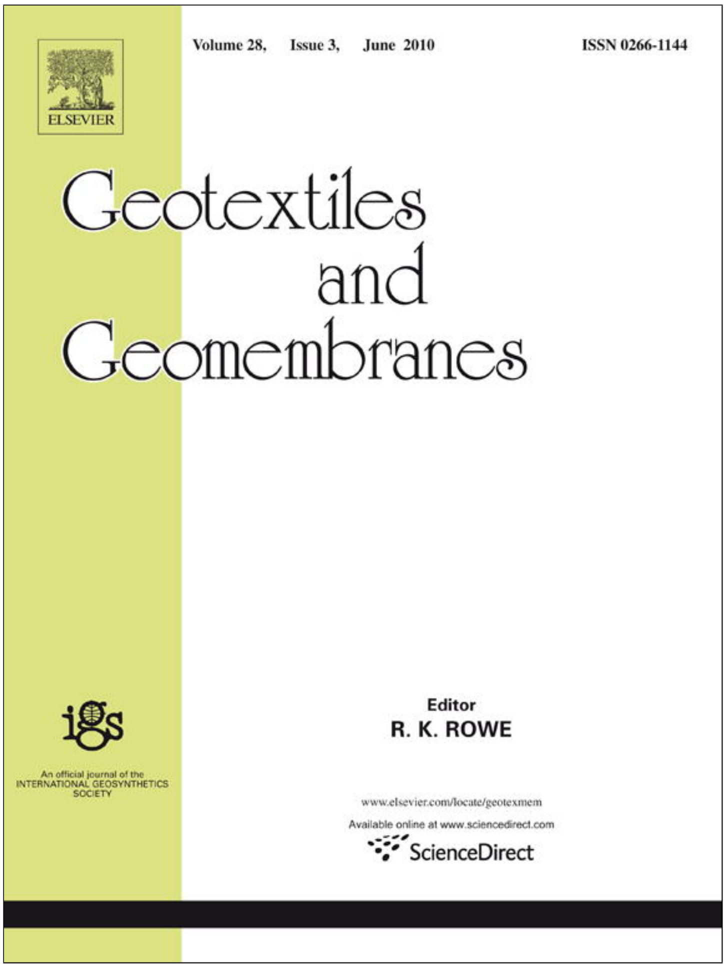
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Fatigue behaviour of a PET-Geogrid under cyclic loading

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ABSTRACT

The lines of 'damage-begin' and 'specimen-break' for dynamic loading of a geogrid were determined in a series of laboratory testing. The cyclic load ratio was set to $R = 0.5$, loading frequency $f = 10$ Hz and $f = 3$ Hz. The test results show clearly that the chosen procedure for the determination and analysis of the beginning of damage and break is reproducible and allow for safe extrapolation for lower load levels. Furthermore the method chosen enables explicit decrease of the required testing time. The assumption of linear damage accumulation was examined in two-step-trials. The number of load cycles to 'break' evaluated in 'one-step-tests' compared with those of 'two-step-loading' are practically the same. The existence of 'damage-lines' for the examined geogrid under a dynamic pulsating load of 10 Hz and 3 Hz and a R-value of 0.5 could be verified. Damage of the specimens occurs only for load-cycles lying between the 'damage-line' and the 'stress-cycle-diagram' ('Woehler-curve'). When it comes to dimensioning against 'damage-beginning' or 'break', higher loading frequencies present the critical case.

1. Introduction

1.1. Dynamic loading of geosynthetics

High strength geosynthetic reinforcement materials in earth structures like road- or railroad embankments are exposed to dynamic loading. The pulsating tensile forces in the reinforcement are greatest near the ground surface in the zone of traffic load application. They decrease with depth quite rapidly (Auersch and Rücker, 2005). Whenever possible, in design practice it is avoided to install geosynthetic reinforcement layers in the narrow zone of extreme dynamic loading. A certain minimum distance from the source of dynamic load generation is commonly maintained. However, there are cases where it is advisable by technical or by economic reasons to install geosynthetic reinforcement in the zone where dynamic loads must be considered. Usually, in such situations, a reduction factor RF_{dyn} is taken into account in static design analyses. Up to now there have not been any systematic evaluations of the dynamic reduction factor RF_{dyn}, which is essentially treated like an additional factor of safety in static structural analyses.

The question whether construction members made of polymeric material exhibit a well defined fatigue strength which depends on the number of load cycles, frequency, amplitude, magnitude of loading and temperature, comparable to the performance of steel under dynamic loading has been studied by material scientists for some time. The behaviour of steel is well known on the basis of more than 100 years experience, and extensive dynamic testing has been executed on light metals as well as on fibre-composite-materials for the aero-space industry. In this regard, little attention has been given to the dynamic behaviour of geosynthetic products. Yet, since high tenacity geosynthetic reinforcement is being employed in structures which are exposed to dynamic loading such as railroad embankments, there is a demand for a better understanding of their long term performance under cyclic loading.

1.2. Principles and definitions

1.2.1. Fatigue

Fatigue is a comprehensive term to describe the decrease of strength of a material caused by variable loading conditions. Ultimate failure is initiated by a process of progressively developing fissures. The higher the number of load cycles N, the smaller the ultimate failure stresses. Fatigue, and thus long term strength under repeated cyclic loading is considerably influenced by the difference between maximum and minimum stress and by the effect of grooves or notches in solid materials. The progressive development of fissures leads to a reduction of the intact load bearing cross section and ultimately to brittle failure of the structural member.

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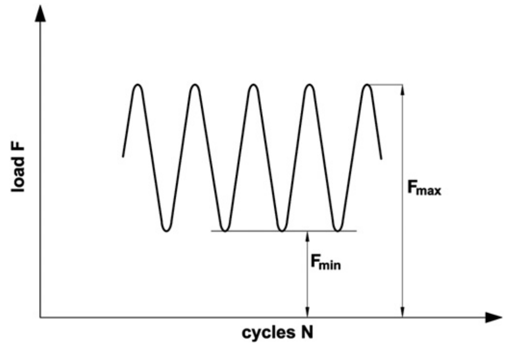

Fig. 1. Denomination of symbols.

1.2.2. Long-term cyclic loading

Under cyclic loading, the stress varies continuously between the maximum load F_{max} and the minimum load F_{min} (Fig. 1). The load ratio R is defined between lower load F_{min} and maximum load F_{max}.

1.2.3. Stress-cycle-diagram – 'Woehler-curve'

The German engineer August Woehler in the period between 1858 and 1870 had carried out the first series of systematic long-term cyclic loading tests ('Woehler-tests') on structural members made of steel. He elaborated the first 'stress-cycle-diagrams', presenting the relationship between number of load cycles to failure and stress. In the international literature 'stress-cycle-diagrams' are often called as 'Woehler-diagrams'.

In the 'Woehler-test', specimens are subjected to cyclic loading following sine-load-time functions (load collectives). The load amplitudes as well as the load ratio R of minimum load to maximum load are kept constant in 'Woehler-tests'.

For the determination of the relevant parameters of a 'Woehler-diagram', the sample is tested at several stress levels. A test is conducted until a defined mode of failure is observed (break or initiation of cracking) or until a predetermined number of load cycles are reached. The 'Woehler-curve' is generated from data sets of loading (stress or force) and number of load cycles. The diagram is commonly presented on a semi-logarithmic or on a double-logarithmic scale. Usually the nominal load amplitude F_a is plotted versus the endured number of load cycles N.

A typical 'Woehler diagram' for a steel sample shows the following features (Fig. 2):

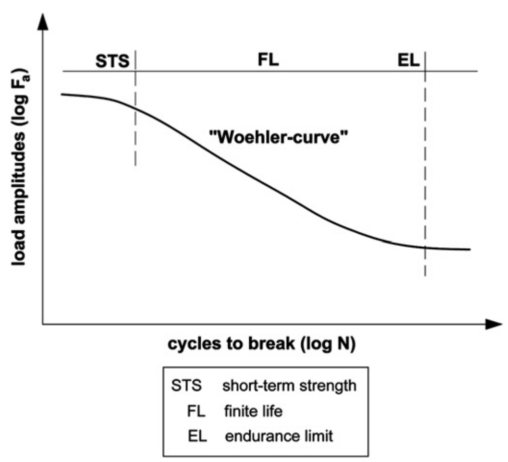

Fig. 2. Typical 'Woehler-diagram' for steel.

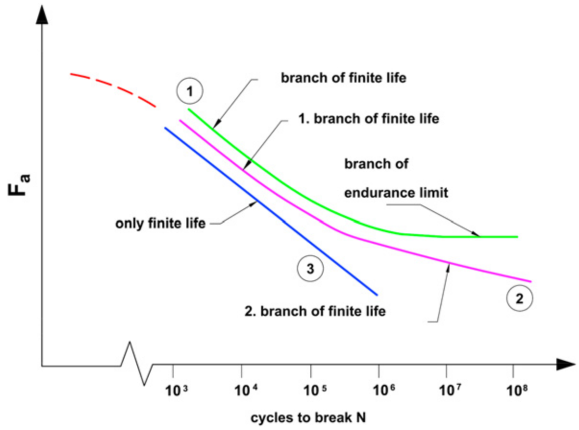

Fig. 3. Schematic stress-cycle-diagrams of different materials.

- region STS of short-term strength (static strength determined in tensile tests)
- region FL of finite life (time dependent strength), approximately straight line portion of the 'Woehler-diagram' on a double logarithmic plot
- region EL of the so called endurance limit

1.2.4. Endurance limit

The region endurance limit (EL) is beginning at about 1–5 million load cycles in case of steel (curve 1 on Fig. 3), and at about 100 million load cycles in case of light metals (curve 2 on Fig. 3). If a structural member undergoes continuous corrosion or is exposed to elevated temperatures then a pronounced endurance limit cannot be expected.

It is not known whether polymeric materials possess a pronounced endurance limit. Their stress-cycle-diagrams consist of the straight line portion only, representing the finite life region FL (curve 3 on Fig. 3).

1.2.5. 'Damage-line'

In principle, a structural member can resist an arbitrary number of load cycles below the endurance limit (region EL). Loading above the finite life (i.e. time-dependent strength region FL) causes failure of the structural member after a certain number of load cycles. Within the region FL of time-dependent strength, a test sample can withstand elevated loads for a limited time. The region of finite life is subdivided into two parts by the 'damage-line' (Fig. 4):

Below the 'damage-line', a test sample can be charged with elevated loads for a limited time without suffering fissure initiation. When subjected to loads between the 'damage-line' and the 'Woehler-curve' for a certain time, the sample does not break under elevated loading however, it is suffering damage in the form of small fissures. The 'damage-line' indicates after how many load cycles initial damage occurs without total failure of the test specimen.

1.2.6. Reproducibility, statistics

In materials testing practice, it has been observed that 'Woehler-test' results show a wide spread with respect to the number of cycles until fatigue failure for identical test samples subjected to the same loading conditions. So it has become state of the art to consider 'Woehler-diagrams' under statistical aspects. Likewise, the 'damage-line' can be regarded statistically. However, such practice requires a substantial volume of testing.

Within the ranges of statistical reliability for operational working conditions (variable load amplitudes) the number of loading cycles that a structure can resist may be predicted on the basis of the

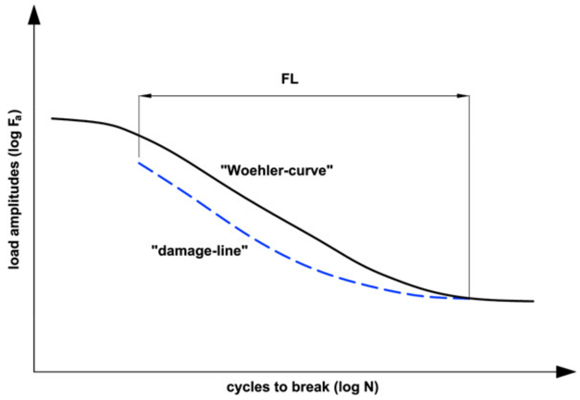

Fig. 4. Typical 'damage-line' of steel.

'Woehler-diagram'. For this purpose the method of linear-damage-accumulation after Palmgren (1924) and Miner (1945) is used. The concept of linear-damage-accumulation facilitates assessing the influence of a load-collective on the fatigue behaviour namely, the number of load cycles until failure.

1.2.7. Load-collectives, damage accumulation

In the normal case, a structural member is not subjected to cyclic loading with constant load amplitudes (rectangular load-collective) only as in the 'Woehler-test' but the magnitude of the load varies. To account for varying load amplitudes in the determination of number of load cycles that can be endured, the amplitude-collective is subdivided into several rectangular-collectives with constant amplitudes each, and partial numbers of load cycles. For each of the partial collectives, the partial damage is determined according to the method of linear damage accumulation. The partial damages are then summed up and result in the total damage of the structural member. If the total damage exceeds the value of 100%, then for the load-collective in question failure has to be anticipated.

2. Dynamic fatigue tests on a geogrid

The fatigue behaviour of a geogrid was examined via an extensive testing program (SKZ, 2005) by 'one-step-cyclic-fatigue-tests' or 'Woehler-tests' with specified parameters. The specimens were submitted to cyclic tensile forces following a sine-load-function with constant amplitude from the beginning of the test until fatigue failure.

The main parameters were the applied frequencies of 10 Hz and 3 Hz and the load ratio $R = 0.5$ in the tensile loading domain.

Experience gained from in-situ measurements of railway embankments shows that such loading can be considered to conservatively represent very intensive traffic loading, lower speed and high weight as well as high speed and comparatively lower weight.

As a result of these 'one-step-cyclic-fatigue-tests', 'Woehler-diagrams' demonstrating the numbers of load-cycles until fatigue failure depending on the maximum stress and the test frequency were obtained.

Besides focusing on fatigue failure, attention was paid to specimen temperature, deformation amplitude, energy dissipation (loss work) and dynamic stiffness. These parameters were recorded simultaneously and evaluated during the cyclic tests. The analysis of these data indicated that specimen damage is not initiated at the first loading cycle but starts at a later stage of the test. This means that there is a region of working stress below the 'Woehler-curve' in which the specimen does not suffer any damage. The hypothetic 'damage-lines' for the beginning of damage, respectively 0% damage, are presented subsequently, taking statistical aspects into account. The 'Woehler-diagram' can be regarded as the 'damage-line' representing 100% damage, equivalent to 'break' or specimen failure. This view does not give an indication of the mechanisms that cause the damage.

In the literature on 'Dynamic Material Testing' e. g. Renz (1987), Renz et al. (1986), specimen damage is often evaluated qualitatively on the basis of hysteresis measurements. The hysteresis method is very sensitive and suitable for the determination of rupture of fibres e.g. used in the matrix of glass-fibre-composite synthetics.

In the case presented here, specimen fatigue during dynamic testing is influenced by several factors which are acting simultaneously. The synchronous data evaluation described subsequently accounting for reproducible changes in the performance of the tested material clearly and plausibly indicates the beginning of damage at a certain number of load cycles which depends on the magnitude of loading. For the verification of this hypothesis, additional tests using different methods were necessary (SKZ, 2006). These controlling 'multiple-step-tests' are presented in Section 4.9.

3. Testing

3.1. Test set-up

The test samples consisted of knitted polyester (PET) geogrid with a short-term tensile strength of 560 kN/m. The dynamic tests were carried out in the load controlled mode with servo hydraulic dynamic testing machines by keeping the dynamic maximum loads F_{max} and minimum loads F_{min} constant for each test. The test set-up is shown in Fig. 5. The load cell for the measurement of time dependent forces is seen at the top. Loads were generated hydraulically and transmitted via the piston that is seen at the bottom. The movement of the piston is recorded by an internal displacement transducer. In addition, the deformation of the test specimens was measured by an extensometer attached to the them.

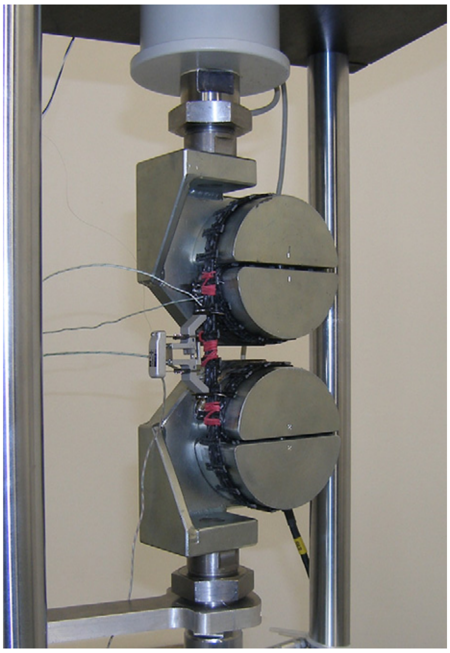

Fig. 5. Test set-up showing one thread (warp direction of the geogrid), clamping arrangements, extensometer (in the middle) and three thermocouples.

The design strength of such high strength geogrids required for ultimate limit state design would typically vary between 40 and 60% of the short term tensile strength and it is depending on various input parameters like loading time, environmental influences and design concept. Clamping was done using Capstan-clamps consisting of a rigid and a mobile half-cylinder each which are tightly fixed in order to grip the test specimen.

3.2. Data acquisition

The hydraulic testing machines for cyclic loading are controlled by electronic devices. Specialized computer software was used for acquisition and recording of all relevant data: number of dynamic load cycles, piston movement, readings of the extensometer, forces (F_{max} and F_{min} etc.) and temperature measurements at three locations.

These data were used to compute derived values for a more comprehensive evaluation of test results. Some of these derived values are loss work or stored energy per load cycle, dynamic stiffness or dynamic modulus of elasticity and phase angle between force and displacement.

3.3. Testing concept

When similar test samples are subjected to identical dynamic loading, fatigue failure is not experienced by all test samples at the same number of endured loading cycles. There is always a certain scatter of test results. Therefore the tests have to be repeated sufficiently, in order to yield statistically secured information.

In the present case at least 9 tests were carried out for each of three load levels. The evaluation of all test results lead to 'Woehler-diagrams' presenting the number of load cycles until fatigue failure for each of the loading levels tested. On a double logarithmic scale, the diagram of maximum cyclic load F_{max} versus number of cyclic loads until failure N_F appears as a straight line. The probabilities of failure P_F were computed under the assumption of normal standard distribution of failure events.

Most of the synthetic materials show a strength decrease with increasing temperature. In order to evaluate the influence of the temperature effect on the results of the fatigue tests, tensile tests were carried out using the same equipment as for the dynamic testing but at different temperatures (see Section 4.5).

4. Test results

4.1. Definition of damage

Analysis of the test results, in particular of plots of dynamic modulus, stiffness and temperature versus number of load cycles, which are indicative of hysteresis, shows minima, respectively maxima well before failure occurs (Fig. 6).

For the testing arrangement of the present case it may be assumed that the signs of fatigue of the test sample are not indicated by a single effect but with a high probability by several effects. It may be deduced that after passing the mentioned minima and maxima (Fig. 6), changes in the properties of the test sample have occurred.

Fig. 6 presents data of a single test. This allows insight into the process of damage development. The computer software used for the evaluation of the test results facilitates simultaneous presentation of different parameters as functions of the number of load cycles, and it is possible to navigate with a cursor within the diagrams simultaneously.

In all four diagrams, the number of load cycles is presented on the abscissa. The upper diagram (Fig. 6a) shows the displacement amplitude of the extensometer, the second diagram (Fig. 6b) shows the dynamic modulus (stiffness). The loss work is plotted on the

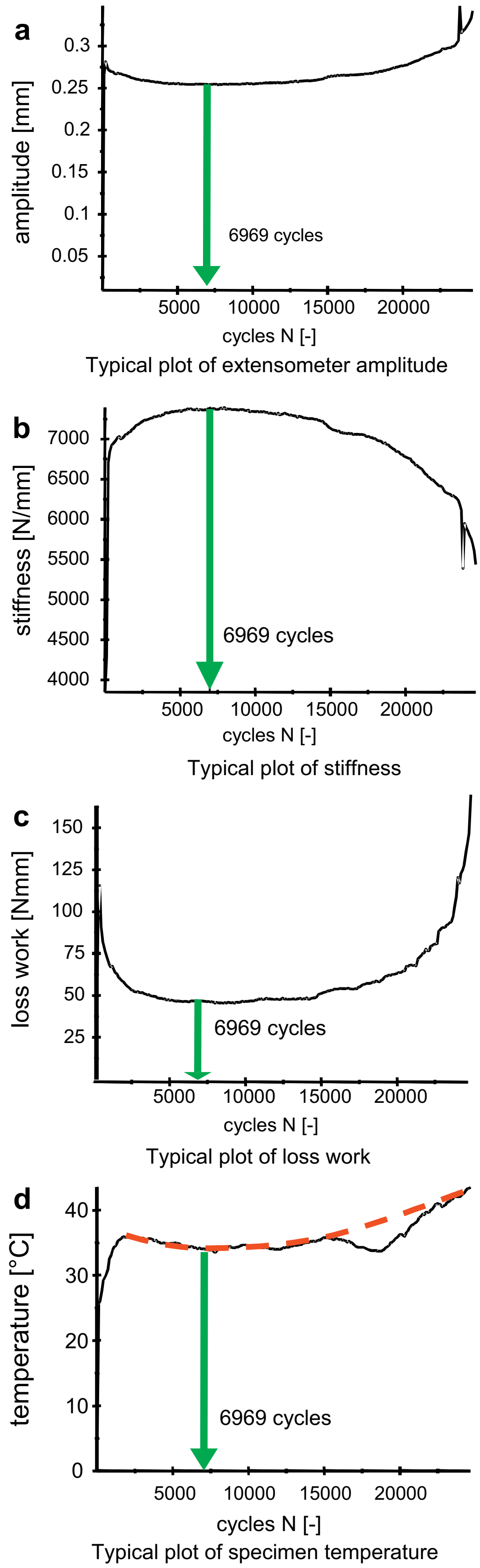

Fig. 6. Evaluation of specimen damage on the basis of different data, typical plot for one single test.

third diagram (Fig. 6c), and the temperature in the middle of the specimen is plotted on the fourth diagram (Fig. 6d). In the diagrams, the position of the cursor on the screen is marked by a cross (in Fig. 6, it is shown as an arrow; in the given example at 6969 cycles). The cursor that moves along the plotted curves has reached minima/maxima on three of the four diagrams indicating a good correlation between the respective numbers of load cycles at which these extreme values are reached. Like in case of the probabilities of failure, the probabilities of the appearance of these extreme values were determined with statistical methods and it was noticed that the relationship between minimum of displacement, minimum of loss work and maximum of stiffness and the number of load cycles follows similar rules as the relationship between fatigue failure and number of load cycles. Also the temperature in Fig. 6d showed a minimum at the same number of load cycles. After that minimum there was a variation of the temperature which might be due to poor contact of the temperature sensor with the geogrid surface. Finally the temperature reached a maximum at failure. The doted line shows clearly that the minimum in this example was at around 7,000 cycles. Therefore it can be stated that all measured data indicate that the change of the properties occurs at a certain number of cycles. This significant number of load cycles will be used in the further evaluation as 'begin of damage'.

4.2. Life-time-curve, 'Woehler-curve' for 10 Hz loading cycles

For all evaluated test results, the values of maximum cyclic load F_{max} are plotted versus the respective number of load cycles on Fig. 7. The triangles represent the data for 'damage-begin' and the circles for 'fatigue-failure'.

After computation of the median values for each loading level and evaluation and computation of the regression function for the median values, the 'Woehler-curve' and the 'damage-line' can be plotted.

When a potential function is used as regression function and it is plotted on a double logarithmic scale, the 'Woehler-curve' and the 'damage-line' do appear as straight lines. Visually both curves are almost parallel, an observation which is verified by the fact that the exponents of both regression functions are almost the same. The parameter r^2 of both regressions is very good. Since log-normal distribution was assumed for the statistical analyses, the plotted regression functions describe the location of the maximum of the respective distribution function in each case.

4.3. Lifetime-curves for 3 Hz loading cycles

Like for the test series with 10 Hz loading frequency, the acquired data of the test series with 3 Hz loading frequency were evaluated for each load level by determination of the median values for failure and for 'damage begin'. The obtained values are plotted on the double logarithmic diagram of Fig. 8 together with the respective regression curves which represent the 'Woehler-curve' and the 'damage-line'. The equations of the regression functions are also given. The potential functions plot as straight lines in the double logarithmic graph.

4.4. Comparison of the 'Woehler-diagrams' for 10 Hz and for 3 Hz

When the cyclic load tests are carried out at a load frequency of 3 Hz, failure occurs at considerably higher loading cycles than at the load frequency of 10 Hz. The difference increases with decreasing maximum cyclic load. The 'damage-lines' show similar characteristics.

It is remarkable that, for a certain load frequency, the curves for 'damage-begin' and for 'fatigue-failure' are almost parallel. This incidence may indicate that the observed divergence of the two failure curves is not of an arbitrary nature.

The geogrid specimens are members with a somewhat complex internal structure. Together with the influences caused by the boundary conditions of the selected test set-up and test-procedure this may lead to complicated processes of specimen decay under cyclic loading, to which load-, temperature-, and velocity-dependent material reactions are contributing. It is conceivable that this complex material behaviour is also the reason for increasing scatter of test results with decreasing values of maximum cyclic load which was observed for the tests with both loading frequencies. A reduction of the load frequency like a reduction of the load amplitude at a higher frequency results in smaller loading- and deformation velocity. This effect influences the divergence of the regression curves for fatigue failure as well as for 'damage-begin'.

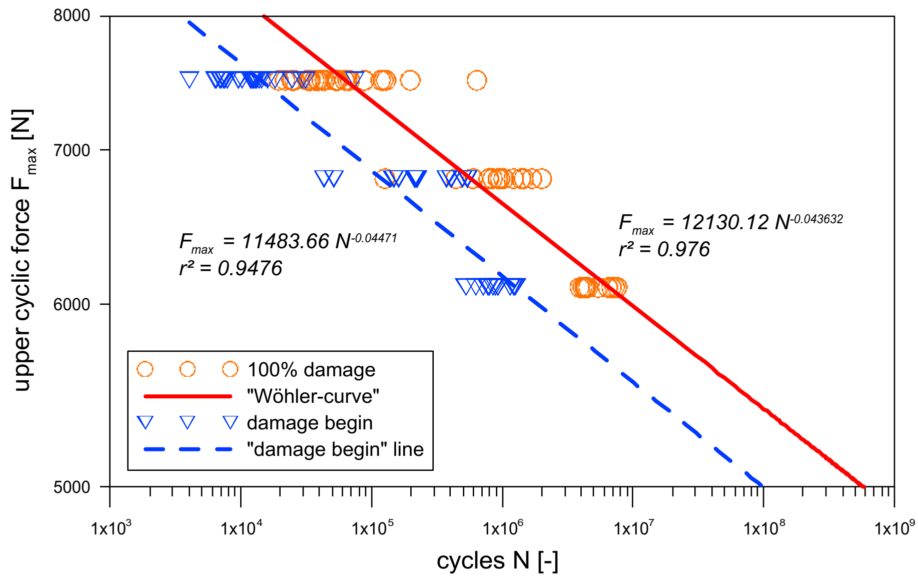

Fig. 7. 'Woehler-curve' and 'damage-line' of the geogrid for cyclic tests with a frequency of $f = 10$ Hz at a load ratio $R = 0.5$.

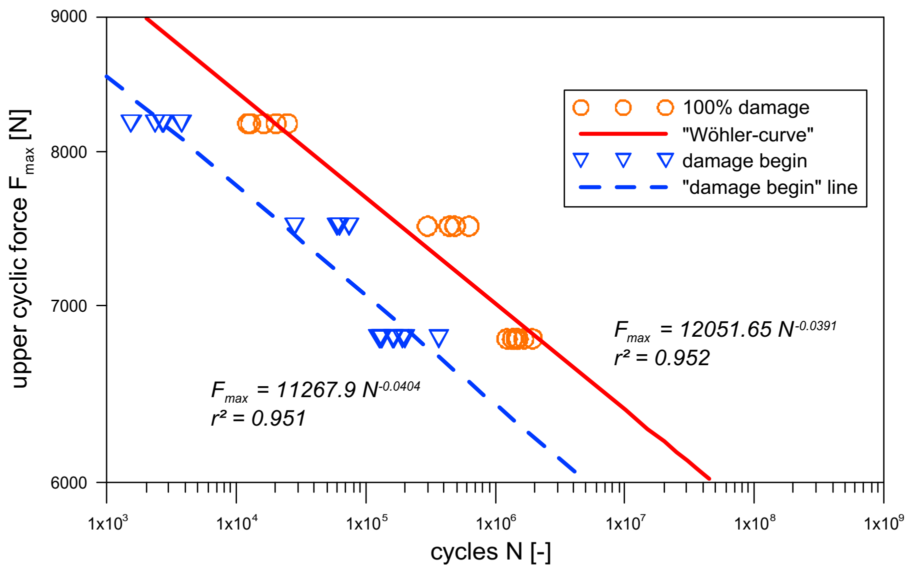

Fig. 8. 'Woehler-curve' and 'damage-line' of the geogrid for cyclic tests with a frequency of $f = 3$ Hz at a load ratio $R = 0.5$.

The dynamic material properties of the geogrid were studied for two different load frequencies only. However, with caution it may be justified to conclude that the number of load cycles to fatigue failure and/or to 'damage begin' depend on the load frequency. The higher the load frequency, the lower the number of load cycles to fatigue failure and/or to 'damage-begin'.

4.5. Influence of temperature

In order to judge the influence of an increase in temperature occurring during the dynamic load tests, supplementary static tensile load tests were carried out on specimens of the geogrid material at 4 different temperatures between 21.5 °C and 40 °C. The static load was applied by means of Capstan-clamps that are used for dynamic testing to make sure that no adverse effects could result from these boundary conditions. The test results showed that different temperatures had only little effect on the strength of high crystalline material like the PET-geogrid in question. Based on a reference room temperature of 23 °C, the reduction of the tensile strength was only in the order of about 2.5%–4%. Geogrids made from other raw materials – polymers with high amorphous parts – like, e. g. HDPE, may exhibit a more pronounced influence of temperature in tensile strength. Cyclic loading tests on an extruded HDPE-geogrids showed temperatures on the specimen during testing of up to 60 °C. These tests needed to be cooled to avoid such high temperatures becomes the dominating influence on these tests (Sürken and Marth, 1994). Since the temperatures recorded during the cyclic load tests were in a range of maximal 30 °C to 34 °C, it could be assumed that external temperature influences were negligible for the cyclic tests on PET-geogrids reported in this paper.

4.6. 'Ideal stress-cycle diagram' – 'ideal Woehler-curve'

Structural members subjected to dynamic loading experience damage accumulation, if beyond the number of load cycles at which the first signs of damage are initiated, each additional load cycle contributes to further damage until ultimately fatigue failure occurs (ref. Section 1.2.7). The most fundamental hypothesis to describe this kind of damage accumulation was presented by Palmgren (1924) and Miner (1945). Their concept known as the 'linear Miner rule' originally served the purpose of predicting 'life-time' for specimens subjected to multiple dynamic load steps on the basis of fatigue test data which had been obtained by single load step dynamic testing ('Woehler-diagrams') and vice versa.

The concept of damage accumulation is explained subsequently on the basis of data obtained in the dynamic testing program on a geogrid presented in this paper.

In the following text, fictive cases will be discussed for 'ideal Woehler-curves'. Assuming all the tested specimens would be identical and have 'ideal material properties', then on any one loading level fatigue failure of all specimens tested at this load level would occur at the same number of load cycles. There would be no scatter in the test results, and the observed numbers of load cycles until fatigue failure would plot on an 'ideal stress-cycle-diagram' or 'ideal Woehler-curve'. The second important assumption for the 'ideal material properties' is that, damage is initiated at the first loading cycle. In this case there is no 'damage-line', that means there is no line limiting the number of loading cycles with 0% damage.

Fig. 9 indicates four levels of dynamic loading F_{max} at 7,000 N (level 1), 6,500 N (level 2), 6,000 N (level 3) and 5,500 N (level 4). If 'one-step-cyclic load tests' would be executed at each of these four load levels then the tests would end after the numbers of load cycles $N_{F,1}$ until $N_{F,4}$, when the respective 'life-times' of the specimens end.

4.7. 'Ideal damage-line', linear damage accumulation

Fig. 10 shows the solid 'ideal Woehler-diagram' with numbers of dynamic load cycles to fatigue failure $N_{F,1}$ to $N_{F,4}$ for loading levels $i = 1$–4. However in case 2, the damage begin is not initiated with the first load cycle but later at numbers of load cycles $N_{0,i}$ which are limited by the dashed 'damage-line'. The 'damage-line' subdivides the area below the 'Woehler-curve' into two sections: Dynamic loading of test samples with numbers of load cycles which plot below the 'damage-line', e.g. $N_{T,1}$ to $N_{T,4}$ for load levels $i = 1$ to 4, does not cause any damage to the sample. Dynamic loading with numbers of load cycles which plot between the 'damage-line' and the 'Woehler-curve' $N_{D,i}$ experience damage, and the damage accumulates with the number of load cycles. So at any load level i, the specimen has a lifetime $< N_F$ depending on the degree of damage experienced $N_{D,i} = N_{F,i} - N_{0,i}$. The closer the point representing the number of cycles to the 'Woehler-curve', the greater the accumulated damage.

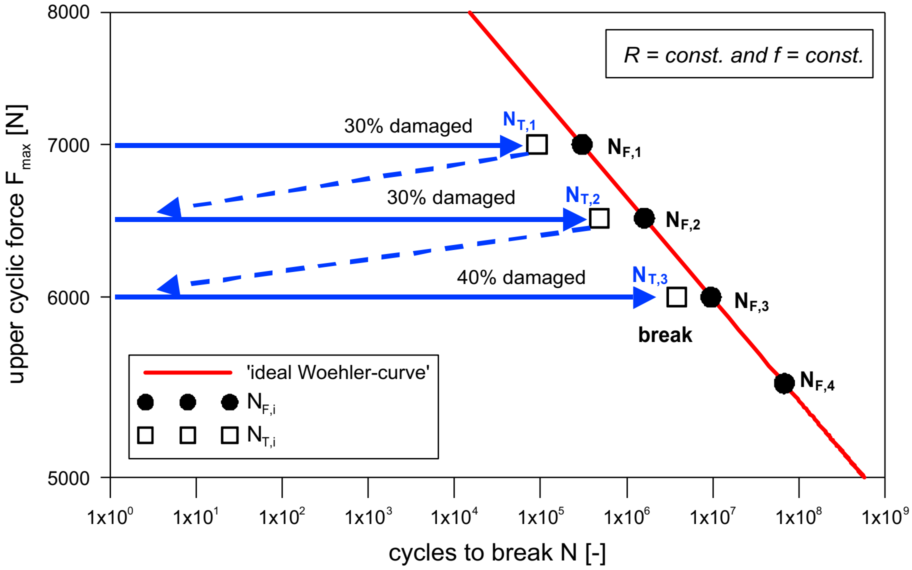

Fig. 9. Case 1 (fictive example) – 'ideal Woehler-curve'.

Case 3 on Fig. 11 represents a dynamic load test which starts at load level $i = 3$ marked as 'start' at a maximum cyclic load of $F_{max} = 6{,}000$ N. The test is run at this level until the accumulated damage reaches 20% of ultimate damage at which failure would occur. The number of damaging load cycles for this condition is $N_{T,D,3} = N_{0,3} + 0.2^*(N_{F,3} - N_{0,3})$, the number of cycles experienced is $N_{T,3} = 2{,}060{,}524$. Then the load level is increased by two steps to $i = 1$. At this level the dynamic test is continued until again 20% of ultimate damage are reached, the number of load cycles is $N_{T,1} = N_{0,1} + 0.2^*(N_{F,1} - N_{0,1})$. By now, the sample has experienced 40% of ultimate damage. Next the load level is decreased to $i = 2$ and the test continued for the number of cycles $N_{T,2}$ to reach 40% of ultimate damage, so the total accumulated damage adds up to 80%. Now, only 20% of ultimate damage are left for the test to continue at load level $i = 4$ with a maximum load $F_{max} = 5{,}500$ N. The number of load cycles to reach fatigue failure at this level is then $N_{T,4} = N_{0,4} + 0.2^*(N_{F,4} - N_{0,4})$. The total number of load cycles that the sample experiences until fatigue failure occurs, according to the dynamic testing program with stepwise changes of the magnitude of the cyclic load amounts to $\Sigma N_{T,i} = N_{T,3} + N_{T,1} + N_{T,2} + N_{T,4} < N_{F,4}$. Table 1 presents all relevant values for the testing program of case 3.

The total number of load cycles on all load levels is $\Sigma(N_{T,i})$. The sum of damaging load cycles is $\Sigma(N_{T,D,i})$. In case 3 the total number of load cycles amounts to $\Sigma(N_{T,i}) = 17{,}219{,}076$, and the number of damaging load cycles to $\Sigma(N_{T,D,i}) = 1{,}671{,}384$.

4.8. Determination of a 'damage-line' under real conditions

For simplicity 'ideal Woehler-curves' and 'ideal damage-lines' were assumed for the description of the concept of damage accumulation. However, in reality, test results show considerable scatter, and a statistical evaluation of test data is necessary. In order to demonstrate the existence of a 'damage-line', essentially an analysis in the opposite direction, such scatter of data would be

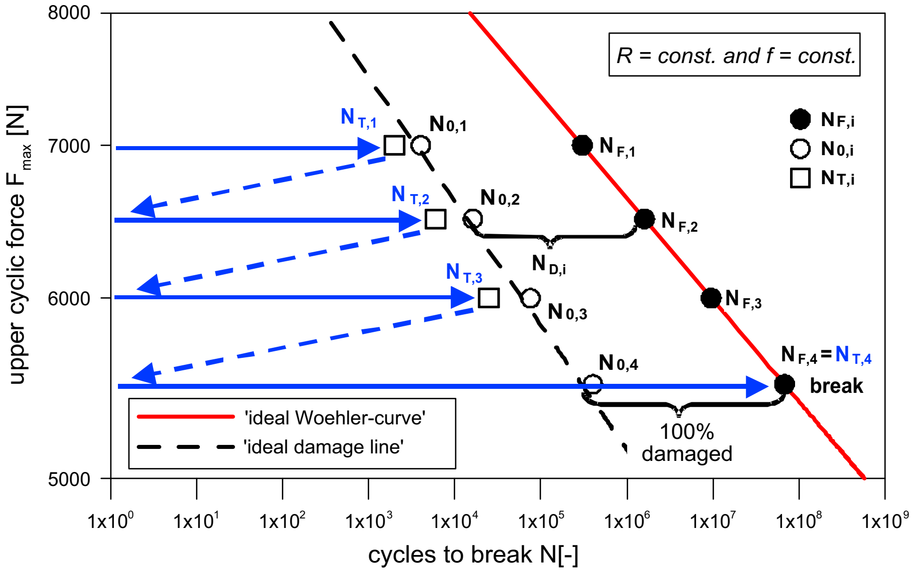

Fig. 10. Case 2 (fictive example) – 'ideal Woehler-diagram', and 'ideal damage-line', specimen without partial damage.

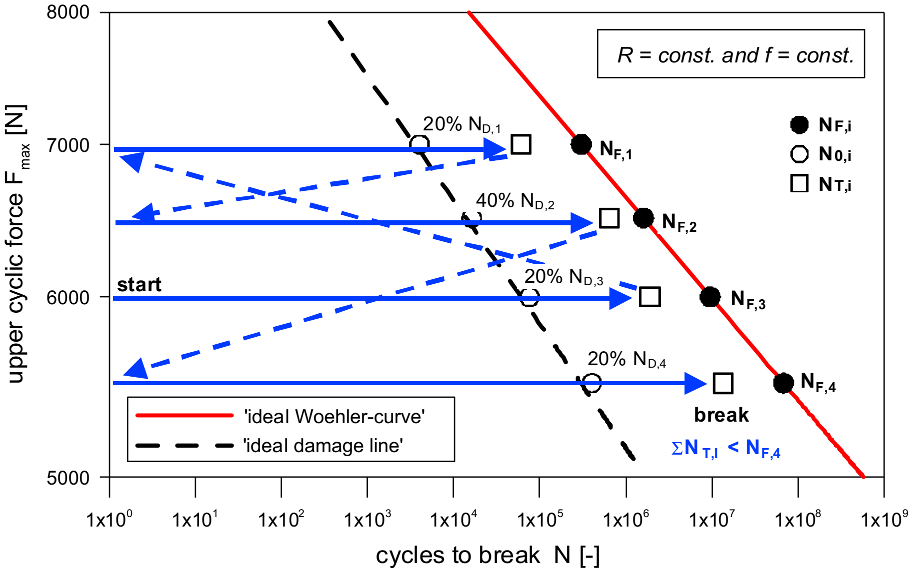

Fig. 11. Case 3 (fictive example) – 'ideal Woehler-curve' and 'ideal-damage-line', specimen with partial damage.

disturbing and demand for more elaborate statistical methods. However, when the principle question whether a 'damage-line' does exist or not has to be answered, its precise location in a 'stress-cycle-diagram' is of secondary interest.

For 'single step' dynamic loading tests the measured values and respective median values together with the 'Woehler-curve' and a tentatively assumed 'damage-line' are plotted on Fig. 12. It is evident that the events 'damage-begin' are subject to considerable scatter. In case of 'two-steps' dynamic load tests, the length of the first block was always chosen in such a way that they comprise 50% of the damage-free lifetime by this reason, starting from the respective median value as 'damage-begin' on each load level. It is apparent on Fig. 12 that thereby, all first steps end essentially outside the damage-scatter, which diminishes the influence of statistics and makes later evaluation of test results remarkably easier. The controlling software of the hydraulic cyclic load testing machines facilitates two- and multiple steps testing programs without interruption and without unloading. The desired load sequences are entered into a listing which contains all relevant data as frequency, number of load cycles and method of control and values of amplitudes per block, i. e. per step. After the start of the testing program the blocks from the listing are executed one after the other by the software. The transition from one block to the next is exercised without shocks continuously within the course of a few load cycles.

4.9. Two-steps tests on real samples

The application of the linear 'Miner rule' was demonstrated by means of idealized cases for three- and four-steps tests with variable sequences of the loading steps in the previous chapters 4.6 and 4.7. However, for the proof of the existence of a 'damage-line', two-steps tests are sufficient. If in the first loading step of a two-steps test the number of applied load cycles is kept smaller than 50% of the number of cycles which can be resisted without damage then the specimen has experienced no damage at this load level. This means that the test can be continued in the second load step at a higher or at a lower load level, and that fatigue failure will occur when number of load cycles are reached which would lead to failure in respective one-step tests with constant amplitude. If the assumption of a 'damage-line' would not be true then the sample would have experienced damage at the first load step already, and it would fail at the second load step earlier than at a respective one-step test with the same magnitude of loading.

4.10. Results of two steps cyclic loading tests

If the assumed damage free number of load cycles on the first loading step as mentioned before would not be appropriate then the two-steps test would result in a 'Woehler-curve' with a smaller number of load cycles to failure than the respective one-step test.

Table 1
Case 3 (fictive example) – 'ideal Woehler-curve'and 'ideal damage-line', specimen with partial damage.

F_{max} (N)	i (-)	$N_{F,i}$ (-)	$N_{0,i}$ (-)	$N_{D,i} = N_{F,i} - N_{0,i}$ (-)	$N_{T,i}$ (-)	$N_{T,D,i} = N_{T,i} - N_{0,i}$ (-)	Partial lifetime $N_{T,D,i}/N_{D,i}$ (%)	Partial lifetime[a] (%)
6,000	3	10,000,000	75,655	9,924,345	2,060,524	1,984,869	20	20
7,000	1	305,385	4,037	301,348	64,307	60,270	20	40
6,500	2	1,629,750	16,298	1,613,452	661,679	645,381	40	80
5,500	4	70,548,023	403,702	70,144,321	14,432,566	14,028,864	20	100
					$\Sigma(N_{T,i}) = 17,219,076$	$\Sigma(N_{T,D,i}) = 16,719,384$		

F_{max} = maximum cyclic load in Newtons.
$N_{F,i}$ = number of load cycles to fatigue failure at load level i.
$N_{0,i}$ = maximum possible number of load cycles without damage at load level i.
$N_{T,i}$ = number of load cycles at load level i with and without damaging load cycles.
$N_{D,i}$ = maximum possible number of damaging load cycles at load level i or $N_{D,i} = N_{F,i} - N_{0,i}$.
$N_{T,D,i}$ = number of damaging load cycles at load level i or $N_{T,D,i} = N_{T,i} - N_{0,i}$.
N_{tot} = total number of load cycles over all load levels.
[a] Accumulated damage.

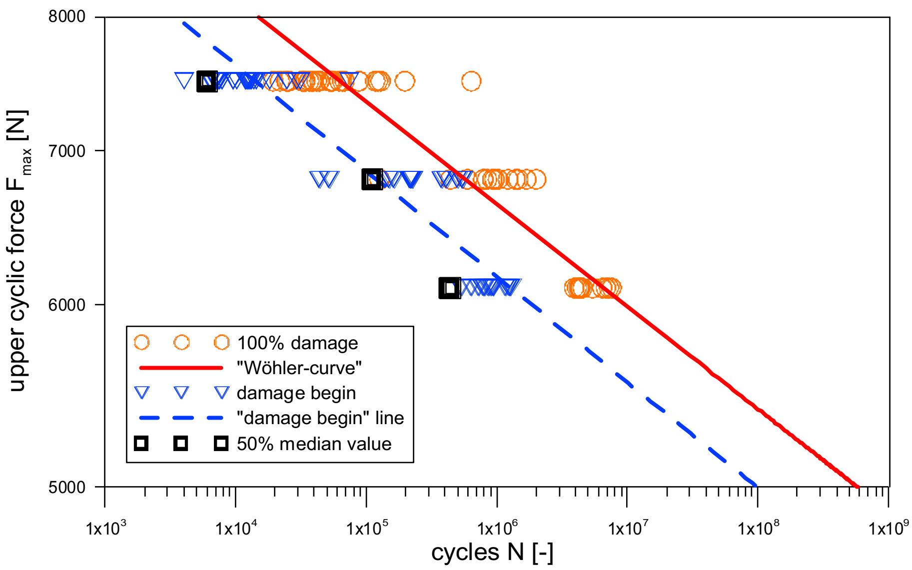

Fig. 12. Determination of number of load cycles of step one (here: 50% of median values ‘damage-begin’), frequency $f = 10$ Hz, load ration $R = 0.5$.

The numbers of load cycles until failure of one-step tests and two-steps tests are plotted in Fig. 13. The diagram also contains the ‘Woehler-curve’ for the one-step tests that is the damage-line for 100% damage. The respective damage line for 0% damage for the proof aimed at is not relevant for the moment. Furthermore, the many additional points would make the diagram confusing. If the failure points obtained in one-step tests and in two-steps tests were plotted into the diagram to scale then the failure points for each load level would be situated above each other. For clarity the individual results for each series and load level are plotted not to scale, situated below each other. The real, undistorted load level is always located in the middle.

The numbers of load cycles to failure presented on Fig. 13 shows that in each case the first step of the two-steps test caused practically no damage to the samples. The assumed beginning of sample damage defined by the ‘damage-line’ (0% damage) is therefore justified.

Since it could be shown that the first load step of the two-steps tests does not influence the position of the failure points of the ‘Woehler-curve’, the first step can be regarded as non-existent, and the second step in each case can be interpreted as individual one-step test to be evaluated accordingly. Exactly this is presented on Fig. 14 in comparison with the ‘damage-line’ and the ‘fatigue failure-line’ of the regular one-step tests.

The dot-dashed line is the regression curve of the two-steps tests, the solid line is the ‘fatigue failure-line’ of the one-step tests. The ‘Woehler-curve’ for the two-steps tests computed by regression analysis shows only a slight deviation in its inclination as compared to the ‘Woehler-curve’ for the one-step test. In the range of the test results its position in x-direction hardly deviates from the position of the ‘fatigue failure-curve’ of the one-step tests. The position of the two ‘Woehler-curves’ in Fig. 14 supports the conclusions presented above but in particular it supports the assumption that a ‘damage-line’ does exist for the tested geogrid beyond which load dependent damage occurs under dynamic loading with $R = 0.5$ and 10 Hz. For similar tests with a frequency of 3 Hz, comparable results are very unlikely because fatigue is less

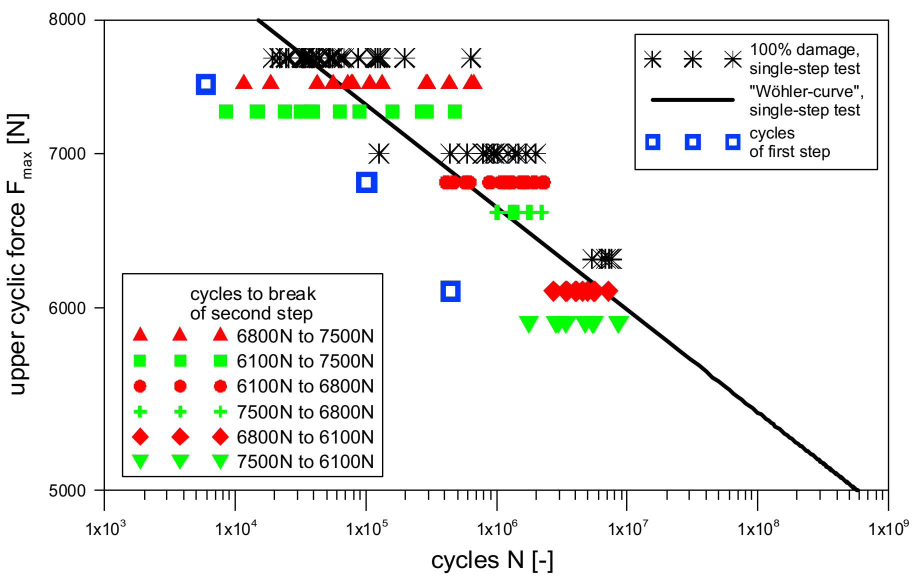

Fig. 13. Evaluation of the failure values of the second step of the two-steps test on the geogrid ($f = 10$ Hz, $R = 0.5$).

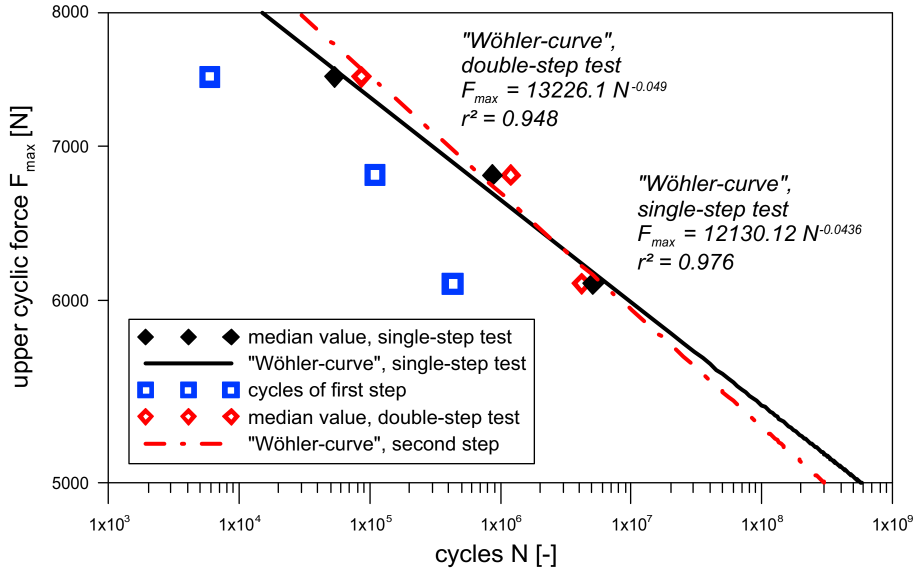

Fig. 14. Comparison of results obtained in two-steps tests with results obtained in one-step tests ($f = 10$ Hz, $R = 0.5$).

critical at 3 Hz than at 10 Hz as pointed out earlier. Therefore verification by test results at 3 Hz was abstained from.

5. Summary

In an extensive testing program, samples of PET-geogrid Fortrac R 560/115-15 T were subjected to cyclic tensile loading. The test conditions were chosen for frequencies of 10 Hz and 3 Hz under a load ratio of $R = 0.5$ as it is believed to represent the dynamic loading for both goods and high speed trains. A load ratio of $R = 0.67$ would be the typical situation but a load ratio of $R = 0.5$ covers all situations. The test data with $R = 0.5$ will be on the safe side in comparison with higher R-values. Such high dynamic loads can occur in applications where the geosynthetic reinforcement is installed in a shallow position under the rail tracks.

The used load levels of the cyclic loading have been chosen in such a way to reach failures within acceptable test durations. This means for e.g. 10^7 cycles at a frequency of 10 Hz, a test runs for two weeks. As the results of dynamic loading tests have a scattering, a statistical evaluation is absolutely necessary. Therefore many tests ($\geq$10 tests per load level) are needed. As the tests are very time consuming, testing at high load levels are meaningful. In the case of the tested geogrid, the maximum loads in the tests correspond to 43 till 58% of the short-term tensile strength of 560 kN/m.

With regard to the question in how the material behaviour of the tested geogrid would be representative for the same family of geogrid (i.e. same raw-material and production technology but different ultimate strength) it is to be noted that definite answers to this question would require additional testing. However, from a comparison of the static behaviour of different grades of this material (e.g. short term tensile testing, creep behaviour, durability) it can be assumed that the performance of this geogrid is basically related to its raw material. Therefore, significantly different behaviour should not be expected even under cyclic loading.

The results indicate that the dynamic performance of the material can be characterized by two significant events which depend on the number of applied load cycles, the 'beginning of damage' and 'fatigue failure'.

On account of statistical analyses, the test results clearly show the reproducibility of the method employed. The existence of the 'damage-begin' parameter which can be quantified renders additional safety for dimensioning of the geogrid against operational dynamic loading.

The loading levels were selected in such a way that on one hand no temperature dependent changes in material properties would influence the tests, on the other hand statistically well established loading levels could be executed without increasing the required numbers of individual tests in an unjustified manner. Furthermore the differences between the load levels should be sufficient (about 10% of the maximum cyclic load), and the differences between the average numbers of load cycles to fatigue failure should also be not too large. This approach facilitates the determination of 'lifetime-curves' by means of regression analyses.

Accounting for elementary methods of mathematical modelling, the 'life-time-curves' appear as straight lines with inclinations determined with good statistical safety. The extrapolation towards lower load levels is easy and well secured. This extrapolation is in each case conservative, so it always leads to results on the safe side. However, if the regression functions are used for extrapolations considerably beyond 50 years, respectively for load cycles considerably in excess of e.g. 10^8 then it has to be taken into account that synthetic plastic material is ageing and becomes brittle with time. This phenomenon is known in principle. That kind of changes in material properties depends on operational loading, temperature or temperature variations, and possibly on actions of media (chemical, biological).

The evaluation of the tests clearly showed that specimens tested at 3 Hz possess a longer lifetime than specimens tested at 10 Hz. The difference in lifetime increases with decreasing maximum values of cyclic load. Therefore, in dimensioning against beginning of damage or against fatigue failure, the higher frequencies are more critical.

For the tested geogrid, the existence of the 'damage-line' had to be verified by two-steps tests. The results of the two-steps tests and the comparison with one-step tests can be summarized as follows:

- Measurement and recording of specimen temperature, loss work, dynamic modulus (stiffness) and extensometer amplitude during the tests lead to convincing, reproducible criteria for determination of the damage-beginning when evaluated simultaneously.

- With respect to distribution and magnitude, the numbers of load cycles to fatigue failure of two-steps tests show good agreement with those of one-step tests.
- The results could be presented visually as well as qualitatively in diagrams and quantitatively after statistical analysis.
- The assumed linear damage accumulation (linear Miner rule) was examined in practice by two-steps tests in both directions. Very good agreement was observed, independent of the question whether the second load step was defined by increasing or decreasing the load, and independent of the question how many load steps were skipped between the two applied load steps.
- It was demonstrated statistically that in case of one-step tests and in case of two-steps tests for the second step, fatigue failure events follow a logarithmic normal distribution. Depending on the load level, the widths of the distributions differ only slightly.
- Comprising all test results and the items mentioned before, it can be concluded that for the tested geogrid under dynamic tensile cyclic loading at 10 Hz and $R = 0.5$, a 'damage-line' exists. This means that there is a region of load cycles below the 'Woehler-curve' in which no specimen damage occurs. Damage is initiated for numbers of load cycles only, which plot between the 'damage-line' and the 'Woehler-curve'.
- The method presented here for the determination of the 'Woehler-curve' and the 'damage-line' has enormous advantages in time-saving combined with cost reduction for testing.

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