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Discussion of safety from a study of the creep rupture of polyester

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ABSTRACT: The extensive creep rupture testing by Freyssinet of about 160 polyester tendons used in Paraweb strip soil reinforcement led to interesting results and discussion. The paper first summarises the test program and outcomes. The tests demonstrated that the tendons retain a significant so-called "residual strength" before rupture. This gave rise to the feeling that the combination of reduction factors and safety factors generally used for design might be overly conservative. The paper demonstrates that this idea is misleading and deceptive. The paper however acknowledges that the allowable tensile load could be noticeably larger (in the context of a "Load and Resistance Factor Design") if the resistance factor of safety were applied to the loss of strength rather than to the remaining strength. The paper finally recognises the value of the residual strength with regard to short duration loading, such as seismic effects.

1 INTRODUCTION

Between 1995 and 1998, the Technical Research Centre of the Highways Department in Normandy, France undertook, at the request of the Freyssinet Company, a series of trials on the creep behaviour of Parafil high tenacity polyester tendons. These tendons are of the same type as those which form Paraweb soil reinforcements.

The series was carried out on a large number of samples, 157 in total. For half these samples, the trials consisted of obtaining creep rupture of tendons under constant load, at ambient temperature (20°C). The duration of loading ranged between a few hours and 11 months, i.e. nearly 8,000 hours. For the other half, loading was interrupted after periods of 10 days to 15 months and the residual strength of the tendons was measured.

The results produced by the series of experiments have renewed consideration of numerous subjects, beginning with the admissible strength to use for design, i.e. the definition of a pertinent and reasonable safety factor.

We summarize here some aspects of this reflection in the imaginary form of a discussion which could have occurred between a "salesman" whom we will call Mark, and a "user", whom we will call Bob.

2 DISCUSSION

<u>Mark</u> First of all I will show you a graph summarizing all the creep rupture results, presented in the usual way, with, as abscissa, a logarithmic usual way, with, as abscissa, a logarithmic scale of time at the end of which rupture occurred, and as ordinal, the applied load, expressed as a percentage of the reference nominal strength. I should emphasise that this reference strength has been verified for each trial series on around twenty samples (in particular to detect possible problems with the jaws). From the experimental results a minimal value of the logarithm of rupture time has been calculated for each load level at a level of confidence of 95% (Figure 1).

Then a regression line was drawn for these values and extrapolated to the abscissa which corresponds to a service life of 100 years. It shows that there is a 95% chance that rupture will not occur before the end of the service life if the load is equal to 66% of the nominal strength (Figure 2).

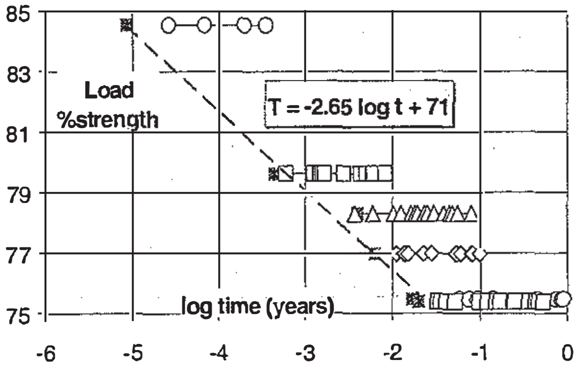

Figure 1. Creep rupture tests. 95% confidence regression line.

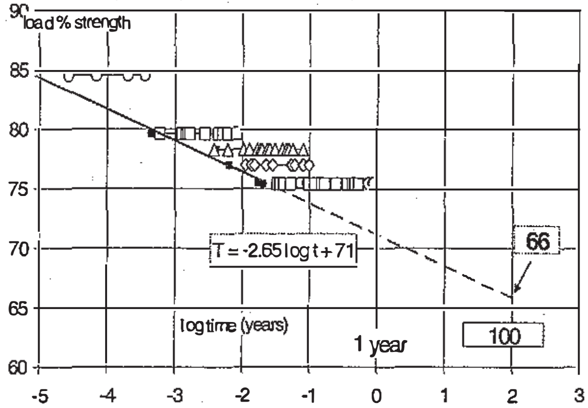

Figure 2. Creep rupture tests. Extrapolation to 100 years.

Bob That's quite clear. It seems to me that these results are very close to those already found in the literature for other high tenacity polyester fibres?

Mark Exactly. But if you examine this graph while remembering that polyester soil reinforcements are generally employed at a level of about 30% of their nominal strength, you will see that under this load the reinforcements have no chance of rupturing before 3 million billion years! The safety is enormous!

Bob Hold on a minute... In your 30% factor you are somewhat mixing everything up. First of all you are including all losses of strength: losses which result from creep certainly, but also those dues to installation damages at the time of construction and those produced by chemical alteration such as hydrolysis. That is not safety - they are real losses. Then you effectively include actual safety, but it applies as much to calculated forces as to the long-term resistance of the material.

Let's try to estimate what safety there is on the material itself. I calculate that, taken overall, in general 95% of the strength remains after construction, 95% after hydrolysis and 66% after creep, that makes 60%, all losses considered together. Safety on the calculated forces depends on the local Codes. It is about 1.35 in France; it will be about the same in the USA under the AASHTO "LRFD" specifications. Thus we arrive at about 45%. In effect there only remains a safety factor in the order of 1.5 on the material strength, if it is employed as you say at 30% of its nominal strength.

Mark OK. But, please, for the moment let us forget installation damages and hydrolysis. Let us suppose that we have a case where the losses caused by them are negligible. Let's only concern ourselves with creep rupture and safety. We will set aside the safety on the calculated forces, because that comes from general standards and has nothing to do with the reinforcing material used. We will consider only the "material" safety factor and we will take it as equal to 1.5 (this is in fact the order of magnitude that everybody has in mind). We will apply it to the creep rupture strength which has been determined for a 100 years service life, i.e. 66% of the nominal strength. The load is brought down to 44%. It can be seen from the graph that it corresponds to a period of about 15 billion years, anyhow!

Bob What you are in the process of suggesting is that safety should be considered over time, on the length of service life, rather than on strength? Don't forget that we are on a logarithmic scale. If you take a safety factor of say 2 on the length of service life (let's be generous!), aiming at 200 years instead of 100, you deduce from the graph that we can work at a level of 65%, instead of 66% (Figure 3). The difference doesn't seem to me to be sufficiently great to make me feel that we have really put ourselves on the side of safety...

Mark I believe that it is now time to tell you about the other phase of the trials, those concerning residual strength. As I have already told you, on half of the samples subjected to the creep tests, they were not taken right up to rupture under constant load. The trial was interrupted at different dates, getting closer to the estimated date of rupture. The sample was released from load and its remaining strength was measured, using the same operating method at controlled strain, used to define the nominal resistance of the product. Half a dozen samples were even not released from their load but the load was progressively increased, with lead balls added to the weight. Whatever the method the result was essentially the same: the residual strength before reaching creep rupture is very high, very close to the nominal reference strength. The shape of the curves which represent the variation in mean residual strength (although some look a bit bumpy..) suggests that this does not really begin to decrease until the last moment, if you can say that, in any case shortly before rupture occurs (Figure 4).

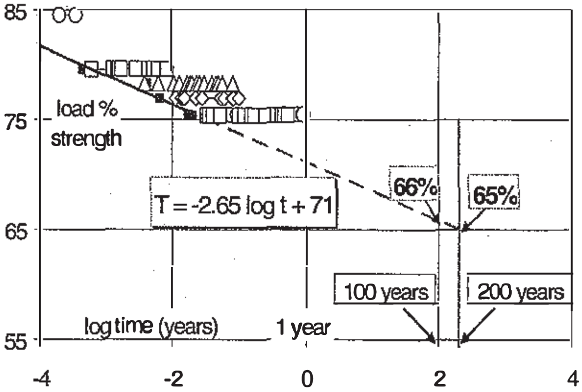

Figure 3. Hypothesis of a safety of 2 over the service life.

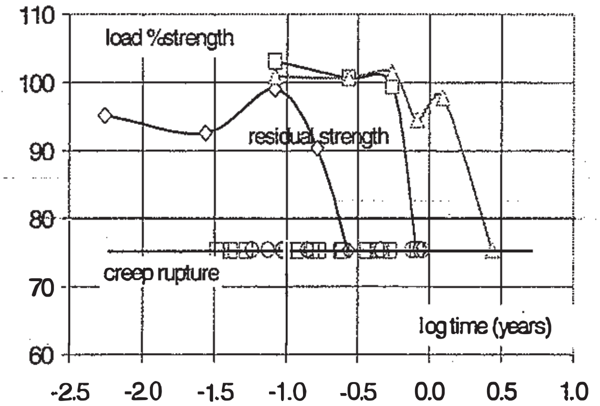

Figure 4. Residual strength.

Bob Don't forget that we are on a logarithmic scale and what appears to you to be an acceleration of the loss of strength shortly before rupture might be a reasonably regular decrease, perhaps even linear, on a natural scale... But what is your point?

Mark This. Suppose that the tendon is loaded to a level corresponding to its creep rupture strength, not even at 200 years as was envisaged just now, let's be more generous, at, say, a thousand years, i.e. at about 63% of its nominal strength. From the shape of the experimental curves of residual strength it can certainly be estimated that at the end of 100 years, i.e. at the end of the service life, the tendon will still have a resistance of at least 95% (Figure 5). In other words, without any problem you will have the safety that you require, because 95 divided by 63 makes precisely 1.5!

Bob Let's think about this, there is certainly a paradox somewhere!...

We have noted that the reinforcement breaks, or risks breaking, at the end of 100 years if loaded at 66%. You are suggesting that by loading it at only 63 it becomes capable of resisting to 95? In other words, you would only need to apply a safety factor of 1.05 to automatically obtain one of 1.50?

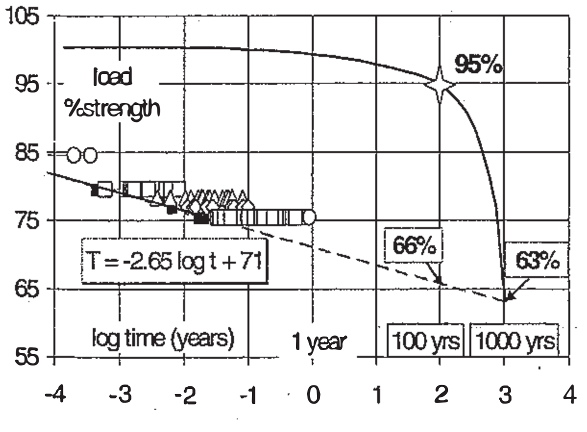

Figure 5. Creep rupture and residual strength.

The error is that we have forgotten that this residual strength of 95% is not permanently available. Like the reference nominal strength it is ephemeral. At any time a load equal to 95% of the nominal strength will cause rupture in a fraction of a second. It is just that which occurs in your measurements of residual strength: you start from a constant load level then at a given moment you increase the load to go as far as rupture. Once rupture has occurred, its over, the reinforcement is out of service...

What interests me more is to know just how far I can permanently load the reinforcement without risk of it breaking before 100 years, and that in the mostunfavourable hypotheses. You have already given me the answer: there is no question of exceeding 66% (allowing that we are only talking about creep).

Mark What do you mean by unfavourable hypotheses?

Bob Let's return to the general question of safety factors. I think that the graph below illustrates it well enough (Figure 6). It represents on the left the probability of the value of the calculated tensile force, on the right, that of the long term strength of the reinforcement.

The problem is to ensure that the minimum long-term strength is greater than the possible maximum force (accepting a priori a very small risk that this is not the case).

In what is called the maximum force is included the load factor, i.e. the partial safety factor which takes into account all the uncertainties concerning the real value of the loads applied, the validity of the calculation methods etc. This has already been talked about, essentially returning us to the common rules for all types of construction.

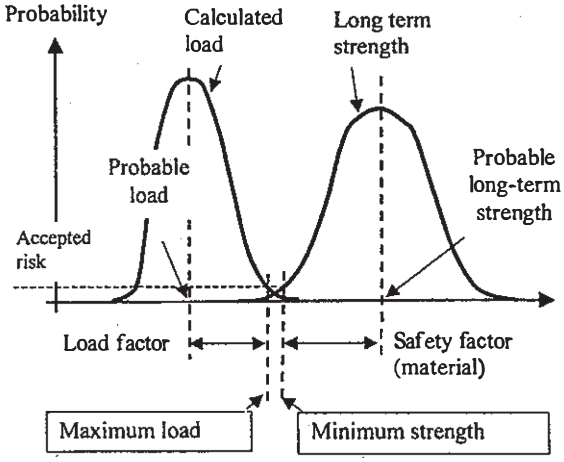

Figure 6. Safety illustration.

For what is known as minimal strength we start from the most likely strength, which is determined from the anticipated losses, i.e. by bringing into play the reduction factors due to installation damages, chemical alteration and creep. Then, safety must be taken into account, i.e. allowance must be made for all the uncertainties which remain. Above all three things must be considered:

- the validity of the extrapolations
- possible synergy between the different types of loss of strength
- and then any unknowns in changes in the material with time, in the environment in which it is placed.

Mark Let's consider them one by one. Concerning the validity of the creep effect extrapolations, it seems to me that there isn't a problem: we have analysed the experimental results statistically and have determined a minimum envelope curve at a 95% confidence level.

Bob That effectively gives us a satisfactory value for the reduction factor. But that does not really include safety. It must be indeed recognised that the loading range is narrow, that there is a lot of dispersal, that the trials lasted for less than a year while they are extrapolated over one hundred, etc. It is doubtful whether with other trial series exactly the same regression line would have been found and particularly the same slope. Thus it cannot be excluded that this line may be inclined a little more.

Mark You also mention synergy.

Bob I am thinking for example about doubts that may exist concerning possible acceleration of creep in a damaged or deteriorated material. But that is in fact already posing the third question that I mentioned concerning everything that is not suspected, everything not yet known about other causes which may affect the long-term strength of reinforcement in the fill.

Mark Finally, how do you propose to take into account all these uncertainties?

Bob Because it essentially involves taking into account unknowns, it is of necessity a bit arbitrary. Inevitably we are again going to think of a safety factor in the order of 1.5. On the other hand, it seems completely logical to suggest applying this safety factor not to the remaining strength, as is habitually done, but rather to the strength which is lost. It is after all the loss of strength that we are trying to estimate, and it is on this loss that there are uncertainties. It is this which should be increased for safety, a priori by 50%. On the other hand it is not satisfactory, as is generally done, to divide the remaining strength by 1.5, i.e. to reduce it by one third. Imagine an extremely stable, extremely durable material, which indefinitely retains 100% strength. Why should we only allow two thirds, as if we estimate the uncertainty on the loss as 33%? Imagine on the other hand a perishable material which, from the extrapolations, may lose 70% of its initial resistance over one hundred years and retain only 30%. Why should we have sufficient confidence in it however to count on 20%, as if the uncertainty this time was no greater than 10%, i.e. less than 15% of the probable loss?

Mark The idea of applying the safety factor to the losses seems to be completely justified. But we must again agree on the losses, or the part of the losses to which the safety factor should be applied. In fact there are losses where there is no uncertainty. This is above all the case for those resulting from installation damages, because they are measured and are not extrapolated. In the case of creep and chemical damage, this should also be the case of what was seen and measured during direct experiments. If we again look at the creep rupture graphs of our polyester tendon (Figures 1 to 3), we can see that the trials carried out over a year cover a loss of about 25% relative to the reference strength (from 100% to 75%). There is no uncertainty on that 25% and there is no reason for it to be amplified by the safety factor.

Bob I agree. Also I propose to illustrate the way in which the safety factor should be applied with the following graph (Figure 7).

On the time axis, still a logarithmic scale, can be seen two periods: the period t_e of the direct experimentation, or more exactly that from which the extrapolations are made, and the required service life t_s. Two strength values correspond to it: F_e to time t_e, and F_s to time t_s, as results from the extrapolations.

If you wish to express these values as a function of reduction factors as defined in most codes (RF_I for installation damages, RF_d for deterioration due to the environment, RF_c for creep), the following can be written adding a suffix relative to the date:

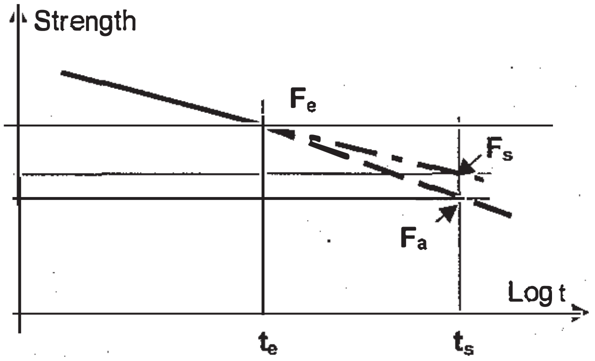

Figure 7. Principle for application of the "material" safety factor.

$$F_e = F_0 / (RF_{ie} * RF_{de} * RF_{ce}) \tag{1}$$

$$F_s = F_0 / (RF_{is} * RF_{ds} * RF_{cs}) \tag{2}$$

where F_0 is the reference strength.

If Γ_m is our safety factor for the material strength, the allowable strength for design, F_a, will be given by:

$$F_a = F_e - \Gamma_m (F_e - F_s) \tag{3}$$

Mark I am curious to know what we arrive at in the case of our polyester reinforcements, if we consider the same situation as before: 95% of strength after construction, 95% after hydrolysis and 66% after creep.

Bob That corresponds to the following values of RF_{is}, RF_{ds} and RF_{cs}:

$$RF_{is} = 1/0.95 = 1.05$$

$$RF_{ds} = 1/0.95 = 1.05$$

$$RF_{cs} = 1/0.66 = 1.52$$

from which $F_s = 100\% / (1.05 * 1.05 * 1.52) = 60\%$

At time t_e, which corresponds to creep rupture tests at 75% of the reference load, the damage is the same, and there is still no hydrolysis, thus:

$$RF_{ie} = 1/0.95 = 1.05$$

$$RF_{de} = 1/1.0 = 1.00$$

$$RF_{ce} = 1/0.75 = 1.33$$

from which

$$F_e = 100\% / (1.05 * 1.00 * 1.33) = 71.2\%$$

With $\Gamma_m = 1.5$, we arrive at:

$$F_a = 71.2 - 1.5(71.2 - 60) = 54.4\%$$

Mark Should this value be compared with 63% which we mentioned earlier, when we were wrongly considering residual strength?

Bob Exactly. And if you want to know how that compares with the "all in" 30% that you talked about at the start, it should be divided by the load factor, which has been estimated as 1.35. We arrive at a little over 40%. You can see we have come some way along the road by looking at things more closely!

You should take note that we can certainly do a bit better if we refer to tests on similar materials running over a longer period, i.e. the period of extrapolation is shorter.

We could also discuss the safety factor and not necessarily use 1.5. This value could be adjusted depending whether the product has been already widely used and documented or not.

Some authors have suggested giving the "material" safety factor the following value (cf. Segrestin, Boyd & Jailloux, 1999):

$$\Gamma_m = \Gamma_k \left[1 + 0.5 \frac{\log(t_s / t_e)}{\log t_e} \right] \tag{4}$$

where Γ_k varies between 1.35 and 1.05 following experience acquired with the product. Because it already depends on the range of the extrapolations, this factor Γ_m should however likely apply to all of the losses from construction until the end of the service life, rather than to those produced after t_e.

Mark I return to residual strength. If we adopt, in a routine case, a working level of the order of 54%, including the load factor, we must sometimes however be able to count on the reserve of strength which the trials brought to light, particularly if this is for a short period and if it does not reach an excessive load level.

Bob Certainly, you are right. Imagine a structure where the reinforcements are designed for a permanent tensile force of about 54% of their nominal strength. We have shown that the risks that they will break before the end of a service life of 100 years is extremely low. If, during this period of service, the load level rises accidentally for only a few minutes to say 70%, that will have practically no consequence (Figure 8).

In effect we know from the creep rupture tests that such a load must be applied in a constant fashion for more than two years for a rupture to ensue. A period of application of a few moments will thus not appreciably affect the length of serviceof a reinforcement which can be permanently loaded at 54% (but more probably only at about 40%). The benefit arising from this statement can be

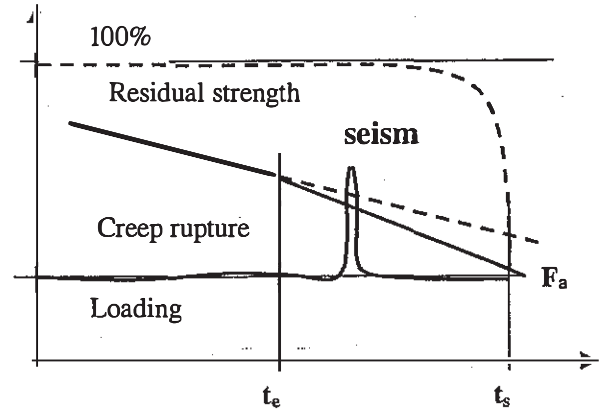

Figure 8. Effect of momentary accidental overload.

appreciated when considering the effects of earthquakes or other exceptional overloads.

Mark Does that also apply to unexpected leaps in temperature?

Bob No, because we cannot see any reason why that should happen accidentally, only shortly, once or twice in the life of a structure. It is true that we have not yet talked of temperature, and all the examples that we have quoted suppose that we are at around an ambient temperature of 20°C. Of course, the values of the reduction factors RF_d and RF_c should be carefully revised when the mean temperature is noticeably higher!

3 CONCLUSIONS

This (fictitious) discussion has mainly demonstrated three things:

- the safety factor on the long-term strength of polyester (as for all other materials used for fill reinforcement) should apply to the loss of strength which will occur during the period from which the data is extrapolated
- an adequate combination of this safety factor and classic reduction factors a priori justifies a small increase in the usually admissible tensile load
- the so-called "residual" strength only plays a role where accidental overloads of short duration are concerned.

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