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Developing Design Requirements for Non-Metallic Tendons

Éléments de précontrainte non métalliques

Bemessungskriterien für nicht-metallische Spannglieder

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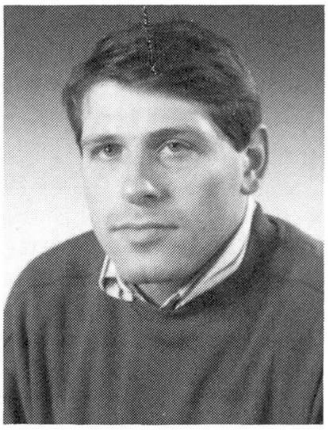

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SUMMARY

The use of non-metallic tendons may involve the introduction of new or less-known problems. Specially the long-term behaviour under constant stress and in alkaline environments needs to be assessed for reliable applications of high strength polymeric fibers. A safety concept for these new materials has to take into account the abovementioned phenomena.

RÉSUMÉ

L'utilisation d'éléments de précontrainte non métalliques peut impliquer des problèmes nouveaux ou peu connus. C'est avant tout le comportement à long terme sous charge constante et en milieu alcalin qui est à examiner pour des applications fiables de fibres polymères à haute résistance. Une évaluation de la sécurité de ces nouveaux matériaux doit tenir compte de ces phénomènes.

ZUSAMMENFASSUNG

Bei der Anwendung nicht-metallischer Spannglieder können neue oder wenig bekannte Probleme auftreten. Für die zuverlässige Anwendung von hochfesten polymeren Fasern muss insbesondere das Langzeitverhalten unter konstanter Belastung in alkalischer Umgebung untersucht werden. Diese Phänomene müssen für eine Sicherheitsbeurteilung dieser neuen Materialen berücksichtigt werden.

1. Introduction

For some applications, e.g. structures in highly aggressive environment, the combination of concrete with non-metallic tendons, e.g Arapree, a prestressing tendon consisting of bonded parallel aramid fibres embedded in a epoxy resin [1], can be advantagous.
Using non-metallic tendons means that new materials are introduced through which new or less-known phenomena, due to the mechanical, physical or chemical properties of these materials, become more critical. Therefore adapted design criteria, based on the properties of the "new fibres" have to be developed.
Specially the long term behaviour under constant stress and in alkaline environment, needs to be assessed for reliable applications of high strength fiber. So it is essential to know about the:

- behaviour under sustained high stress levels (stress rupture)
- behaviour in alkaline and carbonated environment
- creep and relaxation behaviour
- fatigue behaviour
- bond with concrete

and develop a safety concept based on these data. How we approached the above for Arapree and the type of requirements we assume to be valid also for comparable materials will be explained in more detail.

2. New fibres and fibre based reinforcement for concrete

An overview of types of several high strength fibrous tensile elements recently developed for use in concrete which are already more or less commercial use is given in table 1 [2].
The range of types under development is expanding rapidly.

Table 1: High strength fibrous tensile elements

Tensile element	Type of fibre	Fibre-brand name	Type of composite	Producer
Arapree	aramid	Twaron HM	epoxy-resin impregnated parallel fibre bundles	AKZO
Bri-ten	aramid carbon	Kevlar Carbon HS	resin impregnated parallel fibre bundles	Bridon
Fibra	aramid	Kevlar '49	epoxy-resin impregnated braided rod	Mitsui Shinko-wire
Nefmac	glass aramid carbon	var.	resin impregnated mesh	Nefcom (Shimizu)
Parafil	aramid	Kevlar '49	bare parallel fibre in sheating	ICI
Polystal	glass	E-glass	polyester resin impregnated parallel fibre bundles	Bayer

In table 2 the short term mechanical properties of prestressing steel, and three representative man-made, non metallic fibre reinforced elements are given. [2]. The strength and stiffness properties of Arapree are related to the effective fibre cross-section. This relation gives a more accurate value of the characteristics than if these values are based on the gross cross-sectional area, with differing volume. percentages of resin. The available types of Arapree are therefore indicated with the number of filaments.

Arapree f 100.000 for example, is an element of 100.000 filaments, with a cross-section of aramide fibres of 11,1 mm². That gives the element a characteristic strength of 31 kN and longitudinal stiffness (EA) of 1.388 kN.

table 2: mechanical properties of some fibre based composites and (prestressing) steel

property unit	steel (FeP 1860)	Polystal (glass)	Brit-ten (carbon)	Arapree (aramid)	Unit
density	7850	2100	1580	1250	[kg/m3]
char.strength	1,6	1,67	2,4	2,8*)	[kN/mm²]
youngs-modulus	200	50	150	125*)	[kN/mm²]
ult-strain	3,5	3,3	1,65	2,4	[%]
coeff.therm.exp.	12	7	0	- 2,0	[10E-5/°K]

*) Related to the effective fibre cross-section

A comparison of the stress-strain behaviour of the fibre based composites given in table 2 and steel is given in fig. 1.
The main difference of the considered non-metallic tendons and steel is the absence of a form of plasticity. This absence of plasticity does not mean that concrete structures prestressed with high-strength fibrous tensile elements don't have a so called warning behaviour. As will be illustated later on such structures can show a high ductility.

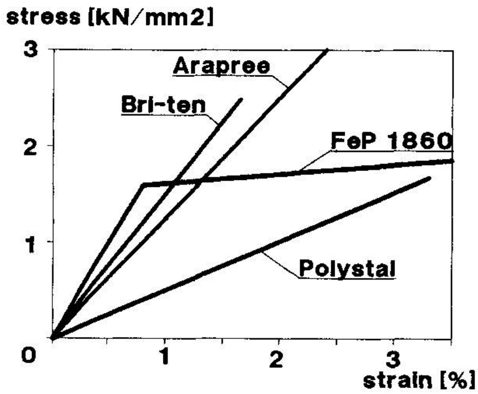

figure 1: stress-strain relation composites and steel

3. Influence of environment and time

Environment

The strength and stiffness values of non-metallic tendons are influenced by time, temperature, moisture content and acidity of the environment. As shown in fig. 2 the residual strength of Arapree after 10^6 hours (ca. 100 years) is 85% of the short-term strength [1].
Creep and relaxation are influenced by the environment. The relaxation of Arapree in an alkaline solution is approximately 20% after 10^6 hours, in a dry, neutral environment it is approximately 15%. [3].
The relaxation is hardly influenced by the stress level and temperature (less than ca. 80°C).

stress-rupture

Materials in general are susceptible to the presence of a sustained loading. Polymer materials like glass, carbon and aramid are more susceptible than steel. This so called stress-rupture behaviour can hardly be measured with steel.
The stress-rupture line in fig. 2 represents the relation between the stress-level in a aramid fibre and the average time that passes before the material fails under specific stress level (extra-polated from measurements upto 30,000 hours).

The residual strength also depends on the stress level and the loading duration.
In fig. 3 is represented the stress rupture, the residual strength of an unloaded Arapree tendon and the residual strength when a constant stress-level of 75% of the short term strength is applied. The figure shows that the residual strength of the loaded tendon follows the strength of the unloaded material, but just before the moment of stress-rupture the residual strength falls down [4].
More information about Arapree and its excellent fatigue behaviour is given in [1] and [4].

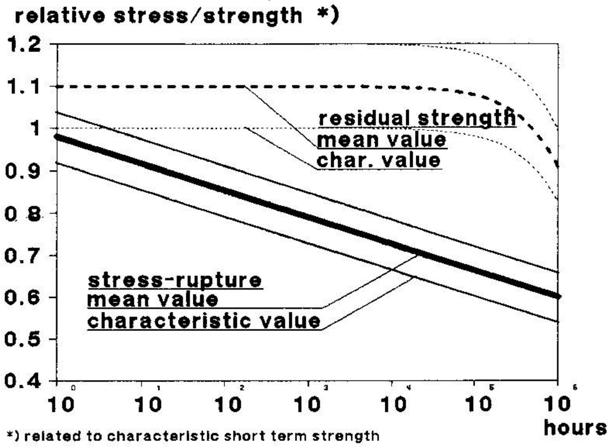

figure 2: stress-rupture behaviour (loaded Arapree) and residual strength of unloaded Arapree

4. Safety-concept

In civil engineering the effective usability of a structure must be ensured for a long period. For concrete structures a life time of 100 years (ca 10^6 hours) should be considerd.
To develop a safety concept we have to take into account at least:
- stress losses
- stress rupture
- residual strength
- enough ductility as warning for collapse.

First of all it is essential to know not only the mean strength values but also the variation of these values.
The characteristic values can be determined with this data.
A safety concept must be based on the characteristic values.

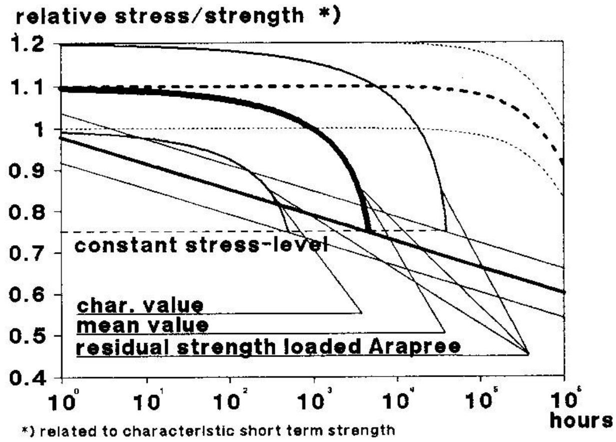

figure 3: stress-rupture and residual strength

It is clear that the stress-curve of a non-metallic tendon under sustained loading may not touch the stress-rupture curve, and a sufficient margin to the residual strength must be available. Therefore losses caused by creep and shrinkage of the concrete and relaxation of the tendon deformations and relaxation stress-rupture have to be considered.

The following formula of the stress losses has been derived:

$$\Delta\sigma_{p} = \{ \Delta\sigma_{p,rel,\infty} (1-0,85 \frac{\Delta\sigma_{p.cs,\infty}}{\Delta\sigma_{po}})\} + \Delta\sigma_{p,cs,\infty}$$

$\Delta\sigma_{p}$ = final stress losses due to the relaxation of Arapree and the creep and shrinkag of the concrete

$\Delta\sigma_{p,rel,\infty}$ = final relaxation of the Arapree

$\Delta\sigma_{p,cs,\infty}$ = stress losses in Arapree due to creep and shrinkage of the concrete

$\Delta\sigma_{po}$ = initial stress in Arapree

As told before the safety of the structure in case of overloading is guaranteed because of the residual strength, which retains practically its short term unloaded strength until just before the moment of stress-rupture.
In figure 4 a maximum stress-curve with respect to losses is given. The stress rupture and the residual strength are shown with their characteristic values.

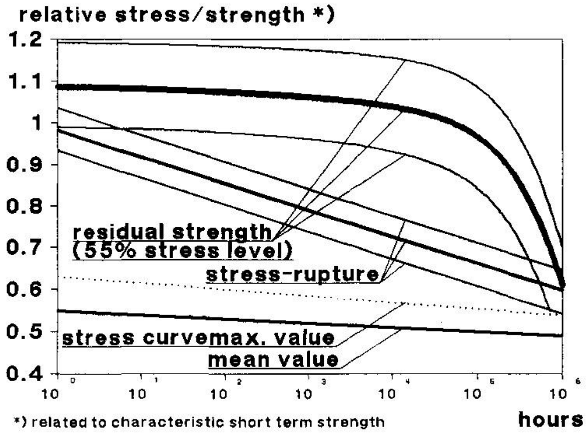

figure 4: stress curve

Although all non-metallic tendons are fully elastic elements, concrete elements prestressed or reinforced with these elements do show a high ductility because of the large strain capacity and due to cracking and deformation of the concrete. This is clearly demonstrated in the figure 5 [6] and figure 6, where the measured deflection curves are shown for two different structures. Figure 5 shows the deflection curve of a fence post prestressed with Arapree, figure 6 shows the deflection curve of an Arapree prestressed concrete panel. Like conventional prestressed concrete the warning behaviour depends on the amount and placing of the tensile elements.

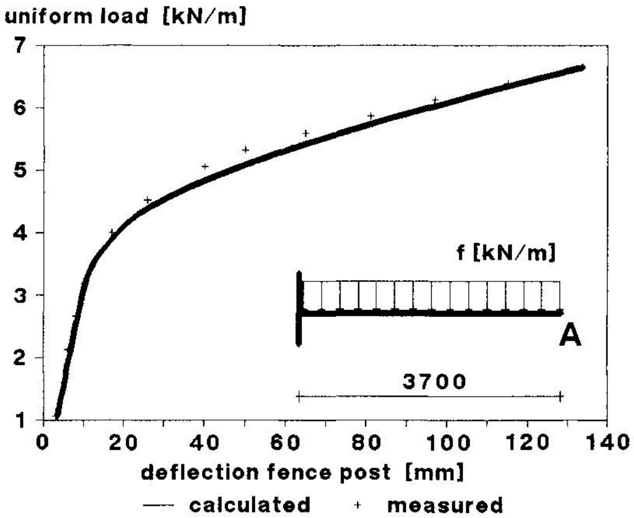

figure 5: load-deflection curve of a fence post prestressed with Arapree

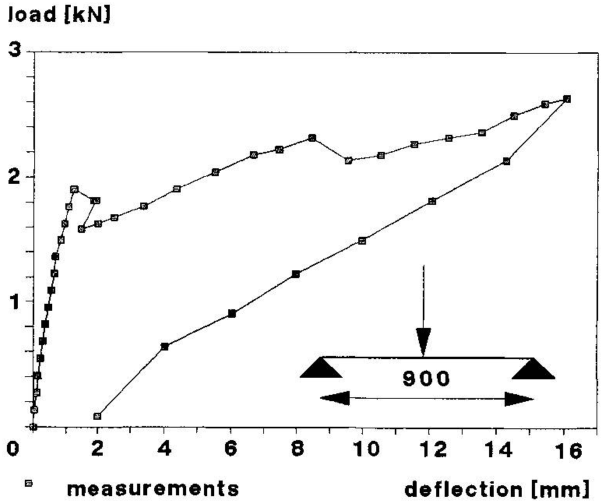

figure 6: load-deflection curve of a concrete panel prestressed with Arapree

5. Design Data

According to the safety-philosophy formulated above the following design criteria can be determined for Arapree:

- initial stress in Aramid fibre after release $\sigma_{apo} \leq 0{,}55\ f^{*}_{atk} = 1550\ N/mm^2$

- relaxation of Arapree (deducted from tests)

$$\frac{\Delta\sigma_{p.rel,\infty}}{\sigma_{apo}} = 0{,}15 \text{ in dry environment}$$

$$\frac{\Delta\sigma_{p,rel,\infty}}{\sigma_{apo}} = 0{,}20 \text{ in wet environment}$$

*) f_{atk}: characteristic short term strength = 2800 N/mm²

- permanent loading should not cause stresses in the fibres that exceed : 1550 N/mm²
- if a stress level higher than 0,55 f_{atk} is chosen in case of a shorter life expectancy (< 100 years), the characteristic stress curve may not touch the characteristic stress rupture curve.

6. Applications:

Applications of Arapree in practice have been realised in a noise barrier, a hollow core floor slab, prestressed masonry, a fish ladder and balcony slabs [6]. More projects are under construction.

7. Conclusions:

To develop a safety concept for non-metallic tendons, one has to take into account the influence of environment, time and stress-level on the mechanical behaviour of the new materials.

Based on this properties it is possible to determine design criteria, in which is taken into account:
- stress losses due to relaxation, creep and shrinkage
- stress rupture
- residual strength

The calculated design data must be based on the characteristic values of the material properties.

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