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Lifetime prediction of PET geogrids under dynamic loading

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ABSTRACT: The lines of 'damage begins' and specimen break for dynamic loading of a geogrid were determined in a series of laboratory testing. The 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-tests' is practically the same. The existence of damage lines for the examined geogrid in a dynamic pulsating load of 10 Hz and 3 Hz and an R-value of 0.5 could be verified. Thus there are considerably high numbers of load cycles the geogrid can withstand without any damage caused by the dynamic load. This area is bounded by the damage line. Damage of the samples occurs only for load-cycles lying between the damage line and the 'Wöhler-curve' (fatigue curve). Higher testing frequencies present the critical case when it comes to designing against damage beginning or break.

1 INTRODUCTION

High strength geosynthetic reinforcement materials are nowadays frequently used for the construction of highly trafficked structures like motorways and railway embankments. Measurement data of highly loaded structures typically railroad structures has been reported e.g. in Auersch & Rücker (2005). For such applications where the stress-strain behaviour is important designers also like to know how dynamic loading affects the tensile properties of the reinforcement. To gain more detailed information about the dynamic behaviour of geosynthetic reinforcement products and to avoid over-conservative design approaches it was decided to carry out a detailed research program.

This paper will present the results of an extensive research program which has been carried out recently with single strip specimens of a polymeric coated high strength knitted geogrid manufactured from PET type Fortrac® R 560/115-15T (with an ultimate tensile strength of 560 kN/m).

2 TEST PROCEDURE, BASIC CONVENTIONS

2.1 *Loading*

Prior to the start of the endurance tests some basic arrangements had to be set. One is the type of dynamic loading. Based on field experience of earlier projects, it was decided that the dynamic service loads of a train could be represented well using a sine shaped loading arrangement. A loading scheme as shown in Fig. 1 was

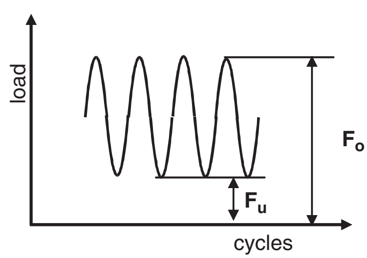


Figure 1. Nomenclature to specify the dynamic loading.

applied during all the tests. Load ratio R is defined as ratio between lower load F_u and maximum load F_o. With regard to the number of different variables of dynamic loading it was decided to carry out two test series with load frequencies of 3 Hz and second with 10 Hz, the load ratio R was always kept constant at $R = 0.5$. This value was chosen as it was seen the most critical condition for a particular railway project. Each series was subdivided into three different load levels where every load level was performed with 10 single specimens.

2.2 *Wöhler-curve*

The 'Wöhler-curve' named after August Wöhler, 1819 – 1914, is an appropriate method to present the relation between the number of load cycles to break and the loading amplitude.

Depending on the nature of the tested material different shapes of 'Wöhler-curves' or fatigue curves may occur: in a half or double logarithmic plot the classic 'Wöhler-curve' has the shape like curve 1 in Fig. 2. It is composed of a branch with load dependent limited life time followed by a branch parallel to the x-axis, the endurance limit, where the number of load cycles N sustained before the break/rupture is independent from the load. Many steels show similar behaviour. Curve 2 has two branches with different slopes but no endurance limit. This type of fatigue curve is typical for some aluminium alloys.

Thermoplastic materials behave more or less elastic-viscous therefore an endurance limit like shown in curve 1, Fig. 2 can be excluded. The 'Wöhler-curve' of these materials should be comparable to curve 3 or somewhat between curves 2 and 3. Similar behaviour can also be observed due to creep under constant static loading. In that regard it seems reasonable and conservative to assume that the fatigue behaviour of the geogrid examined here will be comparable to curve 3, Fig. 2.

It should be noted that Fig. 2 curve 3 is only a straight line when either axes or only the x-axis are in logarithmic scale.

2.3 *Begin of specimen damage*

Due to the magnitude of different influence parameters, it can be expected that the process of material deterioration is controlled by multiple, non-additive effects. In such cases the break events on every load level are often log-normal distributed. With this assumption the expected 'Wöhler-curve' for each series has the appearance of a straight line in a double logarithmic plot. The 'Wöhler-curve' can be interpreted as a line of 100% damage which is equal to the rupture of the specimen.

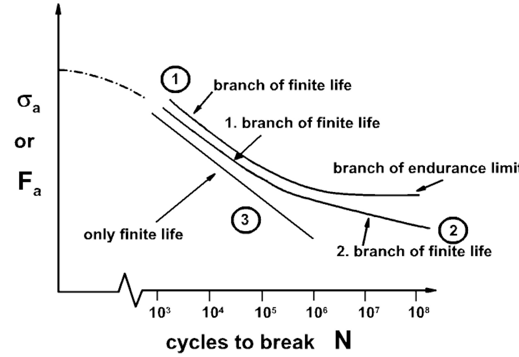


Figure 2. Different possible shapes of 'Wöhler-curves'.

During dynamic loading material damage can start with the first cycle or with any later one. In the latter case this means that there is a first life time cycle, of course depending on the load level, which the specimen can sustain free of any damage corresponding to 0% damage. This is followed by the second life time cycle when the specimen is continuously damaged, damage >0% which is accumulating until the rupture, damage = 100%, is reached.

This idea was formulated by Palmgren (1924) and Miner (1945). To quantify and to detect the limit for the start of the damage which is the end of the first life time cycle and the beginning of the second cycle many researchers, e.g. Renz et al. (1986), have used the hysteresis and its properties. This is appropriate because of its high sensitivity.

3 TESTING

3.1 *Test set-up*

The dynamic tests were performed in the load controlled mode using servo hydraulic machines (SKZ, 2005).

The set-up is depicted in Fig. 3 and shows that the specimen is located in the middle of each clamp, and then wound around the smaller and the larger half of each clamp. Additionally both halves were screwed together so that both ends of the specimen are fixed in its clamp. Although no influence of the cross machine direction was expected it is to be noted that the specimen is prepared and tested always including the node points.

3.2 *Data acquisition*

The strain was measured in the middle of each specimen using a clip-on-gage. Additionally the movement of the plunger was recorded using a 'built-in transducer', not visible in Fig. 3. The load cell is located at

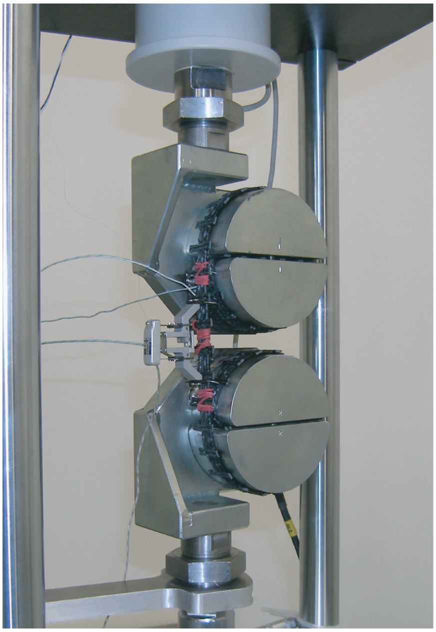


Figure 3. Test set-up showing one thread (warp direction of the geogrid), clamping arrangement, extensometer (in the middle) and three thermocouples.

the top of the rig, ref. Fig. 3. For further analysis it was also required to record the specimen temperature, this was carried out using thermocouples at three locations of the specimen: close to the lower and the upper grip and in the middle. All data was recorded and used to compute online several derived functional values like the hysteresis, the loss and the stored work, the specimen stiffness and the amplitude of the extensometer stroke.

4 EVALUATION OF DATA AND RESULTS

4.1 *Specimen rupture*

Analysis of the test results showed sensible scattering of the data. To that reason it was decided to arrange the number of load cycles to break with increasing number of cycles. The 'break events' then were logarithmized. The calculated probabilities were then plotted into a probability paper. After this linearisation the corresponding length values were used to calculate a linear regression for each load level. The regression line for the three load levels showed high determination factors r^2. This means that the assumption of log-normal distributed break events is reasonable.

After determining the mean or median value for each level the data was ready to perform a regression to generate the 'Wöhler-curve', see Fig. 5.

4.2 *Definition of the damage*

The detection or definition of the start point of the damage process of a specimen is not necessarily easy as there is usually no evident sign to be registered. In this case useful feature of the evaluation and presentation software was used to identify this point: Fig. 4 shows four different plots for one typical test, where the x-axis, displaying the number of cycles, is identical in every plot. The y-axis in contrast is displaying one of the following four parameters: amplitude, loss work, stiffness and temperature. Loss work is the area within the hysteresis loop. It will be analysed online during a running test. When moving the cursor along a master curve, the program would display the corresponding parameter in the remaining plots at the same time. Using this feature specific points of the curve could be marked simultaneously.

Starting with the Fig. 4a, the screenshot shows the extensometer amplitude, Fig. 4b shows the loss work and Fig. 4c the temperature in the middle of the specimen. It is evident that the cursor marks local minima of amplitude and loss work which correspond to the local maximum of the stiffness plot at Fig. 4d. This determination method was applied for every data set. There were some gradual variations in the curve appearances; however, the main tendency was the same as stated in the example given in Fig. 4.

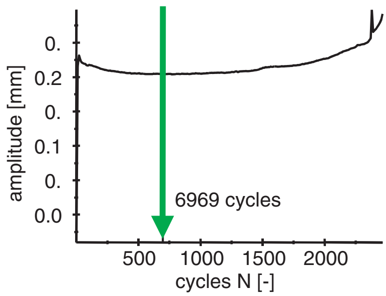
The raw data generated for the 'damage begins' was processed the same way as reported for the break events (section 3.1). The fitting of the regression lines is quite convincing and supports the assumption of the existence of a limit line for the 'damage begins'. Furthermore it can be followed that these events are reproducible and with a sufficient approximation log-normal distributed as well. The r^2-values (determining factors) for the regression lines of the 'damage begins' work out also to high r^2-values.

4.3 *Generation of the life-time diagram/ 'Wöhler-curve'*

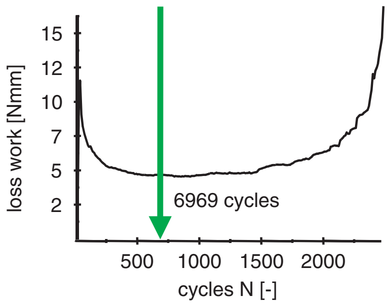
The last step of the evaluations is to display all data points for the 'break events' and for the assumed 'damage begins' in one lifetime diagram.

This is shown in Fig. 5 for the results of 10 Hz loading frequency. The upper curve is the 'Wöhler-curve' for specimen break, the lower line represents the appertaining limit line for the 'damage begin'. Both regression functions and their scatter factor are given in the plot.

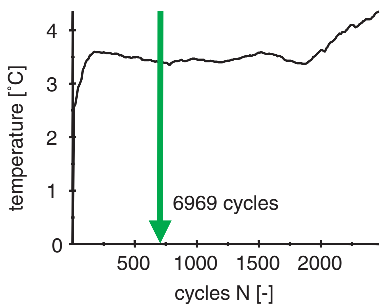
As stated before, tests have been carried out with 3 Hz frequency following the same procedure resulting in a similar plot shown in Fig. 6. The number of cycles to reach break or to reach the beginning of damage is higher with lower frequency. This corresponds to a shift of the 'Wöhler-curve' for 10 Hz frequency towards the 'safer side' (Fig. 6).



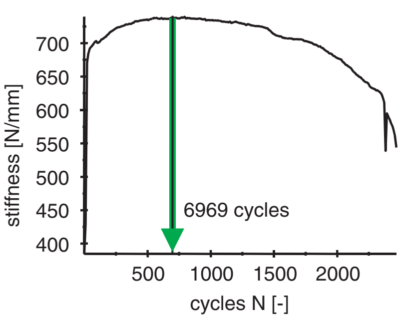
a) Screenshot showing extensometer amplitude



b) Screenshot showing loss work



c) Screenshot showing specimen temperature



d) Screenshot showing stiffness

Figure 4. Typical screenshots of the computer program. In this example the position marks the elapsed number of cycles until a local min. or max. value is reached. Here the upper load is 7.5 kN, frequency is 10 Hz.

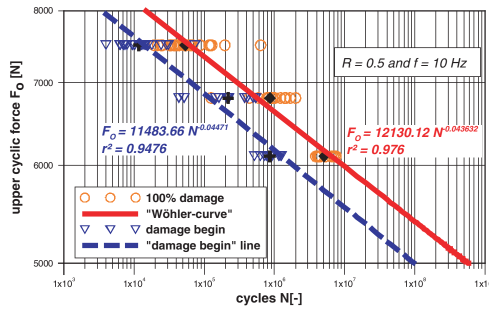


Figure 5. 'Wöhler-curve' and the 'damage begins' line for 10 Hz, both regressions were calculated with the median values. Both regressions have a probability of approximately 50%.

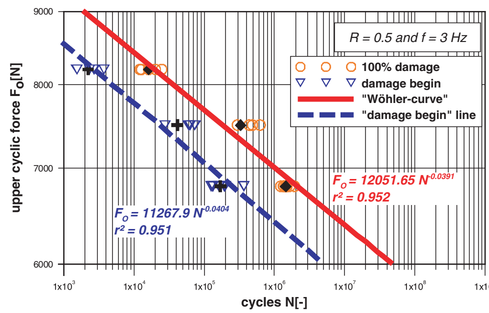


Figure 6. 'Wöhler-curve' and the 'damage begins' line for 3 Hz, both regressions were calculated with the median values. Both regressions have a probability of approximately 50%.

4.4 *Proof of the 'damage begins' line*

In the theoretical derivation of the damage accumulation Zanzinger et al. (2007) show simple ideal 'Wöhler-curves' and ideal 'damage begins' lines. In reality the records show considerable scatter, such that a statistical evaluation is needed, ref. section 4.1. For the proof of the existence of a 'damage begins' line this scattering would be difficult to handle and further measures would be necessary. But just to or proof, that the 'damage begins' line exists, its exact position in the lifetime-diagram is of secondary importance. To proof the existence is the essential point – this will be done using 'double-step-testing'.

4.5 *Double-step tests*

Zanzinger et al. (2007) explained the application of the linear Miner rule by means of ideal examples for double- or multiple-step tests.

Figure 7 shows the 'Wöhler-curve' and the associated 'damage begins' line for a loading frequency of 10 Hz and an R-value of 0.5 each for single-step tests

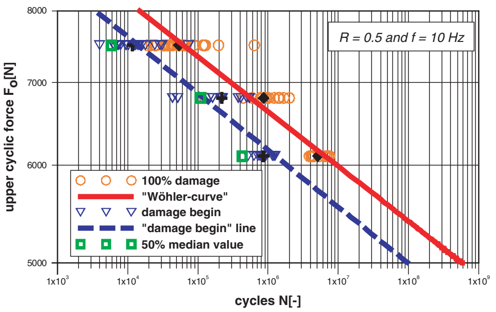


Figure 7. Commencement of the cycles of the first step, geogrid Fortrac®R 560/115-15T (here: 50% of median values 'damage begins').

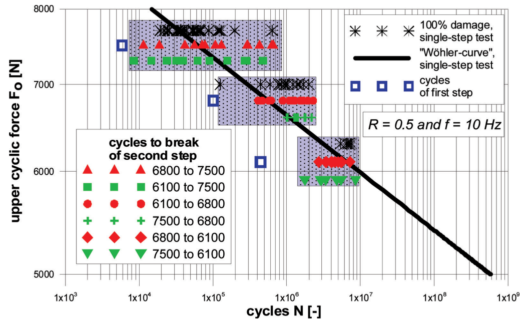


Figure 8. Evaluation of the break events of the second step of the double-step tests. Note: The data points have been spread around the horizontal centreline of the blue boxes for better visibility.

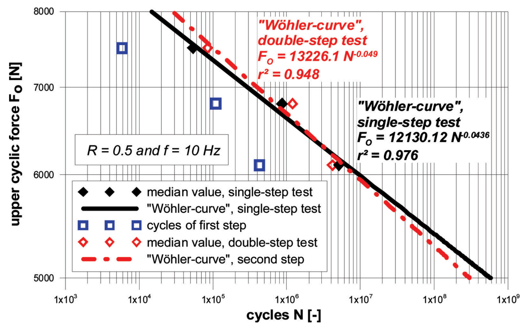


Figure 9. Comparison of results from double-step tests with those from single-step tests.

together with the measurement points and the median values. It is apparent, that the events 'damage begins' as well have a significant scattering. Due to that reason the length of the first loading step of the 'double-step tests' was chosen such that only 50% of the hypothetical 'damage free' lifetime is covered where the median values of each load level is assumed as 'damage begins', Figs 7 and 8 show, that all first steps are largely outside the scattering of the data. This means that the specimen does not experiences any damage by the dynamic loading and that the test can be continued without interruption and relief in an other load level. This could be a higher or lower load level and the break of the specimen will occur as it will occur at the corresponding single-step tests for this load level.

The definition of the load for second step should be made such as there is sufficient distance between each level (about 10% of the maximum upper load) and the differences of the medium cycles to break shouldn't become too much.

If the assumption of a 'damage begins' line is not true, the specimen would get damaged in the first step and would therefore break earlier on the second step if compared with the corresponding 'single-step test' of this load level (SKZ, 2006).

4.6 *Results of double-step tests*

Figure 8 presents the number of load cycles to reach the rupture of the specimen recorded for both single- and double-step tests together with the 'Wöhler-curve' generated form results of single-step tests.

It is obvious that the first loading step of the double-step tests have caused practically no pre-damaging of the samples. Thus the assumed damage begins defined by the 'damage begins' line ($\triangleq$ 0% damage), can be considered to be right.

Based on that one could consider the first step as 'not existent' and each second step can therefore be interpreted as a sovereign single-step test and can be analysed like was described under sections 4.1–4.3.

Fig. 9 shows the comparison of this data with the damage begins- and the specimen rupture-curves of the regular single-step tests. The dashed line is the regression curve for the double-step tests, the full line symbolizes the break curve for the single-step tests. The 'Wöhler-curve' for the double-step tests (calculated with regression analysis) fits very well in comparison with the 'Wöhler-curve' of the single-step tests; there is just a minor deviation in the inclination of the curves. This confirms clearly that the chosen procedure to analyse the available test data was right, but basically the existence of 'damage begins line' for the tested geogrid.

To conclude that testing with 3 Hz loading frequency would give comparable results is highly probable but as explained before, fatigue at 3 Hz is less critical as at 10 Hz frequency. A verification at 3 Hz frequency was not pursued for that reason.

5 CONCLUSIONS

Extensive dynamic testing allowed to establish 'damage begins lines' and 'Wöhler-curves' for the knitted PET geogrid Fortrac® R 560/115-15T.

In line with the statistical evaluation of the data the presented results show clearly, that the procedure used is reproducible for the generation of break and damage curves. The existence of a load depending, ‘damage begins’ offers additional safety for dimensioning of geogrids reinforced structures under dynamic loading.

The selection of the load levels for testing was made such as, potential changes of mechanical properties caused by elevated temperature did not influence the tests at the same allowing for a sufficiently high number of tests in relative short testing time. In consideration of elementary graphical methods the lifetime curves appear as straight lines – predictable with high statistical safety. The extrapolation to lower load levels is possible and on the safe side. In any case it is conservative. For an extrapolation of the regression curves to times above 50 years, which is about 10^8 cycles, the general aging of the plastics has also to be considered.

The evaluation of the tests provide clearly to the results, that specimens at 3 Hz frequency have a longer lifetime than specimens at 10 Hz – whereas the difference becomes higher with falling upper loads. The higher frequencies are the more critical case in a design against ‘damage begins’ or against break.

Through double-step tests the existence of a ‘damage begins’ line should be verified. The results of the double-step tests and the comparison with single-step tests can be summarised as follows:

- The online-acquisition of specimen temperature, loss work, stiffness and amplitude of the extensometer allows to establish a valid criteria for the definition of the ‘damage begins’.
- The loads cycles for the break events registered for the double-step tests show excellent agreement with those of single-step tests, both for the distribution and for the range of the values.
- The results could be shown in plots visually, qualitatively and also, with statistical calculations, quantitatively.
- The assumption of a linear damage accumulation (linear Miner rule) was verified using ‘double-step’ tests. Good correlations were found, independent of whether the second load level was defined as an increased level or as a reduced level.
- It was statistically proven, that the number of load cycles to reach specimen rupture for single-step tests and for double-step tests – if the second step was counted – had a log-normal-distribution.
- It can be concluded, that there is existing a ‘damage begins’ line, nearly parallel to ‘Wöhler-curve’, which is defining the number of load cycles the tested geogrid can be loaded with at 10 Hz frequency and an R-value of 0.5 without damaging the material. The damaging of the sample only happens later for elevated numbers of load cycles which are located between the ‘damage begins’ line and the ‘Wöhler-curve’.
- An enormous advantage of the described procedure is the reduced testing time required, thereby reducing considerable the testing cost. For example, an increase of around 1000 N of the upper cyclic load reduced the cycles to break with a factor of around 30.

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