11 Further applications of polymers and polymer composites

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11.1. Introduction

Previous chapters have discussed uses of reinforced and unreinforced polymers in specific forms in the construction industry. This chapter will discuss other uses of polymers which do not fall neatly into the categories described previously.

11.2. Moisture barriers

Polymers are used extensively in the construction and building industries as ancillary materials. Plastic films serve as permanent moisture barriers, preventing the deleterious migration of water through various building and construction elements. Plastics can be used to protect or modify concrete. Silicones can effectively prevent the entry of water through porous bricks, stone or concrete. Thermoplastic lattices can be added to concrete and mortar to improve adhesion and tensile strength. Concrete formwork can be made of moulded or thermoformed plastics (see section 2.6.3) which allow design freedom, simple erection, good surface finish and compound curves.

Some of the common applications for plastics films in the construction and allied industries are for

(*a*) vapour barriers between walls and ceilings, and between rough and finished floors
(*b*) curing blankets for concrete, to retard evaporation
(*c*) underlays for foundation wall waterproofing, highways, airport runways and apron subgrades (see section 10.4.4)
(*d*) temporary protection for personnel and materials.

Polyethylene film is often used in the above applications. This has a very low water permeability and below ground its life expectancy is superior to that of its competitive materials. Polyethylene is unaffected by water salts or bacteria; its superior toughness is a result of the high elongation of the material when under load.

The Glaswall system, which is a glass fibre reinforced polyester, can be applied to a vertical surface of brickwork and concrete to give a water-resistant and hard-wearing protective surface with a high gloss finish.

11.3. Forms for concrete

Unreinforced and reinforced polymers are used in formwork, treamies, chutes and various tools; their attraction lies in their ease of handling. Glass-reinforced polyester composites manufactured by the hand lay-up, spray-up or by matched metal moulding techniques (section 2.8) are often used for these purposes and have the advantage of economy due to the repeated use of the forms. The initial cost of the mouldings may be higher than that for the timber formwork but the ability to reuse the composite forms can result in an overall lower cost. The glass fibre composite formwork is tough and cannot be easily dented, it does not rust as steel does and it does not react with alkaline constituents of concrete. In addition, if the formwork is damaged it can be repaired easily with no visible evidence on the finished concrete.

Helically wound GRP composite tubes have been used in column construction for marine structures as a replacement for steel tubes; both types of tubes would be filled with concrete. Steel used in this context has certain limitations; for instance, due to its high modulus of elasticity, the axial load taken by the column will be mainly borne by the steel. The latter's Poisson's ratio is greater than that of the contained concrete, thus there is little confinement of the concrete as the steel tube separates from the concrete core. On the other hand, a helically wound reinforced GRP composite tube is an ideal material to use because the axial load will be taken entirely by the concrete, the expansion of the composite in the circumferential direction is smaller than that of the concrete and the tensile strength of the composite is high. Consequently, the GRP casing counteracts lateral expansion of the concrete under load and when used in a short column, the axial strength of the concrete core increases over its uniaxial value and can reach a triaxial failure strength of up to four times the uniaxial strength. It has been suggested that fibre-reinforced polymer casings could be used to encase reinforced concrete beams thus improving their strength and ductibility in the compression zone and, in addition, to provide permanent formwork and corrosion protection.

.4. Resin bonded stems

It is clear that modern forms of plywood and particle board could not exist without the polymer adhesive. The polymer used in the manufacture of plywood is only about 4% of the panel by weight and therefore wood is the dominant material.

Sandwich construction is another form of a composite system using resin bond. Honeycomb is a fabricated cellular structure made of sheet material which is assembled to form nested hexagonal voids. In structural applications it is commonly used as a low cost, low density core in sandwich construction.[11.1] Honeycomb can be fabricated from aluminium, stainless steel, reinforced plastics and, in the building industry, from kraft paper honeycomb which is impregnated with phenolic resin. Paper honeycomb is utilized in many building applications, such as partition, doors and other lightweight structures. To form the sandwich system, the core material is bonded to the face material by resin adhesive to form a stiff lightweight beam system.

.5. Foamed ɔlymer systems

Foamed polymers have been discussed in section 2.2.3. These types of polymers can be hard or soft, rigid or flexible or intermediate between the two extremes. Some foams are only available in the form of board (slab stock) whilst others come as liquids or particles that can be foamed or sprayed in place. The foam density and the proportion of interconnected cells generally control the physical strength properties. Thermal conductivity is a function of density, cell size and gas within the cell. Water absorption and water vapour transmission vary with the water—susceptibility characteristics of the basic polymer and the proportion of open cells.

11.5.1. Thermal insulation foams

Foamed polymers can be used as a thermal insulation material. Polymers generally have a very low thermal conductivity and are therefore ideal as thermal insulations. They have been used as space insulation, pipe, wall and roof insulator mediums.

11.5.2. Foamed polymers in road embankments

The load exerted by embankments on soft fine-grained subsoils often leads to problems of bearing capacity and settlement. Slides may occur as a result of shear failure in underlying clay and peat soils. Such subsoils often yield unacceptable settlements. One method of protecting the road against instability and troublesome settlement is to use lightweight fill material. Expanded polystyrene (EPS) has been used in this context where extremely difficult subsoil conditions exist and where other lightweight materials (which are relatively much heavier than EPS) would not provide sufficient stability. The material is required to form a stable volume with low weight and it should be sufficiently strong to take dead and live loads from the pavement and the traffic, thus reducing the loads transmitted to the weak subsoil.

The properties of EPS which are important for the construction of superlight-weight embankments are

- mechanical properties (in particular the compressive strength)
- geometrical size and uniformity
- resistance to moisture absorption
- chemical resistance (solvents, fire)
- long-term properties (ageing, disintegration, resistance against micro-organisms, etc.)

The compressive strength is important if large deflections of EPS material are to be prevented. A required amount of base material is necessary to obtain a particular compressive strength, but beyond this value the density of the material is not too important. As yet there is no British code of practice relating to the use of expanded polystyrene for sub-base to roads, but Scandinavian countries and the Netherlands do have specifications on this topic: the Norwegian Directorate of Roads has had experience in the use of expanded polystyrene for road embankments and had laid down specifications for EPS used for this purpose. These state that the compressive strength of the material may be determined by an unconfined compression test and the specimens should be 50 × 50 × 50 mm. The average minimum strength should be 100 kN/m^2 at 5% compression (2.5 mm) and no single test result should be less than 80 kN/m^2.

The geometric size and uniformity of the material is of importance in order to obtain a stable construction and to facilitate placing and, in this case, the Norwegian Directorate of Roads has stated that the sides of the EPS blocks shall be cut at right angles to each other and that the maximum allowable deviation from the given dimensions (width, length and height) is $\pm$ 1%. The tolerance on the degree of flatness of horizontal surfaces shall be within 5 mm and the smallest dimension of the block shall be 0·5 mm.

The moisture-absorptive characteristics are important for long-term behaviour of the fill. Stability problems can occur if the blocks absorb too much water. However, at present there appears to be no Norwegian specification on the moisture absorption of EPS for road construction, but it seems likely that, provided the design density of 100 kg/m^3 is maintained, the absorption of water will be at a minimum.

Solvents will dissolve EPS but protection against chemical spillages can be provided by placing high density polyethylene sheet material under the road pavement. Precautions against fire are possibly by using fire-resistant EPS.

Expanded polystyrene has a resistance against chemical attack from soils and against attack from micro-organisms and rodents.

11.5.3. Concrete shuttering with EPS insulant

When concrete buildings are constructed, concrete is poured into a costly system of shuttering which is subsequently removed. When EPS board is used for external insulation (a method of conserving heat often used in West Germany, neighbouring countries and sometimes in the UK) it has to be attached to the wall either mechanically or with an adhesive in a separate operation.

A system exists in which the process is reversed. The shuttering is itself moulded EPS so that after the concrete has set, the insulation is already in place. The system was originally conceived in Austria in the early 1960s but a number of difficulties had to be overcome before it was acceptable and international status could be granted for it. It is now possible to make complete EPS shuttering elements and when assembled the modular elements form a continuous system of thermal insulation both inside and outside the building.

11.6. Sealants

Sealants are elastomeric materials which can be used for the sealing of joints against wind and water in the construction industry. In thin curtain wall construction, which employs highly effective materials to provide the heat insulation, there is no cavity for the dispersion of water that may leak through the joints on the outside; also, there is no effective baffling system to prevent air blowing directly to the inside in the event of open joints. Consequently, adhesive and elastic sealants are needed to enable this type of construction to be used efficiently.

The largest variety of sealants fall into the classification of solvent release and are composed of three component parts; these are

(*a*) the basic non-volatile vehicle (the liquid portion of the compound)
(*b*) the pigment component
(*c*) a solvent or thinner to make application easier.

The non-volatile vehicle can vary from a vegetable oil (e.g. linseed) to a synthetic elastomer; each has its particular property and specific application. The pigment component introduces opacity or colour to the material and also assists the rheology and flow control. The solvent is present merely to provide a reduced viscosity to the material to enable the sealant to be applied easily and to ensure that the correct thickness is achieved. After application the solvent evaporates thus "curing" the sealant and causing it to reach its required viscosity and to shrink by an amount equivalent to the volume of the solvent. The Butyl rubber solution and the acrylic copolymer solution fall into this category.

Another group of sealants are those which are chemically cured. The main sealants under this heading are the polysulphide compounds and the silicone base compounds. The latter is a two-part sealant and is highly dependent upon the environmental conditions for the rate of cure. If the humidity and/or temperature is low, the curing period can be very long. The chemically cured compounds do not generally contain much solvent, but do require adhesion additives in order to bond reasonably well to the surfaces to which they are applied.

The desired properties of a sealant are

- a good adhesion with the joint
- permanent elasticity
- low rate of hardening
- low rate of shrinkage.

The choice of sealants is a compromise as no one product has all the above mentioned attributes.

Most sealants will fail by adhesion rupture. If high elasticity or elastomeric properties are required, the cross-linking within the polymer will be high and this results in high cohesive forces; however, this is not consistent with a good adhesive characteristic. In addition, sealants are generally applied on site and adhesive problems are aggrevated by the construction dust and foreign matter which are deposited on the joints.

Elasticity is a difficult property to measure as the load on joints tends to be of dynamic form with low-magnitude repeated strains being applied. Because of the difficulties of setting up this type of dynamic test procedure, a simple single tensile test is usually undertaken to provide some indication of the amount of elongation before rupture. It must be mentioned that elasticity should not be improved at the expense of adhesion.

Ideally sealants should not harden, although, in practice, a small amount of hardening is not critical. If the sealant becomes too hard, it will be cohesive and will fail in cohesion. A small amount of shrinkage in sealants may be acceptable as this property will cause a corner joint to become concave. However, it is not desirable to have excessive shrinkage as the sealant will shrink into the joint, with an aesthetically unpleasing effect.

11.7. Adhesions

Chapter 6 has discussed the methods of bonding and the analyses of joints to transfer loads; this section will briefly cover the adhesives for bonding polymer building materials.

Resilient floor tile adhesives fall into one of the following types

(*a*) rubber-based mastic with water vehicle
(*b*) rubber-based mastic with alcohol solvent
(*c*) linoleum paste
(*d*) epoxy resin mastic.

There are several types of rubber-based mastics in use, including ones which use low cost reclaimed rubber with a high water resistance and flexibility. Others used for concrete applications are made from synthetic rubber-type mastic with a water vehicle and have good water and alkali resistance.

1.8. Epoxy–itumen ombinations

About 25 years ago the Transport and Road Research Laboratory discovered that calcined bauxite has exceptionally high durability and resistance to polishing of bituminous roads; this problem is caused by heavy traffic stresses and vehicle breaking on the surface of the material. As calcined bauxite was and remains in short supply it can only economically be considered as a top dressing to a conventional asphalt surface. Furthermore, standard bitumen surface dressing binders are not strong enough to hold bauxite chippings in place under conditions of high stress. Consequently, a bitumen-extended epoxy resin binder was developed by Shell Research Ltd (the material system has the trade name Shellgrip, in which calcined bauxite aggregate is embedded in a flexible bitumen Epikote which is also a trade name). The Greater London Council arranged for an experimental patch to be laid in south London in 1966. The system continues to be used in London and is widely used elsewhere in the UK and in many other countries throughout the world. In towns such treatment shows the best return on sites with a high wet-skidding rate such as road intersections, tunnels and pedestrian crossings.

1.9. Structural omposites

In this section, composite structural components and composite structures that are in the development stage will be discussed. It was shown in chapter 2 that composite materials manufactured from glass fibre and polymer resin have a low modulus of elasticity compared with that of steel. It was also stated

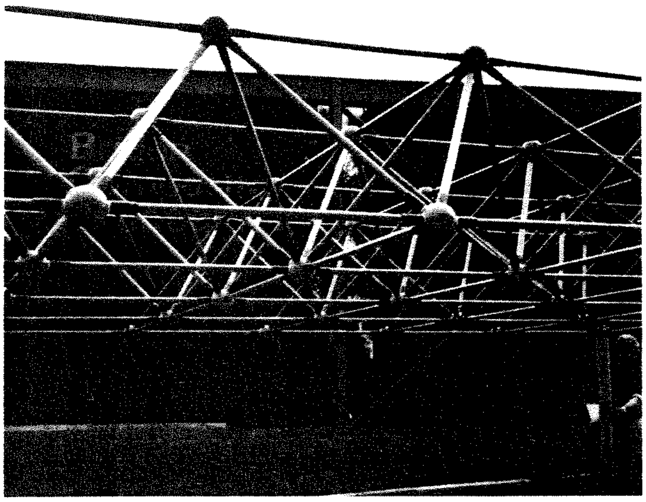


Fig. 11.1. Space frame by Fibreforce Composites Ltd, joint design by Composite Structures Unit of the University of Surrey

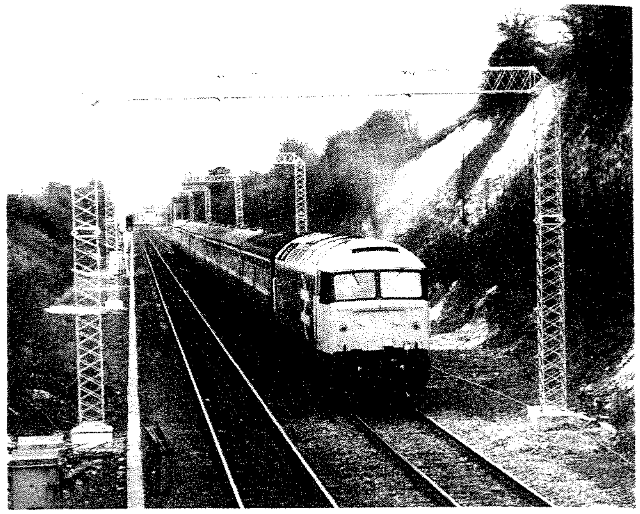


Fig. 11.2. British Railway electrification gantries (courtesy BP Advanced Materials Ltd)

that the modulus and the strength are highly dependent upon the fibre volume fraction and the orientation of the fibres. Consequently, the orthotropy of the material must be considered in the analysis and design of the composite.

11.9.1. Skeletal systems for earth applications

Composite skeletal systems used in the construction industry would, at the current level of technology, be manufactured by the pultrusion technique (section 2.8.2.3), using glass fibre (or a hybrid of glass and carbon fibre) in a polyester matrix or by the geoform (GRP) technique.*

Pultrusion sections which have exclusively unidirectional reinforcement are anisotropic with extremely high axial and flexural strength but relatively low transverse strength. However, by incorporating hooped strands along a reinforcement core, the hoop strength can be improved. Mats, particularly continuous fibre mats, can also be used to improve the transverse strength. To improve the appearance, corrosion resistance and handling of the product, glass fibre and polymeric veils can be added to the laminate construction to depress the reinforcement from the surface, thus providing a polymer rich surface to the composite. The two most commonly used products are surface tissues of high alkali content glass (A glass) or chemical resistant glass (C glass), and polymeric veils of polyester if this is one of the parent materials.

The main properties of the pultruded composite which give it a special significance are

- high strength-to-weight ratio
- dimensional stability
- corrosion resistance.

As the problem of jointing skeletal composite systems has only recently been investigated and a solution found, there are not many examples available to illustrate their use. However, one example is shown in Fig. 11.1 which utilizes the composite end cap discussed in section 6.20. The members of this structure

*Geoform is a light GRP lattice system manufactured by a process in which unidirectional glass fibres are impregnated with a high performance resin system and are progressively layered into the lattice: fixings are incorporated into the structure during manufacture.

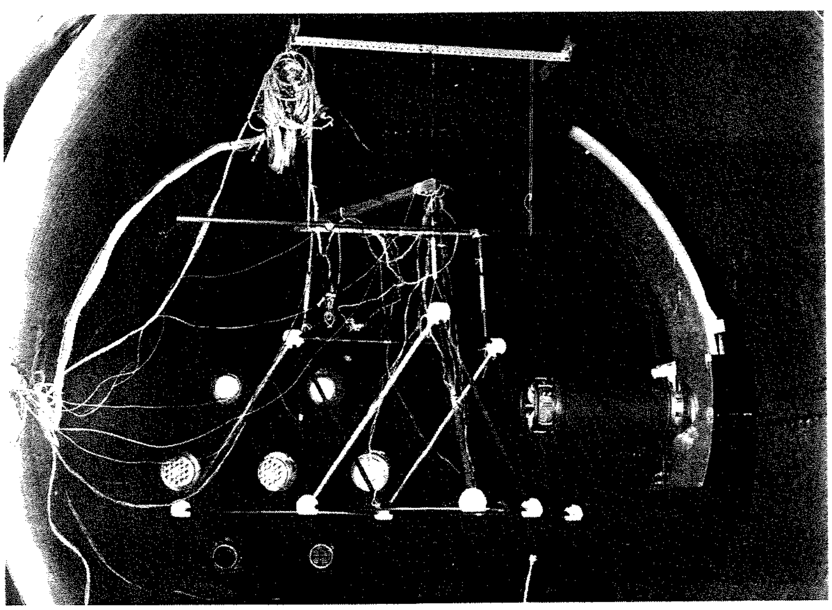
were manufactured by the pultrusion technique by Fibre Force Ltd and are 1 m long, 25 mm external diameter and have a wall thickness of 2 mm. Some research work undertaken during the development of this system has been described in reference 11.2; also given in this reference is a detailed discussion of the pultrusion developments in recent years. Fig. 11.2 illustrates the use of geoform as a lightweight lattice system.

11.9.2. Skeletal systems for space applications

It is likely that some structural engineers will, in the future, become involved in the analysis and design of space structures for communication satellites in which large diameter parabolic reflectors in excess of 50 m diameter and space platforms in excess of 300 m length will be deployed in space. It is almost certain that these structural systems will be of skeletal form and will be manufactured from composite materials because of the latter's unique combination of high specific strength and stiffness, low weight, good dimensional stability and high specific damping capacity. High modulus graphite-reinforced epoxies have been the principal composite material system used for space applications. Initially composites were selected primarily to reduce weight. However, the development of high precision structures, such as the space telescope, required high modulus composites with a coefficient of thermal expansion close to zero to enable the design requirements to be met.

Large parabolic reflectors and space stations will probably be the first large structures where composites are used in the primary structure. One of the composites being investigated for use as the material of construction for a large parabolic reflector contains graphite fibres in a matrix of polyethersulphone. Tube members have been made from this material using the film stacking and hot press moulding technique (section 2.7.2) and units of the structural system have been fabricated.[11.3] Special node joints have been designed to enable the structure to be collapsed and stored in the cargo bay of either Space Shuttle or Ariane and then to be deployed at low earth orbit; it would then be transported to geostationary orbit by either a rocket or space tug. Fig. 11.3 shows a half size model of part of the University of Surrey's tetrahedral reflector manufactured from graphite fibre and polyethersulphone matrix under test in a 3·5 m solar simulation chamber.

Fig. 11.3. Model of part of the tetrahedral reflector under test in a 3·5 m solar simulation chamber



11.10. Polymers for reinforcing and prestressing concrete

Over the last 100 years, concrete has become a major structural material: it is relatively cheap; it can be cast into almost any shape; and, provided that a certain care is taken during the detailing stage in design and also on site, it is a durable material.

Its drawback is of course the very low tensile strength, typically about one tenth of the compressive strength. Thus, with the exception of certain mass concrete structures such as dams and arches, alternative provision must be made to carry the tensile stresses. Traditionally, two methods have been used, both of which use steel. To appreciate the problems associated with the potential use of polymers, it is necessary to look carefully at the way steel is used.

Reinforcing bars can be embedded in the concrete at places where tensile stresses are expected (see, for example, reference 11.4). Typically, a reinforced concrete beam in flexure will have about 1·5 per cent of its cross-sectional area replaced with steel near the tension face, with additional steel placed in other areas to carry shear stresses. Reinforcing steels have working stresses of about 250 MN/m^2 so the strain in the bars is about 0·00125. For normal concrete, with a strength of 30 MN/m^2 the working stress will be about 10 MN/m^2 and the strain, for long-term loads, will also be about 0·0012 (Fig. 11.4). The neutral axis of the beam is thus at about mid depth, and both materials are acting at their full working strength at strains (and hence curvatures) which do not cause problems.

As an alternative to reinforcing the concrete, it may be precompressed by the application of an external force.[11.5] This force puts the concrete into compression, which is then able to resist applied tensile stresses (Fig. 11.5). The force is generally applied by a jack and is reacted by a steel tendon passing through a duct in the concrete. It is the force that is important at the working load, not the tendon itself; the force puts the concrete into such a state of stress that the concrete is able to resist tensile loads. To ensure that some prestress remains after creep of the concrete has taken place, the tendon must have a large strain; with the fixed modulus of steel, this requires high stresses in the steel. It was the recognition of this by Freyssinet which allowed prestressed concrete to become a practical engineering material.

The use of steel as the tensile element in both reinforced and prestressed concrete raises problems of durability. Steel rusts; the high pH of concrete passivates the steel, but carbonation by atmospheric CO_2 may eventually reduce the alkalinity of concrete, which allows corrosion to take place if the concrete gets wet. The quality of the concrete can be improved, but to reduce the possibility of corrosion, the steel is embedded to a considerable depth in

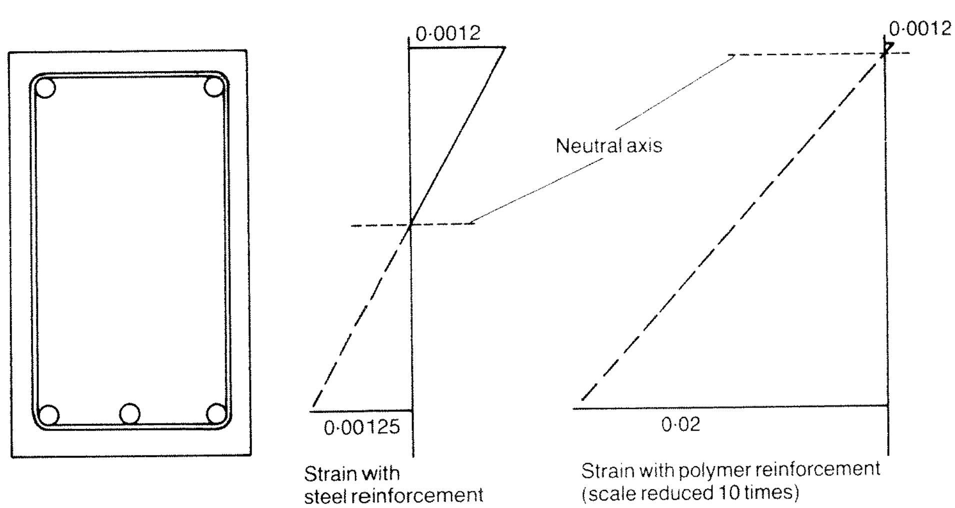


Fig. 11.4. Typical strains for concrete and various types of reinforcements

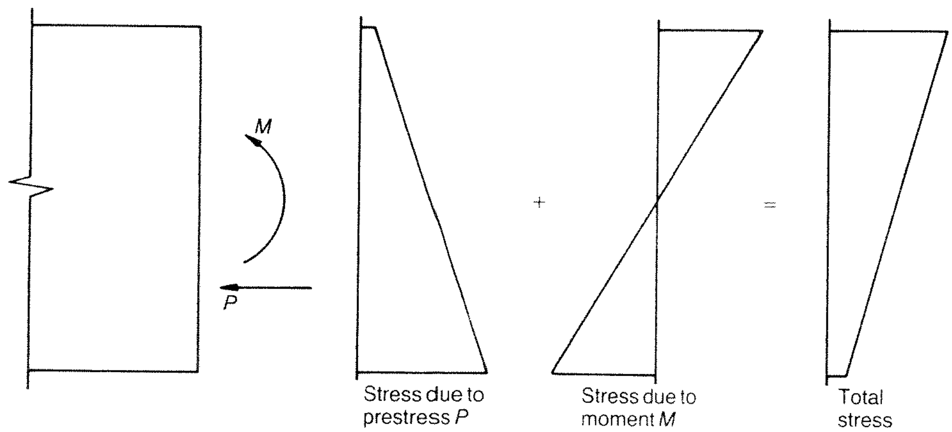


Fig. 11.5. Stresses in prestressed concrete

the concrete. This increases the cross-sectional area, thus increasing weight, and often also reduces the effective depth of the steel, thus reducing structural efficiency. A few attempts have been made to prestress bridges with external cables, more particularly in France[11.6] but much care has to be taken with the corrosion protection and this is not always successful.

Various attempts have been made to overcome corrosion problems, and still allow the use of steel. Galvanizing the steel is not a long-term solution, since the zinc coating is sacrificial and once it has corroded the steel is unprotected. Galvanizing also encourages hydrogen embrittlement in prestressing tendons. Stainless steel is used for both reinforcing[11.7] and prestressing, but is expensive and can suffer from stress corrosion in certain circumstances. Epoxy-coated reinforcing steel[11.8] is widely specified in North America, where bridge decks are not usually waterproofed, and epoxy-coated prestressing tendons[11.9] are also available. The bars are factory coated in epoxy, which then has to be made good on site if the coating is damaged.

Increasingly, cathodic protection is being considered as a method of inhibiting chloride-induced reinforcement corrosion.[11.10] Sacrificial anode systems may be appropriate for buried or submerged structures, but impressed current systems are generally necessary. Cathodic protection has been used extensively to protect bridge decks in North America, but there are relatively few examples of its full-scale application to other types of structure, and continuous monitoring is required to ensure that the system remains effective.

None of these systems fully meets the requirements of a non-corroding reinforcing bar or prestressing tendon; the potential new materials will be considered below.

11.10.1. Reinforcement

Various materials have been considered for use as non-corroding reinforcing bars. These include polyethylenes (PE),[11.11,11.12] polypropylenes (PP)[11.13] and glass fibres.[11.14] Polyesters[11.15] may also usefully be considered.

They all suffer from one primary drawback, however, which comes from the relatively low modulus of the materials. Fig. 11.6 shows the short-term stress–strain curves for typical examples of these materials, with high-yield reinforcing steel for comparison. Although the new materials have appreciable strengths, these strengths are only achieved at high strain levels. Thus, if concrete is reinforced with these materials, significant loads can only be carried once the concrete has undergone severe cracking. It may be argued that since the reinforcement does not corrode, such cracks do not matter, but they reflect a significant loss of stiffness in the structure, and hence a lack of serviceability.

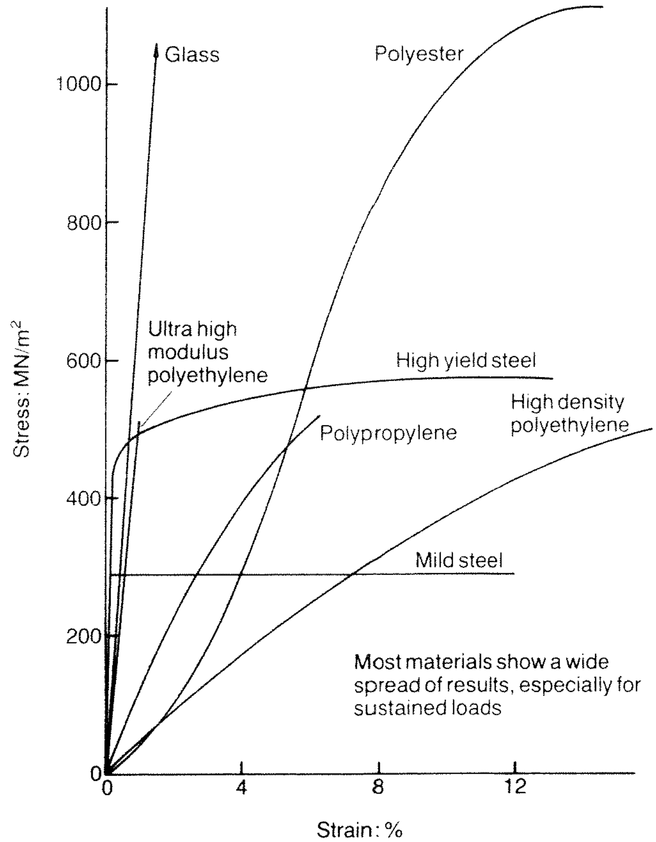


Fig. 11.6. Short-term stress–strain curves for actual and potential reinforcing materials (data taken from references 11.15, 11.19 and 11.24)

There are, however, additional problems. Glass fibres, after promising early uses, have been found to be susceptible to attack by the high alkalinity of concrete. Although alkali-resistant glasses are now available, their use is restricted to non-structural elements such as cladding and permanent formwork. These are widely covered elsewhere[11.16] and since glasses are not, strictly, polymers, they will not be discussed further here.

Most of the true polymers referred to above suffer significantly from creep and the effects of elevated temperature. Thus, sustained loads cannot be carried without significant increases in deflections, and temperatures must at all times be kept close to ambient. Polyethylene melts at 115°C and polypropylene at 175°C, but both lose stiffness significantly at much lower temperatures.

The combination of these effects means that, in the Author's opinion, there is no alternative to steel for reinforcing concrete for *structural* applications at present. Nevertheless, new materials are being developed all the time and the market for an alternative would be enormous, so it is perhaps worthwhile identifying the properties that such a material would need.

It must not corrode, either in the presence of water which might penetrate the concrete, or due to the alkalinity of the concrete. Steel fails the first test, if the passivating effect of the concrete is destroyed by carbonation, and glass fails the second.

The material must achieve a significant proportion of its tensile strength at strains in the range 0·0025–0·005. If the material cannot achieve this, either the deflections in the structure will be very high, or a significant proportion of the material's strength will be unused. Most existing polymers do not meet this criterion.

The strength must be at least 400 MN/m^2 otherwise the proportion of the cross-section taken up by the reinforcement becomes significant, and congestion of the reinforcement becomes a major problem.

The material should not creep significantly. A small amount of creep would be acceptable in most cases (say 10%–20% increase in strain for long-term loads), but creep factors of 3 or 4 for the reinforcement, when combined with factors of 2 or 3 for the concrete itself, are unacceptable.

The material should not soften at temperatures below 200°C, and ideally, should retain significant strength at higher temperatures.

The reinforcement must be capable of bonding to the concrete in order to achieve load transfer, and the bond mechanism itself must satisfy the same creep and temperature criteria as the material itself. This precludes the use of most resin formulations.

The material should be ductile. In reinforced concrete, the reinforcing material has the same strains locally as the surrounding concrete. Thus, there is no possibility of redistributing the high strains that occur in the flexural failure zone (as there is with unbonded prestressing tendons). Thus, to avoid brittle failure, higher partial safety factors would need to be employed for brittle reinforcement than are currently used for ductile steel.

Despite the fact that none of the existing materials is ideal, there is one material which seems to be gaining acceptance in a limited way for reinforcing concrete, primarily for nonstructural applications. This is polypropylene, either in the form of fibres, nets or bars.

Polypropylene is produced as an unoriented thermoplastic, with relatively low strength. It can be drawn into an elongated form, which increases both the strength and stiffness in the direction of the orientation. There is a wide variation both in the precise formulation of the material, and the final properties that are achieved by the drawing process. Four versions are described below which give an illustration of the properties that can be achieved.

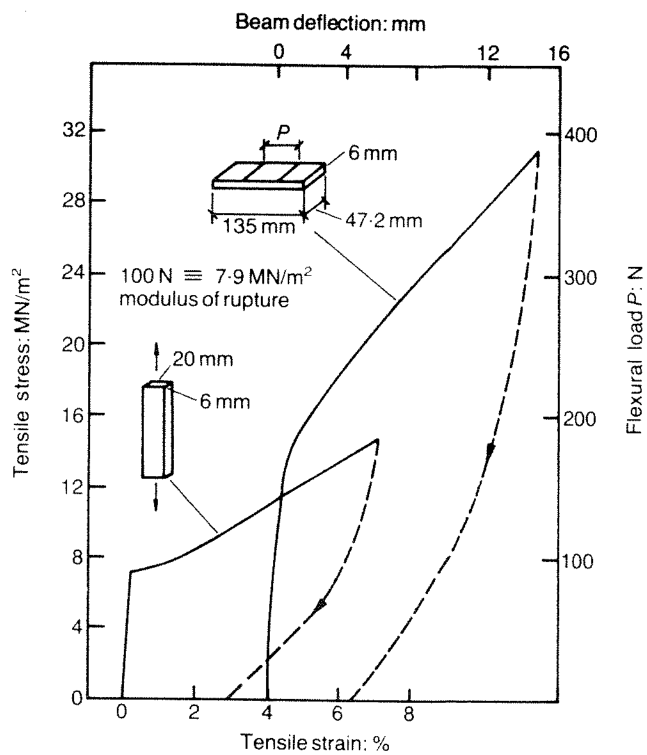


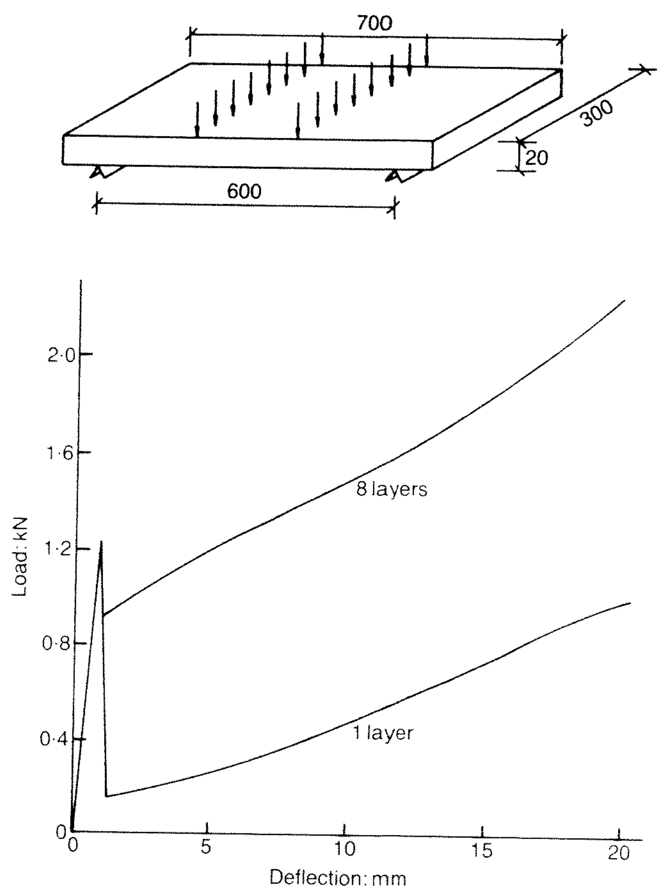
Fig. 11.7. Tensile stress–strain curve and load-deflection curve in flexure for a composite containing 5·7% by volume of fibrillated film networks parallel to direction of stress. 100 N (flexural load) = 7·9 MN/m^2 (flexural stress) (courtesy Royal Society)[11,20]

Fibermesh (which is a trade name of Fibermesh (UK) Ltd) is produced as fibrillated polypropylene, which is then cut into small pieces. The pieces are added to the concrete during mixing, and are broken down into their constituent fibres by the subsequent agitation. The result is a mix containing many individual fibres, each about 20 mm long, with a rectangular cross-section of about 0·5 mm by 0·06 mm. The fibres have an elastic modulus of about 3·5 GN/m^2 and a strength of about 600 MN/m^2. Typical mixes would contain about 0·1% of fibres by volume.[11.17]

The fibres are not primarily intended to contribute to the long-term strength of the concrete;[11.18] they should preferably be regarded as an admixture which serves to resist the short-term shrinkage strains that ocur during the first few hours of curing. However, significant improvements have been quoted for the impact resistance of hardened concrete containing polypropylene fibres.[11.19]

Netcem (a trade mark of Netcem Ltd) uses a material similar to Fibremesh, but the net is not chopped into pieces; the fibres are not separated, and much higher fibre fractions (typically 6% by volume) are used. The result is a cement-based thin sheet composite containing layers of continuous networks of fibrillated polypropylene film. A 6 mm thick sheet may contain between 40 and 60 individual layers of net, each about 0·08 mm thick. Tensile stress–strain curves and flexural load-deflection curves are shown in Fig. 11.7; ultimate strengths of more than 16 MN/m^2 in tension and 32 MN/m^2 in flexure are possible.[11.20] The mechanical properties are characterized by great toughness with closely spaced (1 to 5 mm) multiple cracks after matrix failure. The composite is marketed as flat or corrugated sheeting for roofing and cladding applications as an alternative to asbestos cement.

Fig. 11.8. Load-deflection response of slab reinforced with layers of Netlon[11.21]



Another form of polypropylene reinforcement, this time using much larger components, is the Netlon system (marketed by Netlon Ltd). The manufacture of this system (by the Tensar process) has been discussed in section 2.6.1 and its use for soil reinforcement has been described in section 10.3.2.2. It has also been proposed for use as a reinforcing material. When the polypropylene sheets have been punched into regular grids of holes and mechanically stretched it is possible, by varying the spacing of the holes and the degree of stretching, to produce nets with different properties in the longitudinal and transverse directions. Strips of orientated thermoplastic polymer may also be produced by stretching the material in one direction only.

The strips of polypropylene are not of uniform cross-section, being thickest where the strips intersect. Strengths of up to 500 MN/m^2 have been achieved in certain grids at the thinnest sections, where the amount of drawing has been largest, but 180 MN/m^2 is a more typical figure.

Attempts have been made to produce structural elements using these grids, but tests carried out only serve to show the limitations of the material. Swamy[11.21] has made flat slab elements 700 mm by 300 mm, which were reinforced with layers of Netlon grids. The slabs were 20 mm thick, and each layer of Netlon was 3 mm thick at the maximum point; layers were offset to minimize overall thickness. The slabs were then supported on two opposite sides 600 mm apart and loaded at the third points to produce uniaxial bending.

Typical load-deflection curves are shown in Fig. 11.8. The curves exhibit two distinct phases. On first loading, the concrete is initially uncracked, and is carrying significant tensile stresses. When the limiting tensile strain is reached, which will be between 100 and 200 microstrain, the concrete cracks. At this strain however, the Netlon is stressed only to 1 or 2 MN/m^2 so that a significant drop in load occurs. The load can then be increased again, with the Netlon providing the tensile resistance, but only at very large strains, which are reflected in large deflections. Two curves are illustrated; one shows the resistance with 1 layer of Netlon, the other with 8 layers of Netlon. The most heavily reinforced element eventually reaches a load higher than that of the initial uncracked peak, but at a deflection of about 1/30 of the span.

From this test it can be concluded that it is difficult to provide sufficient reinforcement by means of these grids to contribute significantly to the strength of the concrete. However, the material is extremely ductile, so it may be useful in situations where the ability to resist damage due to short-term impact loads is important.

Use has been made of polypropylene reinforcement using this system for floor slabs[11.22] in which the mesh serves to distribute cracking and prevents the slab breaking up into pieces. However, it is difficult to see how the material can serve any significant structural purpose, since with such a low modulus, integrity is lost before the polymer is carrying significant load.

Another potential use for the material is in repair. Where an additional layer is required on top of existing concrete there are difficulties in ensuring that the fresh concrete remains in place. Steel wire mesh is often used as an armature to support the fresh concrete. Although the mesh has no subsequent structural purpose, it can corrode and cause spalling of the repair concrete. Netlon has been used in this way for the repair of bridges in the West Midlands.[11.23]

The final example concerns an investigation of the use of polypropylene as bar reinforcement by Gowripalan.[11.24] Polypropylene reinforcement was drawn from billet to achieve strengths in tension of 550 MN/m^2 with a short-term modulus of about 12 GN/m^2. The bars were rolled through a mill to produce indentations on the sides of the bar, which enhanced the bond characteristics, and investigations were made of the properties of both the bars themselves, and of reinforced concrete beams and columns made using the reinforcement.

Perhaps the most significant tests carried out were the creep and recovery tests on polypropylene bars in tension, since these results will be reflected directly in the creep properties of concrete reinforced with the bars.

Tests carried out by subjecting the bars to tensile stresses of 20 MN/m^2 (i.e. about 4% of the strength of the bars) for 90 days gave a total strain of 4150 microstrain, equivalent to a creep modulus of 4·8 GN/m^2; 88% of the total strain was recovered 90 days after unloading. At higher loads, much larger creep strains were observed. At stresses of about 50% of the strength, creep strains of about 3% were noted 3 days after loading. Other studies on polyethylene[11.25] and polypropylene[11.26] have observed critical stresses above which the material undergoes creep at constant rate until failure. The tests quoted above did not display this phenomenon, but it is not clear whether the tests were carried out for sufficient time for the effect to become apparent.

Additional tests were carried out by Gowripalan on beams, axially loaded columns and columns with eccentric loads. Broadly speaking, the results are as expected; in compression, the polypropylene has virtually no effect, since its modulus is very similar to that of the concrete it is displacing. In tension, the bars are effective for carrying load in the short term, but lose stiffness significantly when long-term flexural loads are applied to the structures.

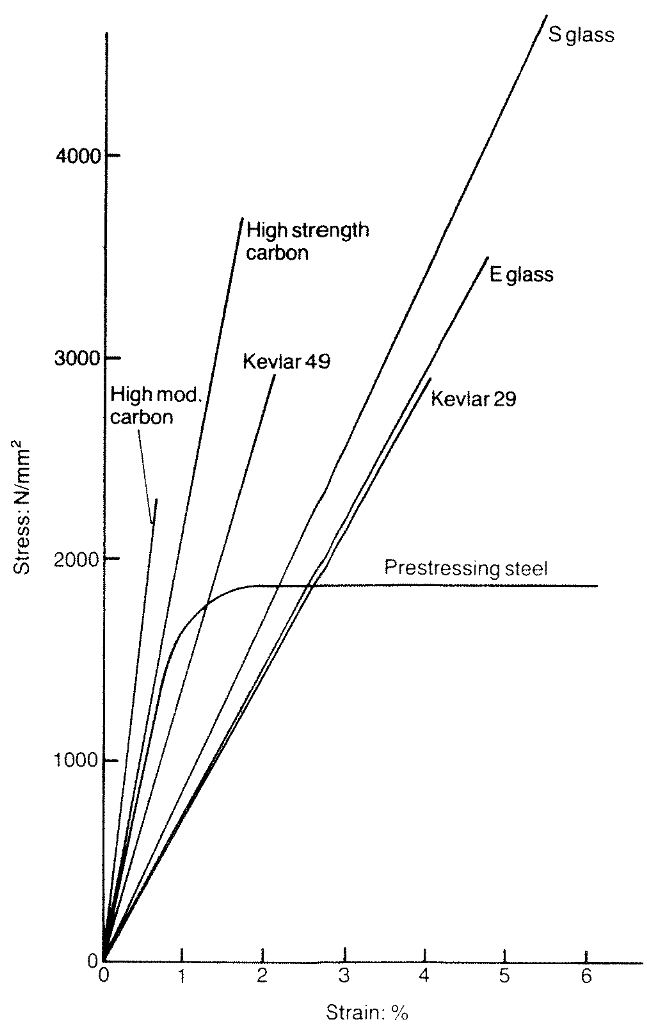


Fig. 11.9. Typical stress–strain curves for fibres that could be used for prestressing

The study concluded that the material is useful in areas where the loading is predominantly compressive, but where only occasional short-term or transient flexural loads are applied. This virtually precludes the use in beams, but may point to specialized use in columns subject to occasional transverse loads, especially when corrosion is a particular problem. Precast concrete piles were particularly identified, since these are subjected to tensile stresses during lifting, and during driving, both of which are known to be of short duration.

It may thus be concluded that the time for polymers as a general replacement for steel reinforcement has not yet arrived, but that there is a fortune to be made if the correct material is invented.

11.10.1.1. Prestressing tendons

The prestressing of concrete is a much more fruitful field of application for new materials. Prestressing is often viewed as a means of giving concrete some ability to resist tensile stresses: at the uncracked stage, that is valid. However, prestressing can also be regarded as a means of allowing, indeed requiring, the use of materials with a high strain capacity.

By taking out some of the stretch of the tendon during the prestressing exercise, the use of high strength but lower modulus materials becomes feasible. Concrete *prestressed* with cold drawn steel wire can be loaded so as to yield the steel without causing excessive deflections in the concrete, whereas concrete *reinforced* with such steel would undergo very large strains before the full strength of the steel was utilized. In a similar way, considerable strains can be applied to polymer tendons during the prestressing process, which thus allows them to be used economically for structural applications.

Prestressing tendons are subject to very high permanent stresses. Thus, resistance to creep becomes of paramount importance. Similarly, an ability to apply the prestressing force and to anchor the tendon must also be provided.

Three materials have been suggested as suitable materials for prestressing tendons: glass fibres, carbon fibres and aramids.[11.27] Typical stress–strain curves for bare fibres of these materials are shown in Fig. 11.9. Glass has the lowest modulus, but has the advantage of being cheap; carbon fibres are made in many grades: some have high strength and relatively low modulus, while others have lower strength and higher modulus. Aramids are available in a variety of forms which have similar strength but different modulus. The original aramids were developed by Du-Pont under the name of Kevlar; these fibres have been discussed in chapter 2. Similar, though not identical, materials are available under the names of Twaron (from Enka) and Technora (from Teijin).

Prestressing tendons utilizing both glass fibres and aramids are now commercially available, but the Author is unaware of any attempts to produce prestressing tendons from carbon fibres, which are the most expensive of the three. An advantage of carbon fibres over aramids in composite applications is the ability to resist compressive stresses as well as tensile stresses. These do not arise in prestressing tendons, so there is little advantage in the use of carbon fibres, and so they will not be considered further here.

The individual fibres must be aggregated to form tendons. Conventional laid ropes, which maintain their integrity by twisting together many fibres, are not suitable, since the individual fibres follow helical paths along the rope. These act like springs when stretched, and the axial stiffness of the rope is very low by comparison with that of the constituent fibres.[11.28] A parallel alignment of fibres is needed, which requires some method of holding the filaments together. This can be done by embedding them in a resin matrix, (as in the pultrusion technique, which is discussed in chapter 2) or by enclosing them within a sheath.

11.10.1.2. Anchorage

The ability of an element to carry significant tensile forces is only as good as the mechanism for getting the force into, or out of, the tensile member. If the range of methods used to load steel wires is considered, comparisons can be drawn between these and the methods used for fibres.

Prestressing tendons are anchored by external wedges, button heads, or bond.[11.29] Stay cables and wire ropes, on the other hand, which have more individual wires, are usually anchored by an internal spike, or by splaying out the wires and encapsulating the ends in a block of a low melting point metal (usually zinc).[11.30] Welding is not used because of the effect of the heat on the properties of the steel.

Which of these systems can work for elements made up from fibres? External wedges (Fig. 11.10(a)) develop high circumferential compressive fores between the outer wires in a strand, but have significantly less effect on

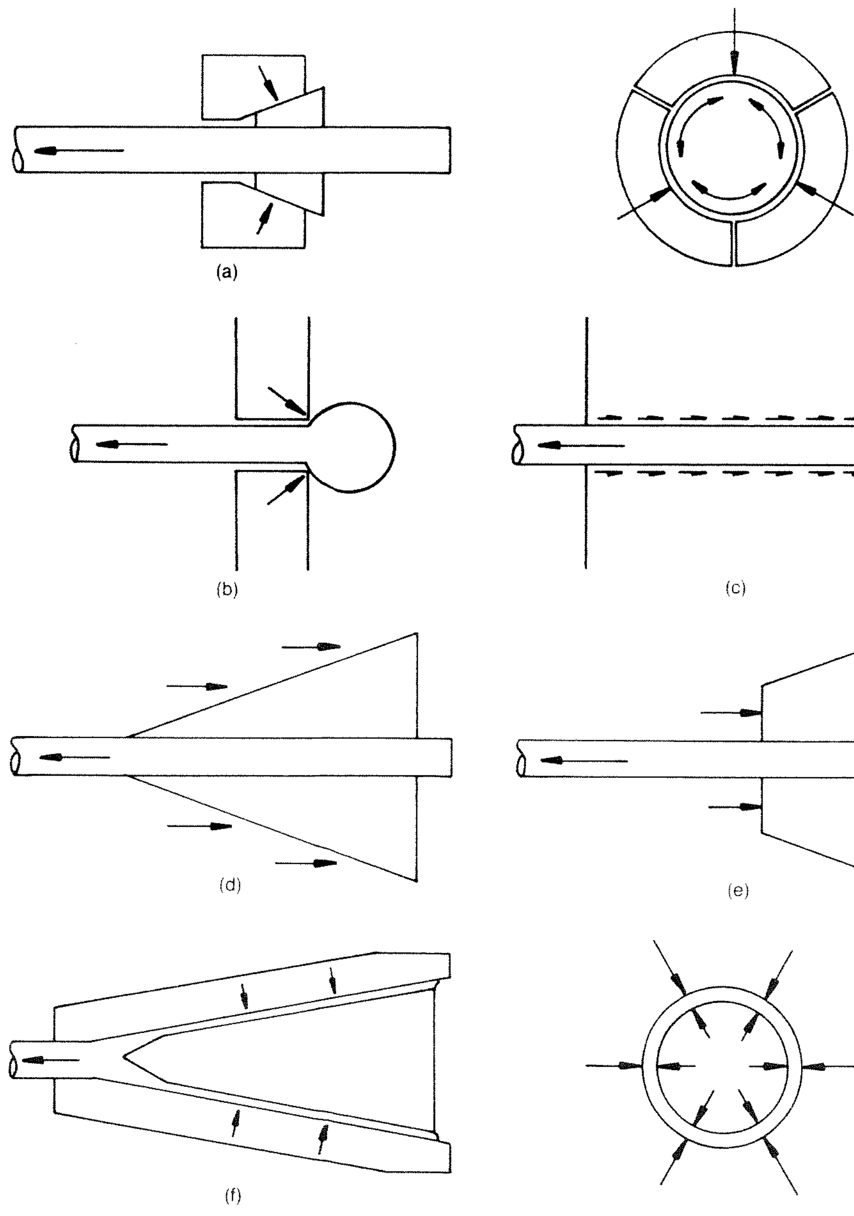


Fig. 11.10. Potential anchoring systems for composite prestressing strands: (a) external wedges; (b) button head; (c) bond; (d) cast cone; (e) truncated cone; (f) internal spike

the inner wires. With the seven wire steel strands usually used for prestressing tendons, this is not a major problem, but 19 wire strands, which have an extra layer of wires, are less popular for prestressing systems because of the difficulty of anchoring the central wire. Thus, the use of external wedges for systems containing millions of fibres is unlikely to be successful. Even in pultruded sections anchoring would be difficult because the anchoring loads of the inner fibres would have to be carried by high shear stresses in the matrix without the benefit of high radial compressive stresses.

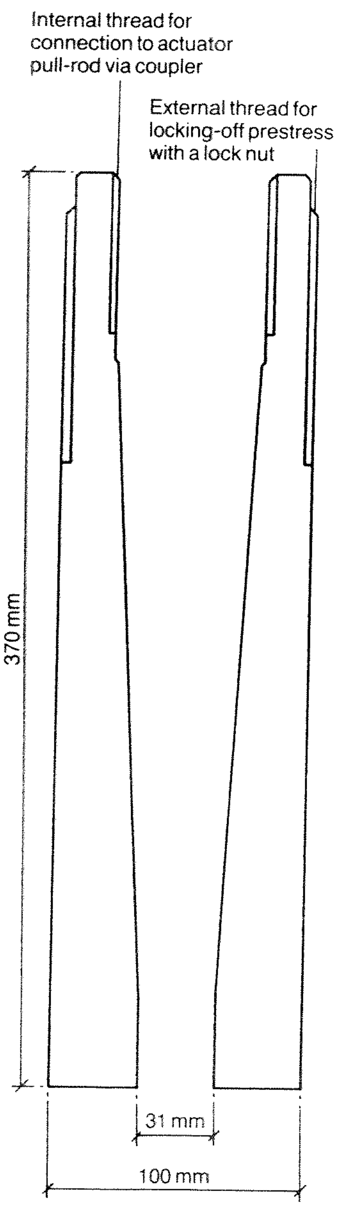
Button-heads on steel wires (Fig. 11.10(b)), as used in the BBRV stressing system, rely on the deformability and the isotropic properties of steel. Modern oriented fibres have high axial strength, but little transverse strength, and they cannot be deformed, so a similar system cannot be envisaged for fibres.

Tension elements can be anchored by the use of bond when the element itself has cohesion (Fig. 11.10(c)) and when some distribution of anchorage along the length is acceptable. Pultruded sections can be anchored in this way when used as pretensioning tendons, but the bond mechanism has the properties of the resin matrix, not those of the fibres. In particular, the creep and thermal properties will be significantly worse than those of the fibres. Anchorage by bond is only possible if the fibres within the rope are themselves bonded together. Tests[11.31] have shown that negligible load transfer capacity is possible on parallel lay ropes which do not have a resin matrix.

An anchorage can be formed by splaying the fibres out into a mould, and then casting a resin cone around them. The cone can be anchored mechanically as required, usually by bearing on the side of the cone (Fig. 11.10(d)) or on the front face of a truncated cone (Fig. 11.10(e)). As with the bond technique, the integrity of the anchorage relies on the properties of the resin, and the shape of the cone is crucial in ensuring even load transfer to all fibres.

The best method for anchoring parallel fibre ropes is the internal wedge (or spike) (Fig. 11.10). The gripping force is provided by radial forces between the spike and the external body, so all the fibres are anchored. The length of the spike can be chosen to ensure that the transverse stresses are within the capacity of the fibres. Fig. 11.11 shows a typical termination for parallel lay aramid ropes. Once the load has been transmitted from the fibres to the terminal body, further connection to the structure can be made by fitting a variety of connections, such as clevis pins, anchorage plates, or whatever is required. The figure shows such a terminal modified for use as a prestressing tendon, in which the terminal body has two threaded regions. The inner thread is used for connection to a pull rod which is attached to the jack during stressing, while the outer thread is used to provide a connection for a permanent back nut, which also allows some adjustment to take account of slack. The anchorage is capable of achieving the full strength of the rope. Reasonable care must be taken to ensure that the spike is fitted centrally within the rope, but otherwise no special skills are needed. Anchorages for aramid ropes with capacities between 1 and 1500 t have been provided using this system.

Fig. 11.11. Longitudinal section through a termination of a 60 t type G Parafil rope modified for prestressing



11.10.1.3. Polymer materials

Three materials are now commercially available for use as prestressing tendons. Polystal is a pultrusion of glass fibres contained within a resin matrix. Parafil is a parallel-lay rope which derives its strength from aramid yarns, while Arapree is a pultrusion of aramid fibres. The remainder of this chapter will concentrate on these three products.

Polystal. This is produced by Bayer AG in association with Strabag AG in West Germany; the product has been under development since 1978.[11.32] In essence, the tendon consists of bundles of bars or rods, each containing E type

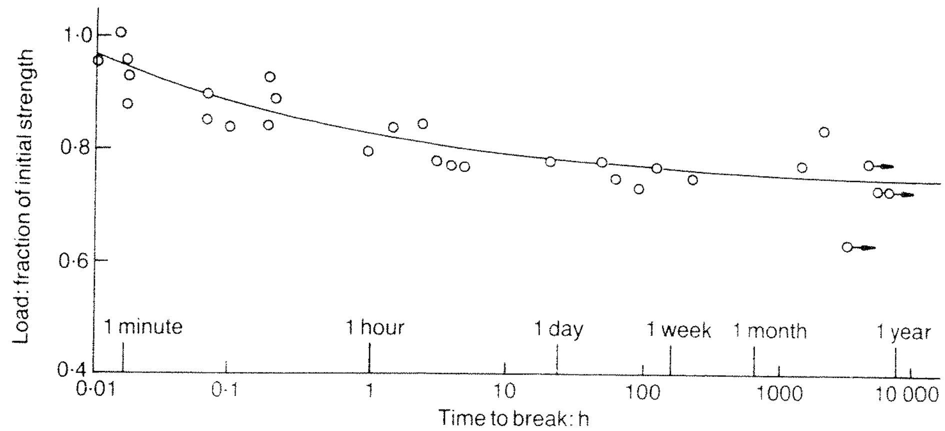


Fig. 11.12. Stress-rupture response of Polystal prestressing strand[11.34]

glass-fibre filaments in an unsaturated polyester resin matrix. A typical bar will be 7·5 mm in diameter, with the volume fraction of fibres being 68%; 19 of these bars will be grouped together to give a tendon with a working load capacity of 600 kN.

The anchorage of the tendons is either by a cast resin anchor, or by external wedges. Once stressed, the tendon is grouted in place by a resin-based mortar.

The Polystal bars have a modulus of elasticity of 51 GN/m^2 with a linear stress–strain curve to failure at 1520 MN/m^2. This corresponds to a strain at failure of 0·033, considerably higher than that of the other materials that are being considered.

Glass has long been known to suffer from stress-ageing, in which cracks develop at surface flaws and propagate through the thickness; indeed, early attempts to use glass-fibre tendons for prestressing[11.33] were not pursued for just this reason. Fig. 11.12, taken from reference 11.34, shows the time to break of Polystal, subject to loads of between 60% and 100% of the short-term breaking load. The published data appears to be limited to durations of about 10 000 h (about 1 year), and a certain amount of caution must be expressed about longer term extrapolations.

These bars are intended for use in grouted tendons, and the behaviour of beams prestressed in this way at the ultimate must be considered. Glass fibres are brittle, so to prevent sudden snapping of the tendon at high beam curvatures either the bond mechanism or the resin matrix must allow a significant degree of slip to occur at high load levels to accommodate the high strains. Alternatively, strains in the concrete at high loads must be kept small, so that the tendon is not approaching its ultimate load.

Considerable research and development have been undertaken in West Germany on the use of these strands for post-tensioning concrete bridges.[11.35] The first prestressed concrete bridge to be built using Polystal tendons was a small 7 m span footbridge in Dusseldorf which was completed in 1980 and was primarily used to demonstrate the feasibility of the prestressing system. The second bridge to be constructed using these materials was a continuous two span structure (die Brucke Ulenbergstrasse) of 21·3 and 25·6 m and was also built in Dusseldorf in 1986. The 15 m wide bridge consisted of a 1·44 m deep slab which was cast in situ with steel reinforcement. The slab was post-tensioned with 59 tendons, each made up from 19 glass-reinforced polymer rods of nominal 7·5 mm diameter anchored in a specially designed block and each tensioned to a working load of 600 kN.

Parafil. This is a rope produced by Linear Composites Ltd which has a core of parallel yarns contained within a polymer sheath. The core yarn can

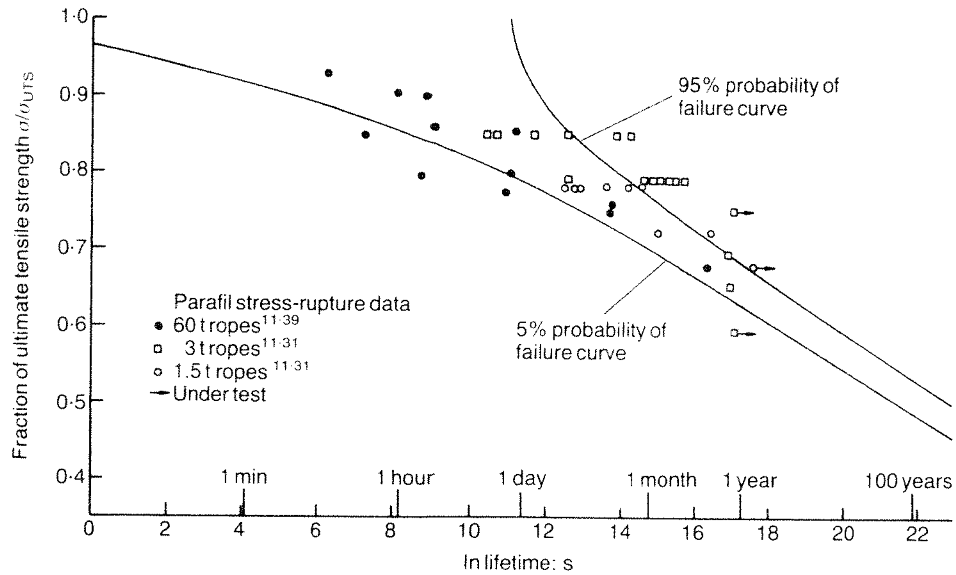


Fig. 11.13. Stress-rupture of type G Parafil ropes[11.31]

be of many different fibres, but the ones most frequently used are polyester (known as type A), Kevlar 29 (type F) and Kevlar 49 (type G). The lower modulus polyester ropes are used for guy ropes and some mooring applications, which is not applicable in this context.

The ropes are anchored by means of an internal spike which grips the fibres against the terminal body. This termination system has been developed after much testing, and can be used for ropes of all sizes (ropes have been made with breaking loads up to 1500 t). All the test results quoted here have been obtained with ropes anchored in this way. As discussed before, this system ensures that all fibres are anchored, and is not affected by heat or creep, which reduces the effectiveness of resin anchorages.

Further details of the properties and uses of Parafil ropes are given in references 11.36, 11.37, 11.38.

The most suitable rope for use as prestressing tendons is the type G rope, which contains Kevlar 49 as its core yarn. This is the stiffest of the available yarns and, although the losses caused by creep of the concrete would be reduced somewhat if the lower modulus versions were used, there are overall benefits from using the Kevlar 49 caused by the reduced jack extension and improved long-term properties of the fibres themselves. Studies[11.39] have shown that the total losses of force in a beam prestressed with type G Parafil are the same as those expected in beams prestressed with steel tendons.

The elastic modulus of Type G Parafil is about 120 GN/m^2 with a short-term ultimate strength of 1930 MN/m^2. As with Polystal, the ropes will creep to failure at high load levels; Fig. 11.13 shows this stress-rupture response. Extrapolations from short-term (up to 24 months) tests, combined with predictions based on the reaction rate theories of chemical processes, predict that a Parafil rope will sustain a load of 50% of the short-term strength for 100 years.[11.40] Applying a material factor of 1·5 to this load level gives a permanent sustainable working stress of about 650 MN/m^2. Work is currently underway to produce reliable cumulative damage laws which will allow the designer to take into account the reduction in stress that occurs in a prestressing tendon due to the creep of both the concrete and the tendon, thus allowing higher stresses to be used for the initial prestress.

Typical stress relaxation results are shown in Fig. 11.14. These are derived from tests carried out on 60 tendons that were stressed to various load levels

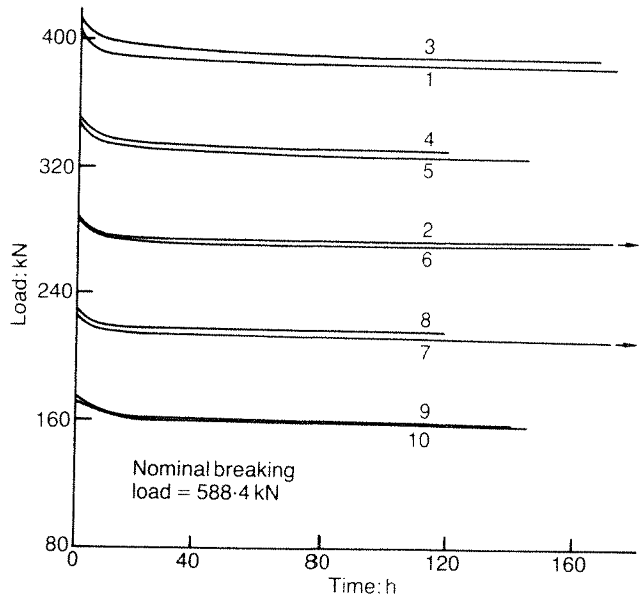


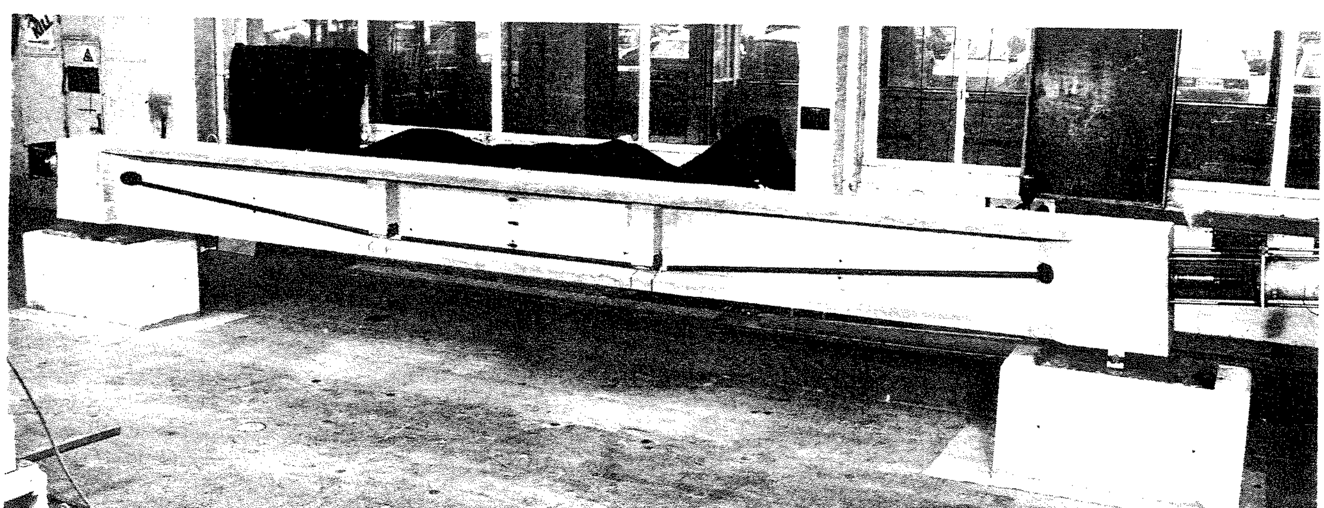
Fig. 11.14. Stress-relaxation response of 60 t type G Parafil ropes from various initial loads[11.39]

against a steel reaction frame, and then locked into place mechanically.[11.39] Relaxation of load of about 8% of the nominal breaking load is predicted at high stress levels.

Test beams have been built using Parafil as the prestressing medium. The first, with an overall length of 5 m, was prestressed with a single 60 t rope, which passed through a straight duct on the centre line of the beam. The second was 8 m long, with two 60 t ropes placed outside the section. The tendons passed under deflectors at about the third points of the beam, so that the tendon was straight and near the bottom of the beam at mid-span. The anchorage was provided near the neutral axis of the beam in thickened end blocks. This beam was more representative of practical beams, since the resistance to corrosion means there is no need to place the tendons inside the concrete, thus saving weight and complexity. Fig. 11.15 shows the beam prior to testing, and Fig. 11.16 shows diagrammatically the stressing sequence that was adopted.

The beams were both loaded by two point loads applied near the centre of the beam, and both beams showed a ductile response to the applied load.

Fig. 11.15. 8 m beam externally prestressed with two 60 t Parafil ropes (each stressed to 30 t)



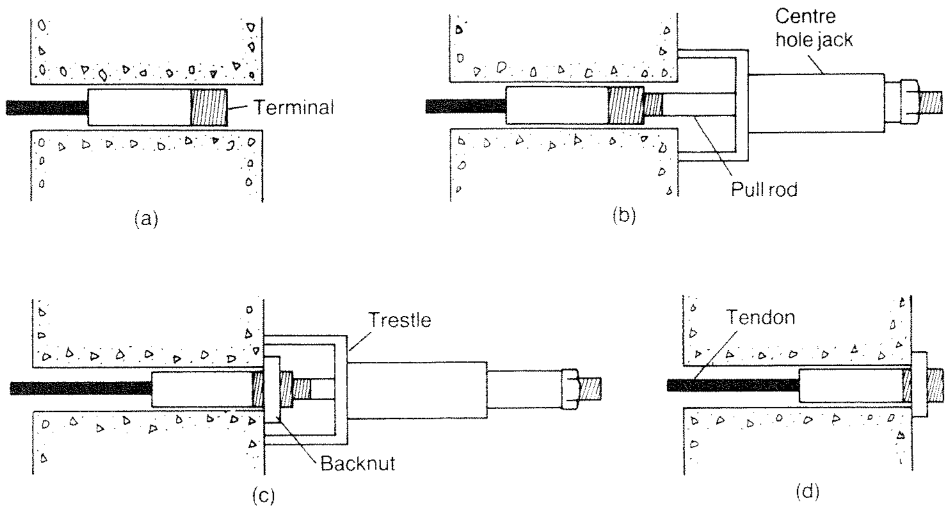


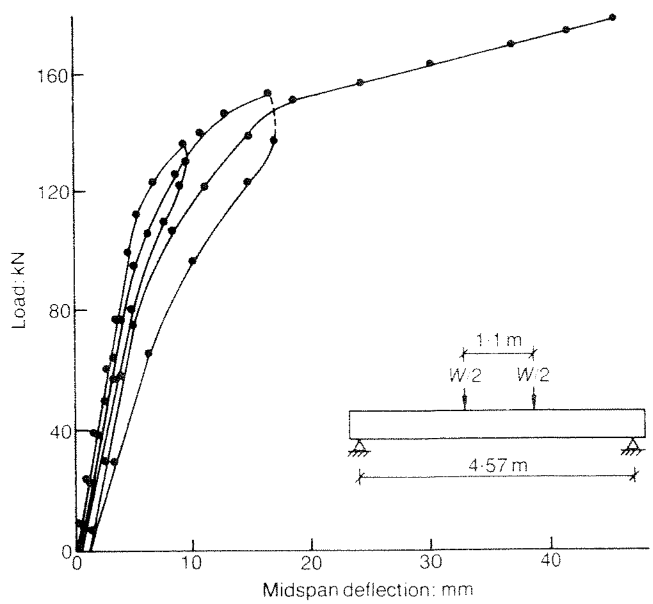
Fig. 11.16. Stressing sequence for Parafil prestressing tendons

When the tensile strength of the concrete is exceeded, cracks form, but the beam can carry significant increases in the load at reduced stiffness before final failure. Failure occurs by crushing of the concrete in the compression zone. Fig. 11.17 shows the load-deflection curve of one of the tests; the curve indicates that considerable energy is absorbed prior to failure, even though the two constituent materials are brittle.

One of the principal benefits of the use of Parafil tendons is that they can be used as external tendons, thus allowing significant weight savings to be achieved, since concrete does not have to be provided merely to give cover to steel tendons.

Parafil has been used for the repair of structures, and this is likely to be a field in which all noncorroding composite materials are useful. Many distressed structures can be reinstated by prestressing, which closes cracks and restores integrity. However, the absence of existing (or spare) ducts means that steel tendons are not suitable for use in these cases, so an alternative must be found. Three cooling towers at Thorpe Marsh Power Station were found to have

Fig. 11.17. Load-deflection curve for a 5 m beam prestressed with a single Parafil rope



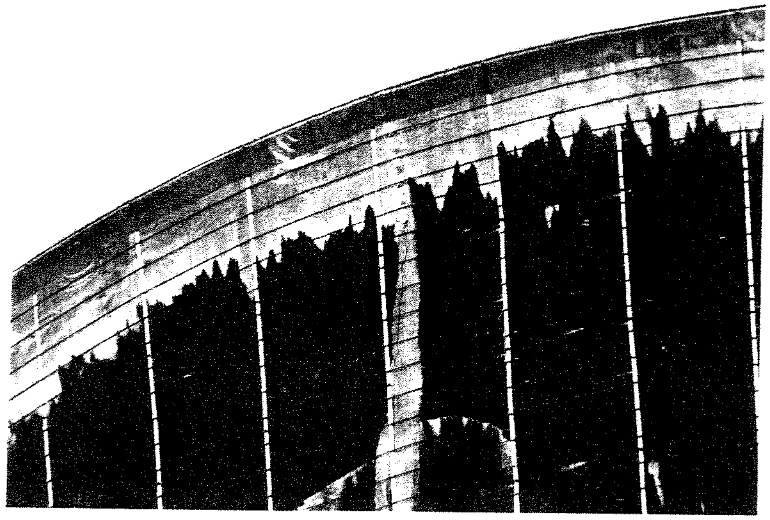


Fig. 11.18. Cooling towers at Thorpe Marsh Power Station repaired by external prestressing with Parafil ropes

large vertical cracks; these were resin-injected to fill the gaps, and then the towers were externally prestressed by circumferential Parafil cables, resting on stainless steel brackets bolted to the towers (Fig. 11.18). In this case, the low weight of the cables was also of benefit, since the whole prestressing system had to be assembled at the top of the towers by steeplejacks working from cradles.

Arapree. Arapree is a pretensioning tendon, produced by Enka, which is made in the form of pultrusions of the aramid fibre Twaron. The tendons rely on bond between the concrete and the pultrusion resin. Pretensioned planks have been made with these tendons[11.41] and the manufacture of railway sleepers has been proposed. The properties of Twaron are broadly similar to those of Kevlar, although higher relaxation figures have been reported for Arapree as compared with those for Parafil.[11.42]

11.10.2. Observations on the use of polymers for reinforcing and prestressing concrete

The materials discussed above offer the designer of concrete structures corrosion-free tendons, in the form of aramids or glass fibres, which are easier to handle on site because of greatly reduced weight. However, these tendons will have to compete with established steel tendon technology by demonstrating their improved long-term durability. Effective non-corroding reinforcement is possibly some way off, although the use of polypropylene to minimize early age shrinkage cracks and to provide an armature to support fresh concrete is now possible.

11.11. The future

The contents of this book have indicated that polymers have a considerable part to play in the construction engineering industries. The parts played by polymers cover a wide spectrum, from subterranean functions such as stabilization and reinforcement of soils, to surface structures involving composites, to extra-terrestrial systems involving the high technology composites; in all these functions the expertise of the civil/structural engineer must play an active role.

As new and improved manufacturing techniques for composites and new polymer materials are developed, even greater emphasis will be placed on the use of these materials for geosynthetics. In addition, as the architect and the structural engineer appreciate the advantages of composite materials in certain applications and the designer becomes more familiar with the analysis and design techniques for composite laminates, the use of composites in the construction industry cannot fail to increase.

In the design of composites it has been demonstrated that the material and structural designs must be undertaken simultaneously because they are both interdependent. This means that many interesting structural concepts which previously have been a figment of the engineer's imagination can be realized. Indeed some very exciting structural applications have been built in very recent times.

An ideal structural use for composites is the new "caretaker" bridge enclosure which was conceived by Maunsell, Consulting Engineers, London, as a membrane which could enclose the steel plate girders of composite or steel-decked bridges in order to provide access for inspection and maintenance, to protect the steelwork and bearings from corrosion and enhance the appearance of this type of bridge. In 1986, a detailed design of a GRP enclosure for the A19 Tees viaduct, the largest composite plate girder bridge in the British Isles, was undertaken. The design was carried out by Maunsell using the developed limit state design methods for composites (see chapter 4); the first panels were erected in 1988. This type of protective system is likely to be adopted for many bridge systems in the future.

The progress in the production and usage of high strength fibres in recent years have increased the potential for advanced structures and this has lead to the design, manufacture and evaluation of lightweight flexible tension members or long continuous lengths. If composite tension members are feasible the applications are enormous and include masts, cables to bridges, wind energy convertor stays, mooring lines for offshore platforms operating in deep water and long-span bridges where design requirements can only be obtained with materials of high specific strengths and stiffness.[11.43]

It has been claimed that suspension bridges with main spans of 4 km are possible with steel cables; but it is interesting to note that the Akashi bridge, with a main span of 1900 m, now under construction in Japan, has necessitated the development of special steels at the limit of existing technology;[11.44] 2 km seems a more practical limit for steel cables. Preliminary calculations have suggested that spans of over 8 km are possible using carbon-fibre composite cables. Richmond and Head[11.45] have suggested that maximum bridge spans have increased by a factor of 3·5 every 100 years since 1770; this would suggest a span of 5 km by 2070. Spans have risen in steps corresponding to the introduction of wrought iron in the 1800s, steel in the late 1800s and high strength steels in the 1930s.

For the future, man-made fibres and fibre-reinforced polymers provide the potential for the next step forward; however, so far innovations, which might have resulted in the use of these materials have not happened; it would seem that there is a time interval of some 30 to 40 years between the introduction of each new material and the engineer's acceptance and confidence in its use.

It is probable that new polymer composite materials for the construction industry would be manufactured from glass, carbon or aramid fibres in the primary phase. They can be bundled together in a protective sheath to form cables, embedded in polymer matrix to form bridge decks or beams and it has been shown in chapters 7 and 8 that the composite can meet most serviceability requirements such as fire retardance and resistance to ultraviolet radiation.

Composite strands made from glass, carbon or aramid fibres have substantially lower breaking strains than steel. However, the specific strength of the glass fibre strand and of the carbon and aramid fibre strand is about twice and four or five times that of steel respectively. Richmond and Head[11.45] have suggested that composites have immediate potential in the construction of bridge decks, with a weight saving, durability and aerodynamic form which could make the material cost-effective. One possibility for a deck system would be to use a sandwich construction in which the core would be of cellular units and the face materials would be steel. The cellular system would probably consist of glass-reinforced polyester composite I beams with or without foam infill.

The use of stress-analysis software packages has been mentioned in chapter 3. They invariably contain solutions to many strength-analysis problems met in the design of fibre-reinforced laminated composite structures. These will include failure criteria, plate vibration and buckling, analysis of bonded joints, stress concentrations, in addition to the calculation of basic stiffness and stresses including built-in thermal stresses. There are more than 600 finite element programs available to the structural engineer, but when the features are specifically addressed to the applications or structural analysis of composites the number of suitable software systems reduces to about ten. In future it will be necessary for all forward-looking engineers, who are engaged in analysis and design of composite structures and systems, to understand and to use the relevant stress-analysis packages.

It can be concluded that polymer composites and polymers do have a very large part to play in the construction industries and their contribution can only increase in the future. In addition, structural engineers need to develop expertise in the field of polymer composite associated with space, so that they can take advantage of the great potential waiting to be exploited.

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