Extrapolation Techniques for Long Term Strengths of Polymeric Geogrids

T. S. Ingold
Consultant, St. Albans, UK

F. Montanelli
RDB Plastotecnica SpA, Italy

P. Rimoldi
Tenax SpA, Vigano, Italy

ABSTRACT: The long term design strength of a geogrid used for slope or wall reinforcement may be controlled by the magnitude of tensile creep rupture strength or tensile creep strain at the end of the design life. Creep rupture strength affects the margin of safety against attaining an ultimate limit state of collapse while creep strain is required to comply with prescribed serviceability limits. To determine long term strength and creep modulus it is necessary to extrapolate test data up to 10^6 hours. Examples of extrapolation models for tensile creep rupture strength are given and test data for uniaxially oriented HDPE geogrids are analyzed to demonstrate the numerical range of extrapolated results obtained for different assumptions.

1 INTRODUCTION

Stability of reinforced soil structures, such as walls and slopes, requires that the reinforcement should not fail in tension within the design life of the structure. The intention of this requirement is to prevent the structure attaining an ultimate limit state of collapse. For the face of a structure to maintain a satisfactory alignment over its design life there is additionally a requirement for strains in the reinforcement to be limited to prescribed values (AASHTO, 1990; BSI, 1990). The intention of this requirement is to prevent the structure attaining a serviceability limit state.

The design strength of a reinforcement may be governed by either tensile creep strain or tensile creep rupture strength and to determine which is the most critical requires examination of both. Any relationship between creep strain and rupture strength is affected by the geometry of the geogrid, its manufacturing process and polymer type. The two most commonly used polymers are polyester and polyethylene. Long term design strengths of polyester geogrids are usually governed by creep rupture alone and therefore they are considered no further. However, long term design strengths of polyethylene geogrids may be governed by either strain or rupture. Assessment of long term strengths, typically defined as 10^6 hours (114 years), may require extrapolation from data running to only 10^4 hours. With this in mind this paper considers various extrapolation techniques and how they might be applied.

2 PERFORMANCE LIMIT STRAIN

Creep strain and rupture strength properties of polyethylene may be improved by mechanical drawing, during the geogrid production process, to induce molecular orientation. Geogrids most commonly used for wall and slope reinforcement are drawn in one direction and are therefore often referred to as uniaxially oriented geogrids. Although the axial tensile strength of a product may be improved by molecular orientation it is nonetheless subject to creep rupture.

Under load, thermoplastics behave in a visco-elastic manner and strain is not uniquely related to load as it is for a linearly elastic material. However, polymer technologists introduced the concept of a limit strain (ASCE, 1984) and the notion that if this strain is not exceeded there would be no creep rupture. This notion was extended to a uniaxially oriented HDPE geogrid by McGown et al. (1984) who concluded that there was no risk of rupture by ductile yield below the performance limit strain. For the particular product considered, Tensar SR2 which is referred to here as Geogrid 1, the *performance limit strain* was determined to be 10%. The basic design strength, excluding a margin of safety, was taken as the *performance limit strain load* of 29 kN/m which was deemed to induce the 10% performance limit strain at the end of a 120 years (≈10^6 hours) design life (McGown et al 1984). This approach to design does not consider tensile creep rupture or margins of safety against creep rupture.

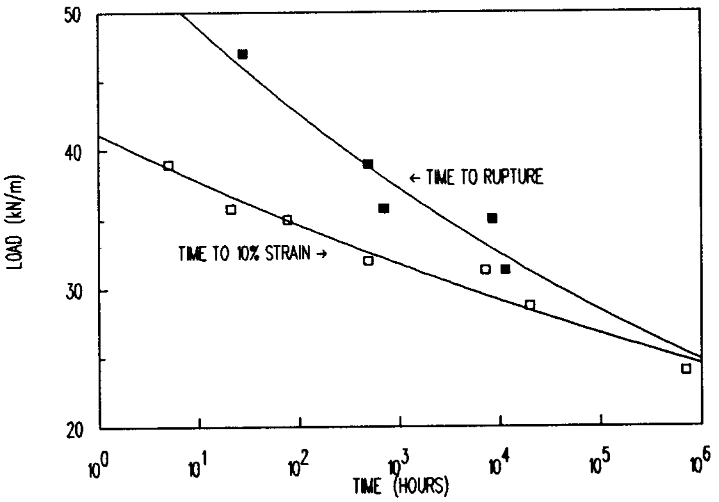

Figure 1 Load versus time to 10% strain or time to creep rupture for Geogrid 1 at 20°C

In the context of avoiding the ultimate limit state of collapse by tensile failure it is logical to consider tensile creep rupture strength and this approach is embodied in various specifications (AASHTO, 1990; BSI, 1990). Until the advent of these specifications there was a dearth of published data for product specific rupture loads. Some information has been given by Small and Greenwood (1992) who have published creep rupture data for the uniaxially oriented HDPE geogrids Tensar SR2, SR55, SR80 and SR110 which are referred to here as Geogrids 1, 2, 3 and 4 respectively.

Figure 1 shows a variation of rupture load and time to 10% strain, at 20°C, in the range 10^0 to 10^6 hours. At small time a design load based on the 10% strain line would seem to be conservative. However, as time increases, the 10% strain line moves closer to the rupture line, indicating rupture occurring at progressively lower strains, until the time to reach 10% strain and the time to rupture coincide at 10^6 hours. Consequently rupture might be expected to occur at a strain of 10% or more up to 10^6 hours. However, at 40°C, Figure 2 indicates that rupture may occur at less than 10% strain for time exceeding 10^5 hours.

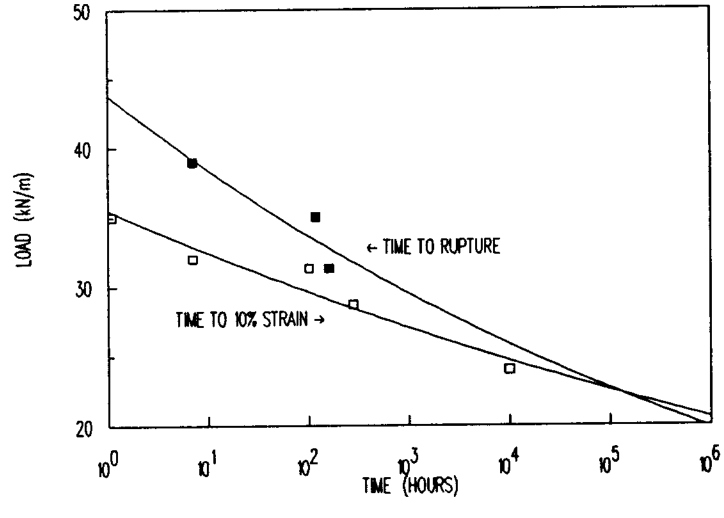

Figure 2 Load versus time to 10% strain or time to creep rupture for Geogrid 1 at 40°C

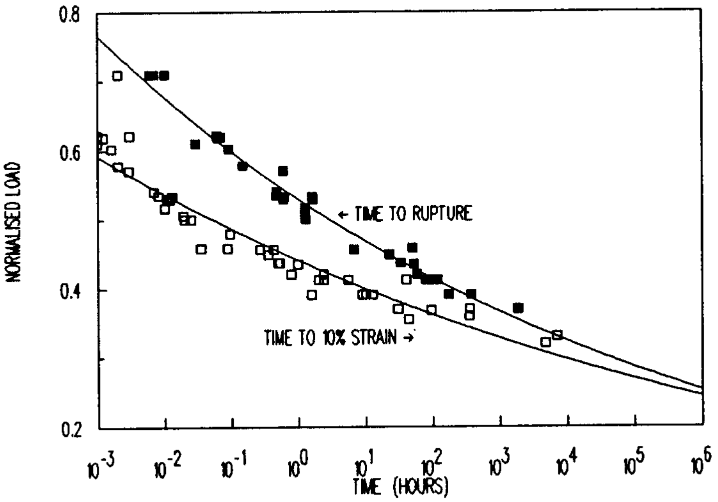

Figure 3 Load versus time to 10% strain or time to creep rupture for Geogrids 2, 3 and 4 at 40°C

Significantly more data are available for Geogrids 2, 3 and 4 which are plotted in Figure 3 for 40°C. There are few data points available for a given geogrid at a given temperature and to provide the larger number of data points in Figure 3, loads for each geogrid have been normalised and time-temperature shifted, from other test temperatures, to 40°C using the relationships given by Small and Greenwood (1992). A best fit curve indicates rupture occurring at strains in excess of 10% up to 10^6 hours. However, it can be seen that time-temperature transposition results in times to rupture down to 4 seconds (10^{-3} hours) and high normalised loads. If times less than 10^0 hours are discounted then, at 40°C, the 10% strain line crosses the rupture line at around $5x10^4$ hours, Figure 4. Such a crossover does not seem to appear at 20°C. Nonetheless, it is quite possible that structures may need to be designed to an operating temperature of 40°C. Consequently it is prudent to assess the ultimate limit state of collapse using the tensile rupture strength of the reinforcement as opposed to a load defined by a performance limit strain. In addition it is necessary to ensure that creep strain is within serviceability limits.

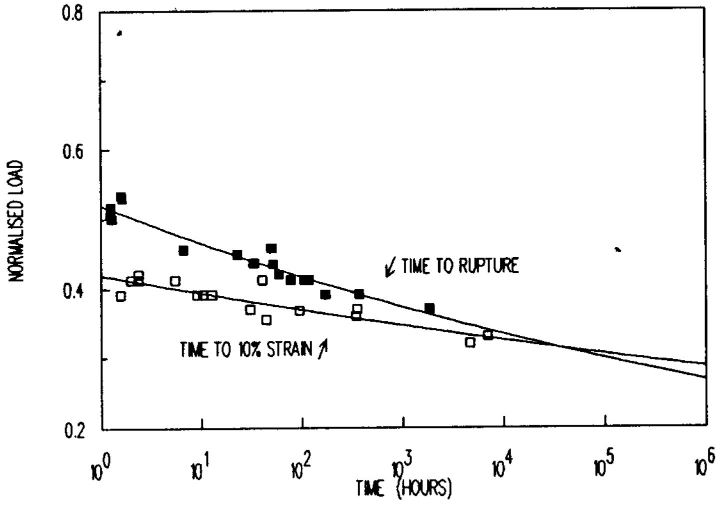

Figure 4 Load versus time to 10% strain or time to creep rupture for Geogrids 2, 3 and 4 at 40°C

3 TENSILE CREEP RUPTURE STRENGTH

To provide basic test data for extrapolation of creep rupture strength at least twelve results are needed for a given geogrid tested at a given temperature. Results for the same geogrid tested at other temperatures may be usefully employed to assess extrapolations made for the given temperature. Similarly, although less credibly, loads for different grades of generically identical geogrids may be normalised by dividing the creep rupture strength by the short term tensile strength. All extrapolation techniques are subjective, although most are based on a load-v-log-time or log-load-v-log-time relationship, whereas Small and Greenwood (1992) have adopted a load-v-log(log[1000×time]) relationship.

To assess the effects of these models, predictions of normalised rupture strength at 20°C and 10^6 hours are made for Geogrid 3 including 95% lower prediction limit values. In general the prediction line is fitted to the test data using a polynomial regression analysis, however, a simple linear regression analysis is also applied to the log-load-v-log-time model. In each case the goodness of fit of the line is represented by the R^2 coefficient where a value of $R^2 = 100\%$ indicates a perfect fit. The creep rupture data, from Small and Greenwood (1992), are considered in three groups.

Group 1 includes data for Geogrids 2, 3 and 4, tested at temperatures of 10, 20 and 40°C, with their strengths normalised and shifted to 20°C. Group 2 includes 20°C test data for all three geogrids with rupture loads normalised by dividing by the appropriate short term strength. Group 3 includes creep rupture loads for Geogrid 3 only shifted, as necessary, to 20°C. In all cases times to failure of less than 10^0 hours have been excluded. Due to lack of space only a limited number of plots are shown, however, all results are summarised in Table 1. Figure 5 shows a typical example of a load-v-log-time plot using Group 1 data including a one-sided 95% lower prediction limit value.

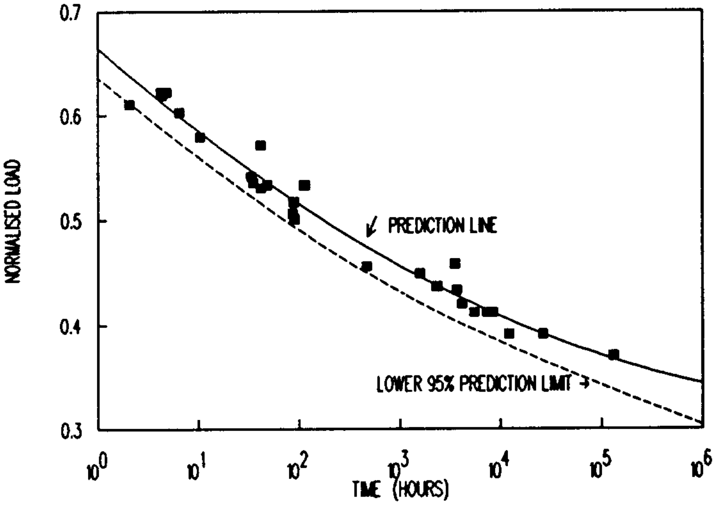

Figure 5 Normalised and temperature shifted creep rupture curve for Geogrids 2, 3 and 4 at 20°C

Polynomial regression analysis of normalised 20°C Group 2 test data for Geogrids 2, 3 and 4 gives an optimistic 10^6 hours value for normalised rupture load of 0.41, however, a power law fit, such as $y=x^n$, renders a more credible value of 0.33. Using the same data, an identical value of 0.33 is obtained by linear regression analysis using the traditional log-log relationship between rupture load and time. Group 3 data involves only time-temperature superposition although for comparison the rupture load has been normalised. Results for predicted normalised rupture load values, N, 95% lower confidence prediction values, 95% PL, and R^2 values are summarised in Table 1 for Groups 1, 2 and 3 data. Each model has been interpreted using a polynomial best fit unless otherwise stated.

Table 1. Predictions of rupture strength for Geogrid 3

Data	Model	N	95% PL	R^2 %
Group 1	N-log(log1000t)	0.327	0.294	96.98
	N-log(t)	0.343	0.304	97.07
	log(N)-log(t)	0.366	0.311	97.22
	log(N)-log(t)†	0.321	0.304	97.03
Group 2	N-log(log1000t)	0.368	0.300	95.54
	N-log(t)	0.410	0.291	95.24
	N-log(t)‡	0.330	0.303	94.09
	log(N)-log(t)	0.377	0.295	94.87
	log(N)-log(t)†	0.330	0.303	94.11
Group 3	N-log(log1000t)	0.324	0.296	98.69
	N-log(t)	0.343	0.299	98.72
	log(N)-log(t)	0.332	0.302	98.60
	log(N)-log(t)†	0.322	0.309	98.55

† linear regression ‡ power law regression

There is some fluctuation in predicted normalised load values, particularly from Groups 1 and 2 data, where the process of normalisation introduces a wider scatter of results. Applying a 95% lower prediction limit gives more consistent results with values for the Group 1 data being 0.303 ± 3%. For Group 2 the values are 0.298 ± 2% and 0.302 ± 2% for Group 3 which involves only time-temperature transposition. Based on the short term manufacturer's index strength of 86.9 kN/m Group 3 data lead to a 95% lower prediction limit creep rupture strength of 26.3 kN/m at 10^6 hours and 20°C. Also for Geogrid 3, Small and Greenwood (1992) derived a value of 25.8 kN/m based on a 95% lower confidence limit value of 0.324 applied to a characteristic short term manufacturer's index strength of 80 kN/m.

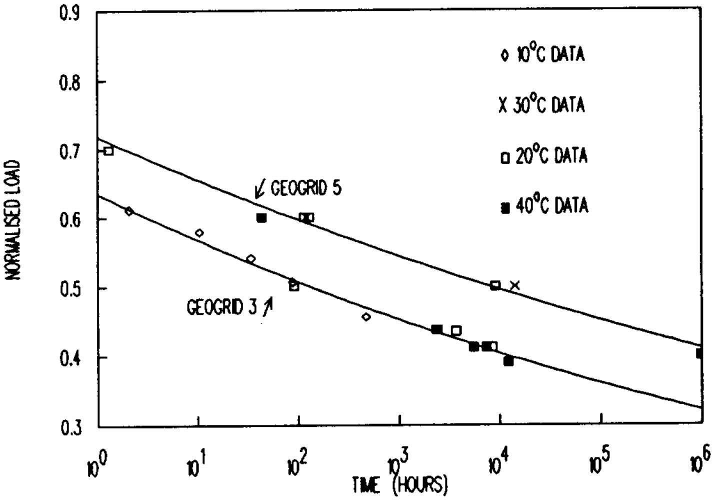

Figure 6 Normalised rupture loads versus time, shifted to 20°C, for Geogrids 3 and 5

It may be acceptable to use normalised loads but care should be exercised if comparing generically similar products. This is exemplified by Figures 6 and 7 which show normalised creep rupture, with time shifted to 20°C, for two uniaxially oriented HDPE geogrids, Geogrid 3 and Geogrid 5 which is Tenax TT401-SAMP. In Figure 6 the regression lines appear to be parallel. However, this is misleading since the rate of strain used for short term testing of Geogrid 3 is around twice that used for Geogrid 5. As would be expected, the lower rate of strain used to test Geogrid 5 leads to a lower measured short term strength and a normalised rupture load which is about 10% higher. For a valid comparison, normalised rupture loads for Geogrid 5 have been reduced by 10% and re-plotted in Figure 7.

Second order polynomial regression analyses of data for both geogrids return a predicted normalised rupture strength of 0.332 for Geogrid 3, at 10^6 hours and 20°C, with a lower 95% prediction limit value of 0.302 obtained with $R^2 = 98.55\%$ and similarly for Geogrid 5, a normalised rupture strength of 0.402 with a lower 95% prediction limit value of 0.375 with $R^2 = 99.20\%$.

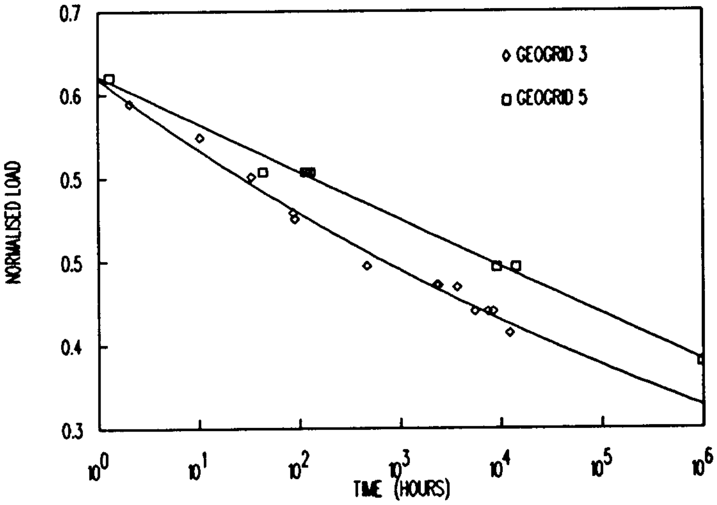

Figure 7 Rationalised normalised rupture loads versus time, shifted to 20°C, for Geogrids 3 and 5

4 SERVICEABILITY

To guard against tensile failure of a reinforcement a margin of safety is applied to its rupture strength so it safely resists the design load (Ingold, 1992). To guard against the development of excessive creep strains in the reinforcement, between end of construction and end of design life, magnitudes of strain are checked, using an un-factored design load, and plots of creep modulus-v-time for a given load intensity. Figure 8 gives an example of creep modulus against time for Geogrid 5 at 35% of its short term tensile strength.

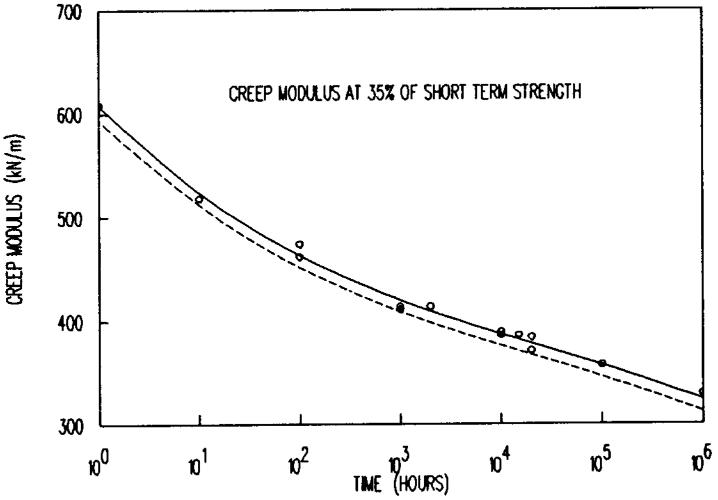

Figure 8 Creep modulus-v-time at 20°C for Geogrid 5

Data points are derived from tests carried out at 20, 30 and 40°C all shifted to 20°C. Close proximity of the 95% lower prediction limit to the prediction line indicates that creep strain data tend to suffer less scatter than creep rupture data and obtain high a degree of correlation; in this case $R^2 = 99.44\%$.

5 REFERENCES

ASCE. (1984) Structural plastics selection manual, *Manuals and Reports on Engineering Practice No. 66.*

AASHTO-AGC-ARTBA. (1990) In situ soil improvement techniques, *Task Force 27 Report*, AASHTO, Washington.

BSI. (1990) BS 8006 Code of practice for strengthened /reinforced soils and other fills, (Draft), *BSI*, London.

Ingold, T. S. (1992) Partial material factors for polymer wall reinforcement, *Proc. Geosynthetics '93*, Vancouver, 217-228

McGown, A. Andrawes, K. Z., Yeo, K. C. and DuBois, D. (1984) The load-strain-time behaviour of Tensar geogrids, *Polymer grid reinforcement*, Thomas Telford, London, 11-17.

Small, G. D. and Greenwood, J. H. (1992) A review of the phenomenon of stress rupture in HDPE geogrids, *GEO Report No. 19*, GEO, Hong Kong.