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Residual strength and its application to design of reinforced soil in seismic areas

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ABSTRACT: In designing for seismic applications it is critical to know the strength of a reinforcing geosynthetic at all stages of its service life. Residual strength tests performed on two polyester geosynthetics using the stepped isothermal method and conventional creep-rupture testing demonstrated that the strength of the geosynthetic is retained as far as the creep-rupture region. The modulus appears to increase. It is argued that, in contrast to current design methodologies, design should be based upon factored lifetime rather than on factored load.

1 INTRODUCTION

At the 1996 Kyushu meeting one of us presented a discussion contribution concerning residual strength (Greenwood 1997), which was developed into a further publication (Greenwood 1998). The point made was that the creep-rupture diagram depicts sustained load against the lifetime under that load. It is not a diagram of reduction in strength against time, even though this may appear to be so. The strength of a geosynthetic is in fact maintained until late in its service life. This was demonstrated by Orsat *et al* (1998).

The unfactored strength derived from the stress-rupture diagram is the sustained load which is predicted to lead to failure on the last day of the design life. The design load is equal to this unfactored strength divided by a safety factor to allow for the variability in material properties. Under this lesser load the tensile strength of the geosynthetic remains at a higher level up to and beyond the end of the design life, Figure 1. The ratio of the strength of the geosynthetic to the design load is thus higher than the intended safety factor. The structure is over-designed. This material behaviour is not recognised in many design codes. Most geosynthetic reinforced soil structures are designed using stress-rupture curves, Figure 2. These do not recognise the existence of residual strength. The difference between Figures 1 and 2 in respect of design philosophy and the assumed and actual design strength of the structure is profound.

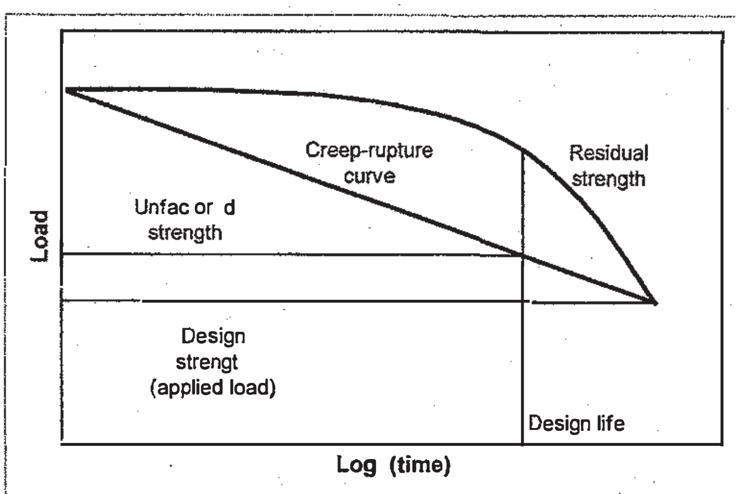

Figure 1. Schematic diagram showing the reduction in strength with time of a geosynthetic under a sustained design load. The unfactored strength is reduced by a safety factor to give the design load. The residual strength at the design life is now much greater than anticipated.

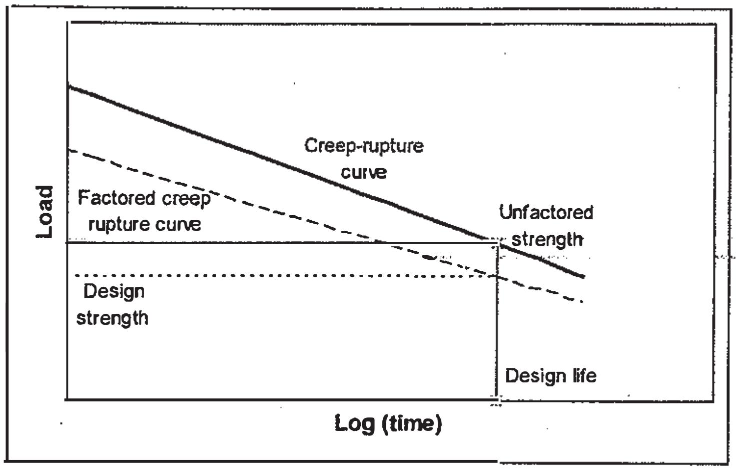

Figure 2. Current design assumptions relating to geosynthetic reinforcement under a sustained design load.

Many soil structures are designed not just to retain a margin of safety under a sustained load due to soil loading, but also to withstand occasional higher loads. Nowhere is this more important than in seismic loading. For effective seismic design, it is essential to know how the soil reinforcement will react to the additional seismic load. In recent earthquakes reinforced soil structures have proved highly stable, Tateyama *et al* (1995).

During seismic conditions a short term increase in the design strength of the reinforcement is accepted, Jones (1996). The increase in required strength to counteract seismic forces can be in the order of 50-100 percent of the design strength. Inspection of Figure 2 suggests that an increase in the design strength of polymeric reinforcement from, say, 40 percent of the characteristic strength (the manufacturer's guaranteed tensile strength) to 60/80 percent could be accommodated early in the design life, but could not be sustained late in the life of the structure. This raises concern over the long term viability of geosynthetic reinforced soil structures. This concern is resolved if the residual strength of the reinforcement is considered, Figure 1.

The purpose of this work was to determine the residual or reserve strength of a number of commercially available soil reinforcements. Since tests at room temperature must either be performed at very high loads or for very long times if they are to produce useful data, time-temperature acceleration was used in addition to conventional room temperature testing. For this purpose the stepped isothermal method (SIM) proved ideal. This paper describes the materials used, the methods applied, and the results of the tests. It also makes some suggestions for the manner in which safety factors should be applied in future.

2 MATERIALS

Several different soil reinforcements were used in this study, of which the three listed in Table 1 have been selected for the purposes of illustration in this paper.

3 METHODS

3.1 *Grips and extensometry*

All tests on geogrid R1 were performed on single ribs held in 50 mm diameter roller grips. If the rib was wound round the roller by more than one turn, a strip of nonwoven material was inserted to prevent the rib catching on itself. The tests were performed using SIM which is described in more detail in the next section. Lengths of strip R2 were held in large roller grips with knurled surfaces to increase the friction between the grip and the polyethylene sheath, and tested in a room controlled to 20 ± 2°C, 65 ± 5% relative humidity.

Table 1. Materials selected

		Tensile strength	Elongation at break (%)
R1	coated polyester geogrid	58.4 ± 1.7 kN/m	11.9 ± 0.6
R2	strip consisting of polyester yarn bundles sheathed in low density polyethylene	40.9 ± 0.4 kN	12.6 ± 0.3
R3	polyester yarn bundles stitched to a non-woven polypropylene backing	45.0 ± 0.6 kN/m	11.1 ± 0.3

Extension was measured by a pair of linear variable differential transformers (LVDTs) parallel to the loading axis but placed at opposite corners to compensate for any rotation of the extensometer mounting. The extensometry was calibrated at the relevant test temperatures.

3.2 *The stepped isothermal method*

The stepped isothermal method (SIM) was developed by Thornton and co-workers (1998a). The temperature of a conventional creep test is increased in steps, using a programmable oven whose temperature control is such that the change occurs within minutes. The sections of creep curve are plotted as creep modulus (load/strain) against the logarithm of the time after the temperature change and are then shifted along the log (time) axis. Corrections, which allow for shrinkage of the fibre on heating and for the thermal history of the sample, enable the sections of curve to be aligned to form a smooth continuous master curve. Thanks to the high level of time-temperature acceleration for polyester fibres – increasing the temperature by 10°C speeds up the rate of creep by a factor of about 8 – and the fact that even as high as 90°C the basic mechanism of creep is unchanged, durations as long as the service life of a reinforced soil structure, typically 75-120 years, can be simulated in less than a day's testing.

The method has been validated against ERA's long-term tests for polyester reinforcements (Thornton *et al*, 1998b). An example of ERA's measurements together with comments on the method were presented by Greenwood and Voskamp (2000).

In these tests the creep was accelerated using SIM but the temperature of the geosynthetic was reduced to the starting temperature of 20°C for the measurement of residual strength. Load was applied to the specimen without interruption.

4 RESULTS

4.1 *Tensile strengths*

The tensile strengths and elongations at break were measured to ISO 10319 but on the specimen widths described. The results, which are used as the basis for the creep and creep-rupture tests, are presented in Table 1.

4.2 *Creep-rupture*

Figure 3 shows the creep-rupture curve for geogrid R1 using SIM plotted as percentage of tensile strength in Table 1 against the logarithm of time to failure in h. The load leading to failure after 10^6

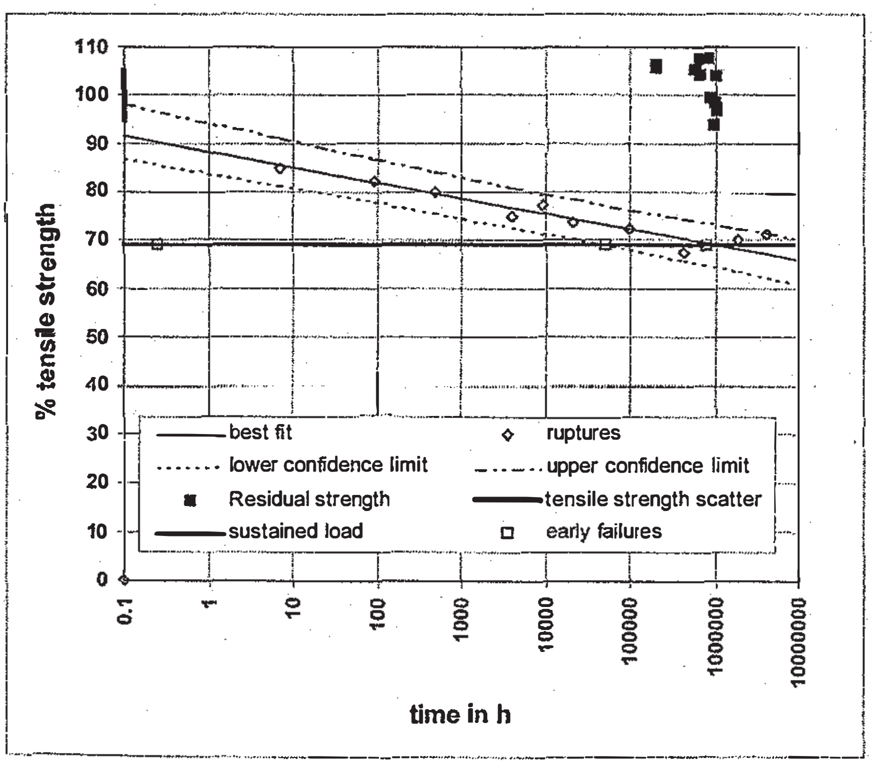

Figure 3. Creep rupture and residual strength of polyester geogrid R1.

(114 years) is 69.2% of tensile strength. Figure 4 shows a creep-rupture curve derived from earlier measurements on an earlier sample of strip R2 (Greenwood, Kempton et al, 2000), superimposed by several measurements made using R2 itself. The load leading to failure after 10^6 hours (114 years) is 68.6% of tensile strength. Both diagrams show the creep-rupture curve with its upper and lower (two-sided) 90% confidence limits, together with the range of tensile strengths with the same confidence limits inserted at the left hand edge of the diagram. The measured ruptures for R2 agree with the creep-rupture curve for the similar strip. Figure 5 shows the creep-rupture curve for geosynthetic R3 measured using SIM.

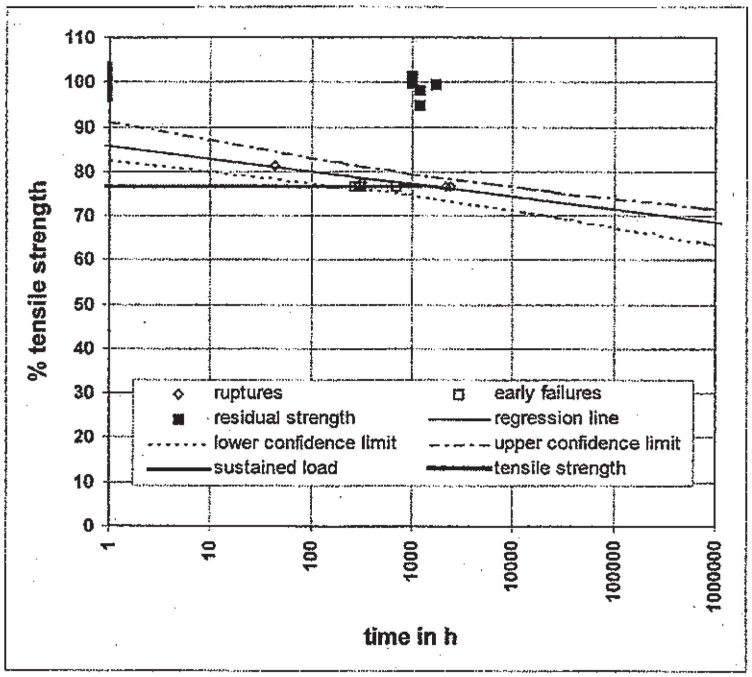

Figure 4. Creep rupture and residual strength of polyester strip R2.

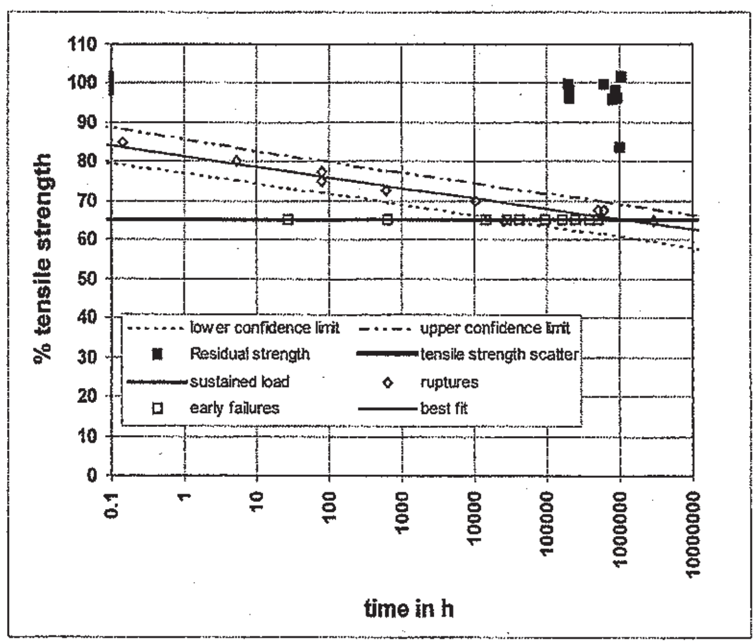

Figure 5. Creep rupture and residual strength of geosynthetic R3.

4.3 *Residual strength*

Residual strength measurements on geogrid R1 were performed by loading a specimen at 69.2% of tensile strength, performing a SIM test to a particular simulated lifetime, stopping the test, cooling the sample under the same load to room temperature, and measuring the tensile strength. The results are shown in Figure 3. The sustained load is shown as a horizontal bar. When the durations of tests under sustained load extend into the creep-rupture scatter band, some tests fail before their residual strength can be measured. This was expected and additional tests were included in the test plan to allow for it.

Residual strength tests were performed on strip R2 at a load of 76.6% of tensile strength, corresponding to a lifetime of 1500 h. The results are plotted in Figure 4 in the same way. Figure 5 shows the results for geosynthetic R3.

The results show that the residual strength is retained over the lifetime of the material with little detectable reduction.

4.4 *Strain at rupture*

Analysis of the strains at creep-rupture strains showed no clear dependence on applied load. The strains at rupture for R1 averaged 13.1 ± 0.5%, marginally higher than the 11.9 ± 0.6% elongation at break in the tensile tests. The strains at rupture for R2 averaged 11.2 ± 1.0%, rather lower than the 12.6 ± 0.3% clongation at break in the tensile tests.

Three measurements were made of the strains during measurement of residual strength at room temperature. One, performed on R1, showed that the additional strain during the residual strength measurement was 1.5%; two on R2 showed additional strains of 1.5% and 1.0%. Considerably larger strains would have been expected from the stress-strain diagram. These results indicate that during the period under sustained load the modulus of the polyester increases, leaving a lower strain margin available in response to any additional seismic load. This is shown schematically in Figure 6 for a high sustained load. The increase in modulus would not be expected to be as pronounced after exposure to a lower load.

5 DISCUSSION

The results show that in response to an additional load the full strength of a geosynthetic is available but that the strain response may be less than predicted from the original stress-strain curve. The residual strengths all lie above the lower confidence limit of tensile strength and/or to the right of the lower confidence limit for creep-rupture for a particular load, such that if these two limits are used in design no further determination of residual strength is necessary.

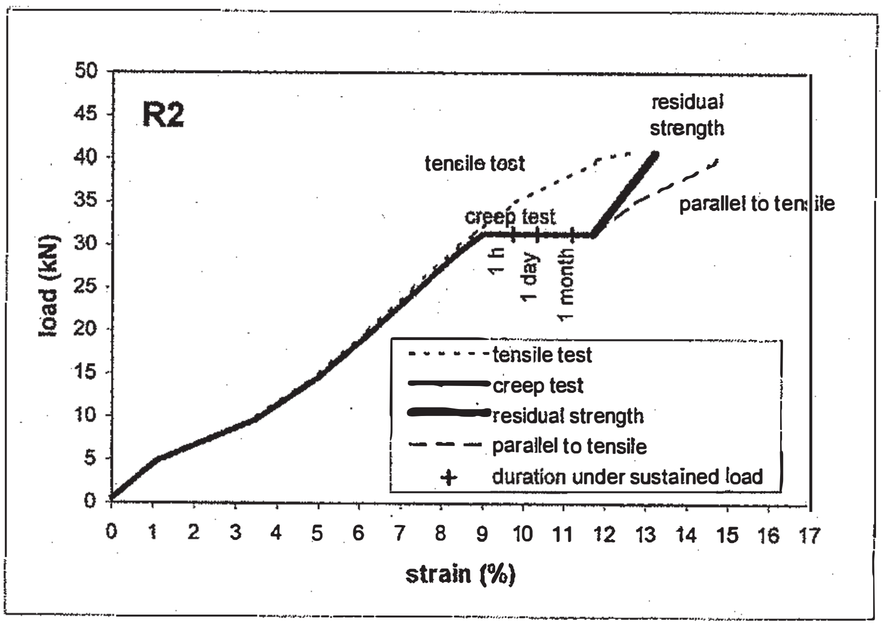

Figure 6. Schematic diagram showing the strain response of strip R2 after a period under high sustained load (creep test) followed by determination of residual strength. The strains in the creep test differ marginally from those in the tensile test because the loading is slower. The durations illustrate that even at this high load (77% of tensile strength) the post-construction strain is small compared with the strains on loading.

The use of safety factors based on material strength is fundamental to limit state design. It has been shown here that the strength of the reinforcement is retained as far as the creep-rupture region.

Since there is no gradual reduction in strength, the application of a reduction factor to design strength is not appropriate. It is more appropriate to predict the lifetime and apply a reduction factor to time (or the logarithm of time) based on the statistical likelihood of premature failure. If the life predicted from the creep-rupture diagram is 200 ± 50 years and a 95% one-sided confidence limit is required, then the geosynthetic should not be relied on to last for more than $200 - (1.64 \times 50) = 118$ years, a factor of safety on lifetime of 1.7.

If this approach is applied to design based on continuous sustained loading, i.e. on creep-rupture, it will lead to the same reduction in applied load regardless of whether the safety factor is applied to the load or time axis. If however the design is for residual or reserve strength, then the requirement is that under the applied load the full strength of the material should be retained over the design lifetime. The design life for that applied load, and its standard deviation, should be determined from creep-rupture measurements as before. A service life should be calculated, an appropriate reduction factor applied as in the example above, and the design load calculated accordingly. As far as the geosynthetic is concerned no further reduction factor is then required.

The same approach based on lifetime rather than reduction in strength applies to any form of degradation that occurs abruptly, for example oxidation when the antioxidant is exhausted.

6 CONCLUSION

The results show that in response to a seismic load the full characteristic strength of a geosynthetic is available but that the strain response may be less than predicted from the original stress-strain curve. The reduction in strength with time implied by Figure 2 is misleading, and geosynthetic reinforced soil structures are safe against seismic loads which occur late in their design life.

It is proposed that the design load should be based on lifetime predictions alone and should not include any further factorisation.

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