New Materials Research at the University of Cambridge

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There is a considerable amount of work underway at the University of Cambridge into the use of new materials for civil, structural and marine engineering applications. Some of that work is described in detail in other papers; it is the purpose of this paper to given an overview of the work and to put the detailed studies into context.

The materials we are concerned with for most structural applications are aramid fibres, with polyester fibres for soil reinforcement applications. The properties of these fibres led to the identification of their use as prestressing tendons for concrete, both pre- and post-tensioning, stay cables for bridges and roofs, and mooring lines for offshore structures, particularly in very deep water. Early studies (carried out while the author was at Imperial College), showed that the basic short-term properties of strength, stiffness and resistance to immediate corrosion were both well-known and satisfactory. But it was clear that much work remained to be done before these materials could be used with confidence by practising engineers, and much of the last ten years has been spent investigating these various aspects.

For post-tensioning, stay cables and marine structures, parallel-lay (Parafil) ropes have been identified as the most logical structural form; for pre-tensioning applications, braided or pultruded FRP rods are considered, and for soil reinforcement applications, webbing strips are used.

Visco-elastic properties

There are a variety of related phenomena which fall under this heading. These phenomena include creep, leading at high loads or long time-scales to stress-rupture; stress-relaxation, strength retention and cumulative damage. They have often been studied in isolation, and at the moment, no single model exists. A considerable amount of data have been obtained for the aramid fibre Kevlar 49, both at ambient and elevated temperatures, and some data about Technora. But there are gaps which make the build-up of a comprehensive visco-elastic model impossible. Information about other aramid fibres is more sparse, as it is for polyester.

Separate experiments have been carried out to measure creep (with stress-rupture, at high loads) and stress-relaxation (at low loads), but the data do not overlap. Other outstanding problems relate to cumulative damage. If a fibre is subject to a high initial stress (for example during installation or stressing), has a significant proportion of the stress-rupture lifetime been consumed, or does the material recover in some way? It is well known that the creep of aramid fibres is significantly reduced when they are preloaded, but it is not known why, nor is it known whether there is a consequential loss of lifetime. Tests are underway which will fill the gaps in the knowledge with a view to producing a single comprehensive model which relates all these properties,

The question of cumulative damage is a major unanswered topic. There is clearly evidence that if a fibre is subjected to high loads for a period of time (insufficient to cause failure by stress-rupture), it will have used up some of its capacity to sustain other loads for a long period of time. Cumulative damage manifests itself in a number of important ways. In prestressed concrete, the tendon would spend a short time at a high (but decreasing) load, due to creep of the concrete and relaxation of the tendon. What effect does this have on the stress-rupture lifetime of the tendon when at its working stress? In fatigue studies, there is evidence that fibres fail after a given time spent under a varying load, irrespective of frequency, rather than after a certain number of cycles. Cumulative damage is also tied in to the question of strength retention; fibres subject to long-term loads show no loss of short-term strength until just before they would fail anyway by stress-rupture.

All of the factors described above have very practical relevance to industrial applications. Designers need to know that their tension elements will be carrying a specified force after the initial creep losses have occurred, and this is very sensitive to subsequent small length changes caused by creep. Contractors need to know how to cut a length of rope off a reel so that, after they have terminated the rope, possibly preloaded it, transported it around the country, installed it in place and then loaded it, it will have the correct length and the correct tension. This factor may seem mundane, but the alternative is to build into the structure adjustable anchorages, which are usually very bulky and hugely expensive; such considerations are known to have put some designers off using these materials.

Bundle theory

Because of the brittle nature of fibres, the strength of an assembly of elements is less than the sum of its parts. Extensive studies have been carried out to relate the variability in the strength, stiffness and area of the fibres to the properties of the assembly. There are two levels of bundle effects in these elements. From filaments (strengths of a few grams) to 1000 filament yarns (kilograms), and then to multi-yarn ropes (tonnes). For most practical purposes, it is best to regard yarns as the basic element, since the degree of twist in the yarns makes the abstraction from filaments very complex and almost entirely empirical. There are both cross-sectional area and length effects, which mean, for example, that in laboratory tests on short specimens, large ropes are weaker than small ropes. Bundle theory predicts that large ropes will lose strength less rapidly with length, so in the field the differences are less marked, or even reversed.

There are additional complications caused by bundle effects. In some systems, load is shared between fibres by resin, but the resin suffers high creep and its long-term effectiveness in load sharing is not clear. In other systems there is no resin, and the individual fibres are free to slide relative to their neighbours if, for example, one fails or one creeps more than another. In most cases, bundle effects lead to a weakening of the bundle, but by how much is not easy to determine. In other cases, bundle effects are positive: for example, it has been observed that a rope gained about 10% in strength after being held at 50% of its break load for 2 months. It is assumed that this effect is due to differential creep between highly stressed and less highly stressed fibres "evening out" differences between fibres for short-term loads, but these effects have not been proved or quantified.

Hydrolytic stability

The long term stability of polyester and aramids are important, especially when the materials will be immersed in water, or variable purity, for long periods of time. Concern had particularly been expressed about the durability of polyester fibres in wet soil, but our work showed that its behaviour is more than adequate. There is also work showing that resistance of aramid fibres to hydrolysis in marine environments is very good. There is known to be a problem of alkali attack on aramids, but the fibres are not embedded directly into concrete and the use of a sheath or resin will prevent alkali attack.

Pretensioned beam behaviour

The author believes that the new materials with which we are concerned need to be considered in their own right, rather than as replacements for steel. We thus have to look carefully at their properties, and then consider how these might best be utilised as a structural components. This is most important when considering reinforced and pre-tensioned concrete. When steel is used as the tension element, under-reinforcement is seen as a 'good thing', since robustness of the structure is achieved from the ductility of steel. The new materials all have much higher elastic strain capacities than steel, but they are all brittle. Large strains are possible, but not the ability to dissipate energy during straining; any energy stored can be released when the load is removed, or if something fails. It is thus imperative that the tendon does not fail, which leads to the view that under-reinforcement has become a 'bad thing'. So all our assumptions about the underlying principles need to be reconsidered.

It is our belief that to use these materials effectively as pretensioning elements, some limits on bond behaviour are needed to allow the tendon or reinforcing bar to slide relative to the concrete, thus dissipating the concentration of strain that is likely to occur when cracks develop in the concrete elements. A separate paper in this conference (by Lees and Burgoyne) addresses this problem in more detail.

Post-tensioning systems.

The effective use of new materials for post-tensioning and most other structural applications relies on the use of efficient terminations. The barrel and spike termination developed for Parafil ropes is able to develop the full strength of the rope, since tests on long ropes almost invariably fail in the middle of the rope, rather than at the ends. But the terminations are relatively large and have to be fitted before the rope is installed in the prestressing duct, which can sometimes be awkward, so work is underway on possible improvements to the design. As part of this work, studies of bulk fibre properties in the transverse direction, and also the analysis of the complex stress state in the termination itself are being studied in detail (as described by Brown and Burgoyne elsewhere in this conference).

Work is also underway in association with the prestressing company, VSL, to develop complete prestressing systems for general use.

Co-workers

In this short abstract it has not been possible to refer in detail to the contributions of others. But all this work has been carried out by research students working in association with the author, to whom he is indebted. John Chambers (now at Univ. of Aberdeen), Giuseppe Guimaraes (PUC-Rio de Janeiro) and Abdul Merii (W.S.Atkins) all worked at Imperial College; Gyesi Amaniampong (Univ. of Waterloo), Marcus Moore (Univ. of Melbourne), Ian Brown, Janet Lees, Gopal Srinivasan and Claudia Campos have worked or are currently working at the University of Cambridge. The work has been supported by funds from a variety of sources, including Linear Composites, Du Pont, Teijin, Costain Dowmac and EPSRC.