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New Horizons with Arapree Prestressed Concrete

Nouvelles perspectives du béton précontraint d'Arapree

Neue Aussichlen mit Arapree — Spannbeton

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SUMMARY
Arapree is a tendon composed of parallel aramide fibres in an epoxy resin. Since they are non-corrosive and non-magnetic they create new applications for concrete. Examples — like the substitution of tropical hardwood —are given in this paper. New materials bring about less common material behaviour, so much attention has to be given to design approach. For the purpose of this paper the damage warning behaviour of fully elastic materials like Arapree is discussed.

RÉSUMÉ
Arapree est un câble composé de fibres aramides parallèles noyées dans une résine époxyde. Etant donné qu'ils sont noncorrosifs et nonmagnétiques ils donnent lieu à de nouvelles applications pour le béton. Des exemples — comme la substitution du ;bois tropical — sont énumérés dans cet article. Les nouveaux matèriaux ayant des comportements moins connus que les matériaux courants, demandent pour cela une attention particulière dans leur étude. Le but de cette note est d'étudier le comportement de la ductilité ("warning behaviour") de matériaux entièrement élastiques comme l'Arapree.

ZUSAMMENFASSUNG
Arapree ist ein aus parallelen Aramid-Fasern und einem Epoxidharz aufgebautes Zugelement. Da es korrosionsfrei und elektromagnetisch neutral ist, eröffnen sich ihm neue Anwendungsmöglichkeiten. Beispiele dafür — wie der Ersatz von tropischem Hartholz — werden in diesem Aufsatz vorgestellt. Dabei müssen die speziellen Eigenschaften dieser neuen Materialien beim Entwurf berücksichtigt werden. Besondere Aufmerksamkeit findet daher in diesem Beitrag die Schadensvorankündigung von Konstruktionen, die mit rein elastischen Materialien wie Arapree bewehrt sind.

1. INTRODUCTION

High tech developments nowadays are well known in the electronic and aerospace industries. In civil engineering however, innovative processes are going on too. For example the development of high tensile prestressing elements, made out of man made fibres.
A range of developments in bars and tendons consisting of continuous high strength fibres, usually embedded in a polymeric matrix, is aiming at structural application in concrete. This concerns at the moment glass, aramid and carbon fibres.
Their strength capacities are in the range of prestressing steels. Several other material characteristics however differ considerably from those of the well-known steels (like Young's modulus, creep, relaxation, stress rupture, behaviour in aggressive environments etc.) These different characteristics are to be considered thoroughly in design and design criteria.

This paper deals specifically with the effects and challenges of applications of Arapree prestressed concrete [1].
Due to the non-corrosivity and other superior properties, these tendons create new applications for concrete. For example (very) thin walled structures which reduce the mass of the structure while still maintaining the advantages of the material concrete.

Arapree tendons are composed of aramid fibres (brandname Twaron) embedded in epoxy and have the following main properties:

* high fibre-strength, up to 3000 N/mm^2 (related to fibre-cross-section)
* excellent fatigue behaviour
* non-corrosive, both in strong alkaline and carbonated concrete
* resistant to aggressive environments as acids, bases and salts (e.g. chlorides and sulphates)
* insensitivity to electro-magnetic currents.
* Young's modulus of the fibres is 125,000 N/mm^2

A practical overview of material properties and recent applications of Arapree is given in [1] and [2].
Because of the relatively low Young's modulus it is apparently more appropriate to use Arapree as a prestressing material.
The capacities of Arapree shape however possibilities to more than only spectacular thin and non-corrosive concrete. Also applications in fields where - up to now - no alternatives are available. Thus uses where e.g. tropical hardwood, chemically treated wood, steel structures etc. are common.
So new horizons are disclosed with Arapree prestressed concrete not only by the structures themselves but also by environmental improvements, such as saving the tropical forest.

2. WARNING BEHAVIOUR

Since important characteristics of this type of material differ from those we are acquainted to, the safety approach has to be reconsidered. Firstly a life span comparable to what is commonly expected of concrete structures (say 100 years) must be ensured. So reliable estimates have to be made on the long term behaviour in the (alkaline) concrete matrix [2].
The next important safety requirement is that there has to be a warning behaviour long before an eventual failure due to overloading occurs. Brittle failure has to be avoided.
Both concrete and Arapree have no plastic zone. That suggests that in case of overloading the structure can collapse suddenly without warning.
A composition of two brittle materials however does not necessarily lead to a new brittle material. Such a composite structure can also show a sufficient ductility and a so called "warning behaviour".

The ductility of a prestressed concrete element is influenced - independent of type of tendons - by:
- the residual strain capacity of the tendons after prestressing
- location and quantity of the tendons
- elastic modulus (Young's modulus) of the tendons
- bond behaviour of the tendons.

From [3] and [4] we can learn that with a careful design the residual strain and the Young's modulus have great influence on deflection. And contrary to other suggestions, [3] and [4] also state that the bond behaviour of tendons has only a restricted influence on the deflection. Good bond with short transfer and anchor lengths will cause a lot of cracks with small crack widths and short crack distances. While worse bond causes less cracks but larger crack widths.
In figure 1 the deflection is calculated for a balcony slab prestressed with Arapree in comparison with a slab prestressed with steel strands. Both slabs have the same moment of rupture and location of the tendons. The calculation is checked by a test at the University of Technology Eindhoven. The calculation and the test results showed good resemblance.

The residual strain capacity of Arapree after pretensioning is 1.2% (prestressed at 50% of the ultimate strength) and that of the prestressing steel 2.9% (prestressed at 60% : (3.5 - 0.6 * 1860/200.000 = 2.94%).
Although the Arapree slab has a lower rotation capacity (see fig.2) the deflection at the centre is greater.
The lower residual strain is "compensated" by the lower Young's Modulus, as a result of which the slab deflects more at the range where it is cracked. Thus to obtain a high deflection, criteria have to be stated not only on the ratio M_u/M_{cr} (M_u = ultimate moment ;M_{cr} = cracking moment) but also on the ratio κ_u/κ_{cr} (κ_u = ultimate rotation, κ_{cr} = rotation at the moment of cracking).
If the prestressing force of Arapree (P_0) is limited to 50% to 60% of the ultimate strength (P_u) the requirements on κ_u/κ_{cr} and M_u/M_{cr} are met [3]. By coincidence $P_0/P_u \leq 0.55$ is the same criterium that has been proposed to be used in relation to durability and long term safeguarding of the strength of Arapree [2].

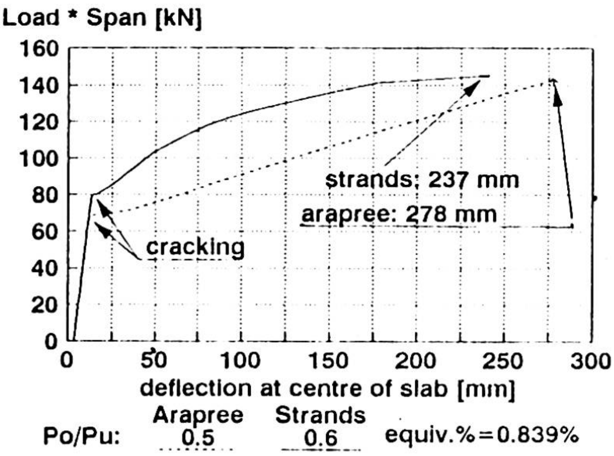


fig. 1:deflection at mid.span of a slab pre-stressed with steel and with Arapree

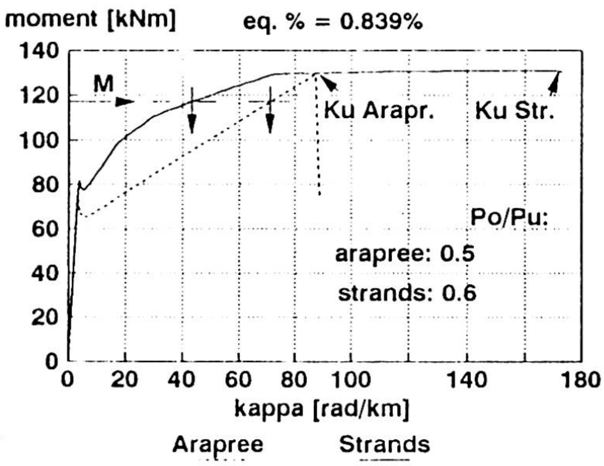


fig. 2: moment-rotation curves of the slabs of fig.1

The afore mentioned leads to the following conclusions:
- it is possible to design structural components composed of brittle materials in such a way that the components show satisfactory flexibility and rotation capacity in bending.
- in order to achieve that goal it is necessary to define requirements on the constituent materials as well as on the design of the composed structural component.

3. DESIGN

3.1 Design data for prestressing

Taking into account:

- a life-span of ca. 100 years
- stress losses due to creep, relaxation and shrinkage
- stress rupture, a phenomenon very important for all high strength fibres
- residual strength
- warning behaviour

The following design values can be determined for Arapree:

- initial stress in Aramid fibre after release $\sigma_{apo} \leq 0{,}55\ f_{atk} = 1540\ N/mm^2$ (f_{atk} : characteristic short term strength = $2800\ N/mm^2$)
- total relaxation of Arapree (after 100 years) may be taken as 15% in dry environment and 20% in wet environment.

3.2 Application areas

Since artificial fibres as aramid are non-corrosive, market prospects are good for applications where total costs of a steel reinforced construction exceed those of an Arapree reinforced construction due to corrosion. Maintenance costs are also to be considered!
Therefore the main fields of applications of Arapree are (very) thin elements and structures in highly aggressive environments. Other interesting fields are non-magnetic or non-conductive elements and structures exposed to severe fatigue loads.

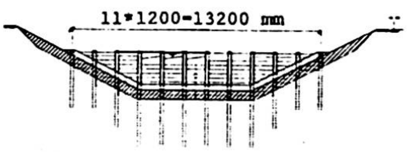
3.3 Environmental protection

A good example of a promising application area is the substitution of tropical hardwood; the use of which is under discussion nowadays.

3.3.1 fish-ladders

In the Netherlands a hydro-electric power station has been built in the river Meuse. To allow fish to by-pass the station, a fish ladder was constructed near the power station.

The fish ladder has been built up out of 24 weirs. Each weir consists of concrete piles with concrete shutters in between. Additional to a weir, a foot-bridge by which the winch of a sluice can be reached, has been constructed (fig. 3,4 and 5).
All these elements are made out of concrete prestressed with Arapree. Concrete elements are made in colours and have the required surface structure. The shutters have a thickness of only 35 mm. Such thin walled elements with a weight of just 18 kg are easy to handle and have been installed using light equipment.



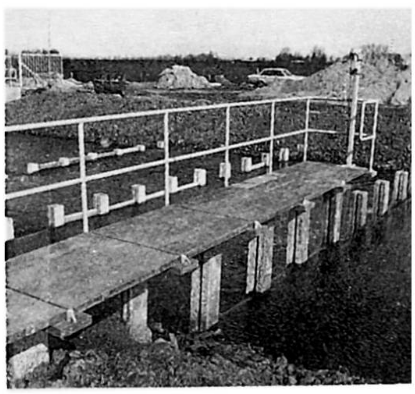


fig. 3: View of a weir fig. 4: piles and shutters fig. 5: foot-bridge

One of the conditions was that the water stream in the passage could be changed at any time and any place. That required a flexible system with shutters that could easily be handled by hand.
Technically a thickness of 35 mm is not the minimum. Smaller thicknesses (e.g. 25 mm with a weight of 13 kg) can be considered. However to avoid steel secondary reinforcement the tensile strength of the concrete must be quite high to overcome splitting forces due to stress transfer.

3.3.2 **Bank protection**

Bank protection with a soil-retaining height from 1.0 to 3.0 m consists normally of wooden shutter piles or of wooden sheet walls.
A feasibility study [6] made clear that concrete elements prestressed with Arapree can substitute wooden bank protection. In this study was taken into account dead load, ground parameters and costs. Construction costs were excluded but they are obviously lower for thin elements. For retaining heights of 6.0 m and more conventional reinforced concrete is more attractive because then required thickness (ca. 120 mm) becomes that high that reduction of the cross-section thanks to less cover is no longer significant.

Three pile wall types are chosen from nine designs and further analysed.
The following systems are considered the best alternative:
- up to 1.0 m: a system of piles and shutters (fig. 6).
- from 1.0 m: a pile wall (fig 7).
- from 3.0 m: a pile wall of profiled elements (fig. 8).

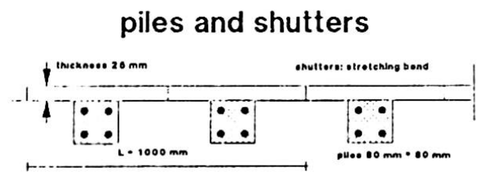


fig. 6: heights up to 1 m

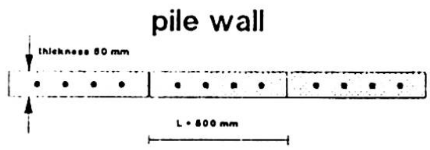


fig 7: heights 1 - 3 m

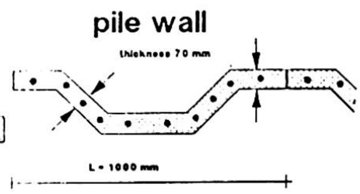


fig 8: heights 3 - 6 m

The price optimum of Arapree concrete elements is reached at a height of ca.3.0 m. At that height the elements are even cheaper than wooden protection.

3.4 Creative design

Since the first pilot project in 1988 a lot of experience is acquired with regard to design and performance of Arapree prestressed concrete structures. This experience proved that making a good design in Arapree requires a new way of thinking.
Arapree is a material with its own advantages and disadvantages. Although not all problems are solved yet, spectacular structures are possible if one is prepared to leave the beaten paths.

An excellent example is the design of a tunnel daylight screen. The screen is aimed to protect drivers against direct sunshine. It consists of 600 Arapree prestressed concrete elements of 250 mm width, 90 mm height and a span of 12.8 meters. The elements are slightly curved with a rise of 1.0 m and therefore fully self supporting in spite of their very small dimensions (fig. 9). Elements prestressed with steel would be too thick due to corrosion protection and therefore not meet the conditions on minimum and maximum sunlight. This daylight screen is an alternative to the originally planned extruded aluminium lammellae supported by a beamgrid of coated steel.

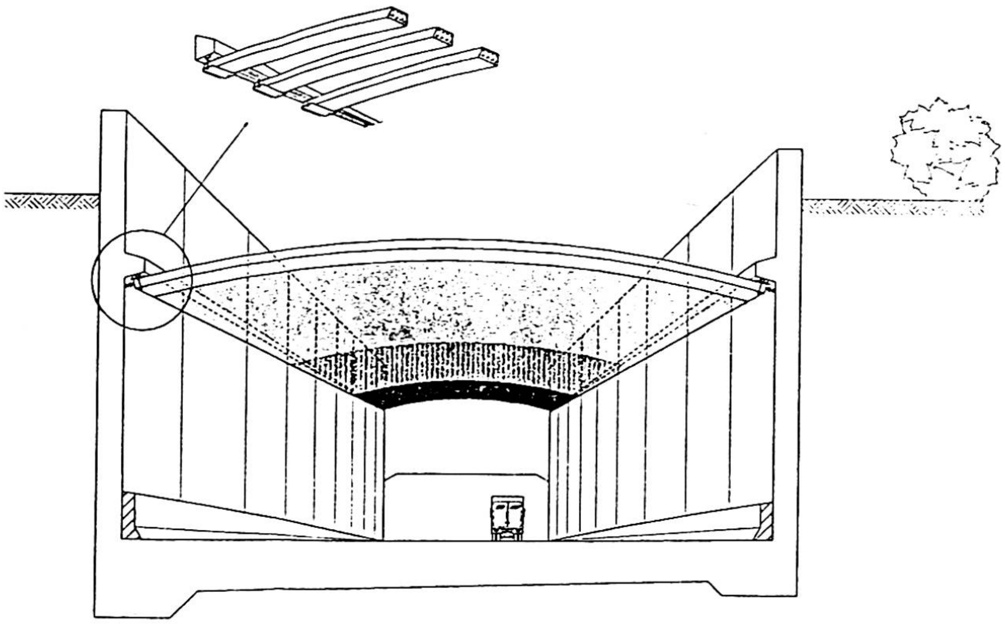


fig. 9: Perspective view of a tunnel daylight screen

More information on creative designs and examples of structures in Arapree is given at the poster presentation.

4. CONCLUSIONS

To realise structures in new materials a reliable safety concept is essential. For Arapree a safety concept has been developed in which a life-span of 100 years is ensured.
Warning behaviour is taken into account in this philosophy.
If the prestressing force of Arapree is limited to ca. 55% of the characteristic short term strength, the deflection - at mid span - will be equal to the deflection of a comparable steel prestressed structure.

For more than four years now experience with the design and performance of Arapree prestressed elements has been gained. Attractive application areas are thin walled elements and structures in highly aggressive environments. Also chances in the substitution of tropical hardwood and chemically treated wood by concrete becomes attractive. New markets are opened for concrete as is shown by the design of a tunnel daylight screen.

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