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Rational use of advanced composites in concrete

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Knowledge of the properties of advanced composites leads to conclusions about the most logical ways in which they can be used. The paper considers the elastic properties, the bond properties and the lack of ductility, and concludes that structures should be designed as over-reinforced, with partially bonded internal tendons, and resin-free external tendons. It concludes that enhancement of the compression zone is possible by fibre-reinforcing or confining the concrete, and that requirements for shear need to be totally reworked in the absence of plasticity. It considers the economic justification of advanced composites in concrete, and concludes that innovation is still required, but now on a commercial scale.

1. INTRODUCTION

The use of advanced composites in various forms has been developing over the course of the last 15 years, during which time knowledge of their properties has been improving. It is now possible to review that knowledge and consider how these materials might most sensibly be used. Parts of this paper have been presented to specialised conferences,[1,2] but the work has been extended and background information added for those less familiar with the materials. The use of composites is now at a turning point—most of the technical knowledge is in place—what is needed now is commercial involvement.[3]

This paper looks at the generic properties of advanced composites and considers how these properties lead to conclusions that differ from conventional thinking on reinforced and prestressed concrete. The implication is that if these materials are to be used successfully, the type of structure into which they are placed must be reconsidered.

The three materials with which virtually all this work has been carried out are glass, aramid and carbon fibres; they have been selected because they possess a combination of strength, stiffness, resistance to creep, resistance to corrosion and cost, which lead to the view that they are sensible engineering materials. But along the way, mistakes have been made, and indeed, are still being made, because they are seen as replacements for steel. There has thus been a considerable amount of work trying to make fibre-reinforced polymer (FRP) bars that look like reinforcing or prestressing steel by giving them a surface texture, with a view to replacing one material with another. Instead, however, consideration should be given to how they might best be used in their own right.

The paper does not consider two specialist areas for the use of FRP. Carbon fibre and, to a lesser extent, aramid fibre are being used for repair in the form of glued-on plates for tension reinforcement and shear reinforcement, and as wrapping to enhance the earthquake resistance of columns.[4–6] There is also work relating to the use of filament-wound tubes for permanent shuttering and to provide triaxial concrete compression for columns in new construction.[7] Nor does it look at fibre-reinforced concrete, where bare fibres are put directly into the concrete matrix.[8] Instead, it concentrates on ‘conventional’ reinforcement (in the form of bars) and prestressing (in the form of rods or tendons).

1.1. Review of properties

The new materials are all available in the form of fibres, with strengths of the order of a few grams each. They are elastic, with no yield before failure, and they are all highly oriented. Their transverse properties are markedly inferior to those in the axial direction. They have to be aggregated together to form useful components, without inducing high stresses. The mechanics of production, and the mechanisms for getting force into the fibre, raise very different problems from those present in steel.

Figure 1 shows typical stress–strain curves for composites made from the three fibres, with prestressing steel for comparison. They are linear elastic, with no plasticity, but they have high strengths and high strain capacity. These values should be taken as representative only; different manufacturing processes mean that stiffnesses and strengths can vary by a factor of 2, and the volume fraction of fibre within a composite will also cause variation from these values; however the variation within a given product will be small.

All the materials suffer, to some degree, from stress-rupture problems, in that they can creep to failure. Fig. 2 shows test results for aramid fibres, which indicates that a load of 50% of the short-term break load can be sustained for well in excess of 100 years.[9] There is a widespread perception that this is associated with ‘deterioration with time’, which would imply that the short-term strength is reduced after time spent under load, but this is false. The strength retention of materials is good; when samples are tested under sustained loads for long periods, and then subjected to short-term break tests, they retain virtually 100% strength.[10] The effect on prestressing tendons will not be too severe; the virtually constant pretensioning load will be governed by stress-rupture, while the

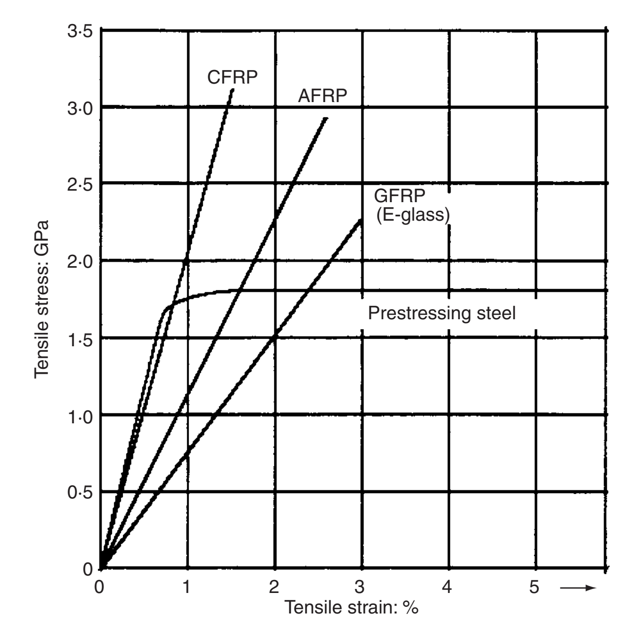

Fig. 1. Stress–strain curves for pultrusions made from carbon fibre (CFRP), aramid fibre (AFRP) and glass fibre (GFRP), with prestressing steel for comparison

Material	Working strain	Maximum strain
Reinforcing steel	0.0012	0.1
Prestressing steel	0.0060	0.03
Glass fibres	0.02	0.045
Aramid fibres	0.012	0.025
Carbon fibres	0.008	0.015
Plain concrete	0.001	0.002
Confined concrete	0.0015	0.0035→?
Fibre reinforced concrete	0.0015	→0.03?

Table 1. Typical material strain capacities

ultimate strength of the tendon for short-term load excursions will remain at the initial strength level.

The thermal behaviour of composites also needs to be assessed properly. There is some justification for thinking that the response to fire needs to be reconsidered and the difference between the thermal expansion of composites, and that of concrete, needs to be taken into account. The very low thermal conductivity of composites by comparison with steel is also a significant factor.

The cost of fibres and resins is high, particularly when considered in terms of small-scale production.

1.2. Current status

Despite the fact that there are still a few gaps in our knowledge of the properties of the materials, research in Japan, Europe and North America has shown that composites made in various forms have the structural capacity to act as reinforcement or prestressing tendons in concrete.[11–13] Sufficient information has been obtained to allow some conclusions to be drawn about the way structures should be designed. If the new technology is applied inappropriately it will fail, either structurally or economically, which would have the effect of preventing even the most appropriate uses if the materials gets a bad name. The remainder of this paper draws together many ideas to show where composites might most effectively be used.

2. REINFORCE OR PRESTRESS?

One of the first decisions to be made is whether it is sensible to use advanced composites as reinforcement. It is fairly clear that this is unlikely to be a major structural use. A simple study of the relative strain capacities shows why. Table 1 shows the typical strain capacities at the working load of various materials together with their ultimate strain capacities. Some of these figures are very approximate; there has not been much benefit, hitherto, in increasing the capacity of concrete, but as will be argued below, that may change.

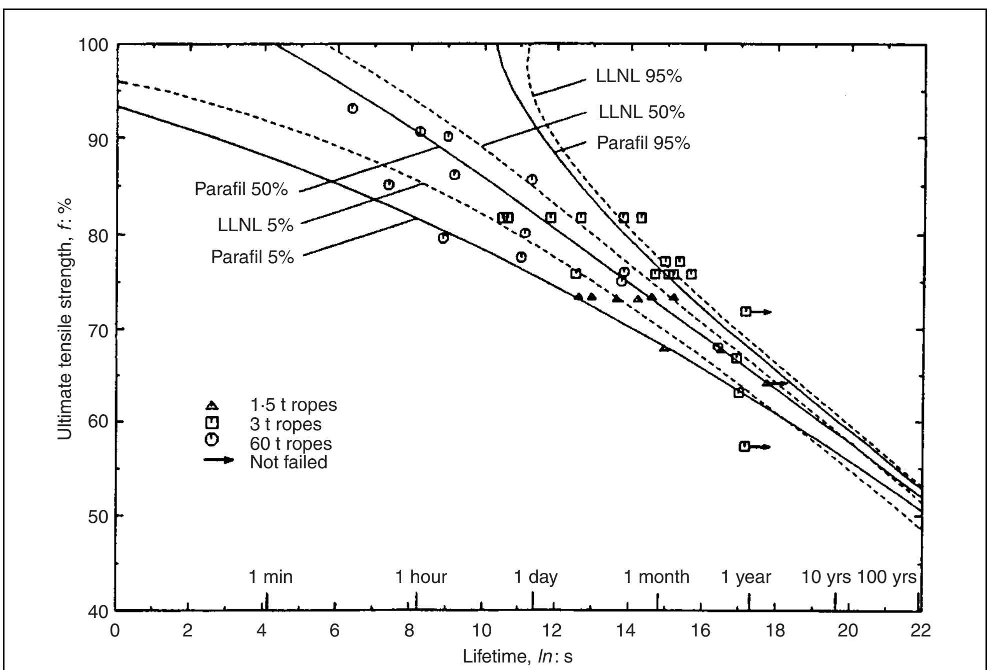

Fig. 2. Typical stress-rupture behaviour of components made from aramid fibres[9]

Consider the strain distribution of sections reinforced with steel or advanced composites (Fig. 3). With steel reinforcement, the neutral axis is at about the mid-depth, while for the section with composite reinforcement, the neutral axis is very near the compression face; the compositely reinforced section has much lower moment capacity because of the reduced area in compression (and hence will be uneconomic), and much higher curvatures (and hence will be unserviceable). A similar argument can be used to show why prestressing steels are not suitable as simple reinforcement.

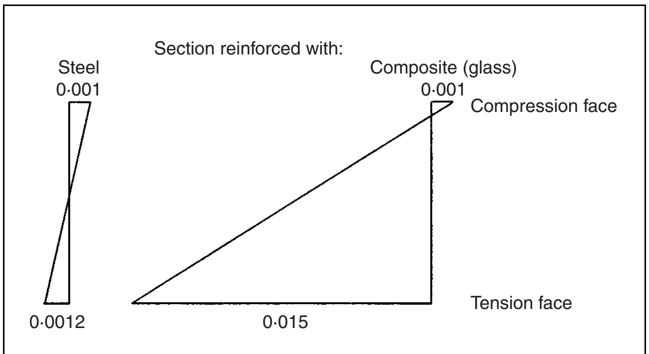

Fig. 3. Strains in reinforced sections at the maximum working load

Contrast this with a section which is prestressed. One of the justifications of prestressing with *steel* is that it allows a smaller area of very high strength steel to be used at higher strains, without inducing large curvatures.[14] By taking out some of the excessive strain capacity of the tendon, the full strength of the tendon can be used while still keeping a large element of the concrete in compression—the result is high strength and high stiffness. An exactly analogous argument applies to composites. By pre-stretching the tendon, a large amount of its strain capacity is absorbed without inducing large cracking in the concrete. This is illustrated in Fig. 4. The values in the figure for a compositely prestressed beam can be varied significantly, with considerable impact on the moment capacity and curvature at the working load, which leaves plenty of scope for designers. The curvatures at the ultimate load with composite prestressing will also be large, and could be even larger if the concrete were confined, a topic to be addressed in detail below.

There may be some uses of composites as reinforcement in special applications where resistance to corrosion is of crucial importance, but these are likely to be in only lightly loaded specimens where deflections are not critical.

2.1. Conclusion 1

To be economic, advanced composites will be used for prestressing tendons, but not for reinforcement.

3. TO BOND OR NOT TO BOND?

Steel is bonded to concrete for a variety of reasons. The intimate contact with the concrete ensures that the steel is passivated, thus preventing corrosion, at least in the short term. It also ensures that the steel has the same strains as the concrete locally, as well as globally. If a crack forms, the local strain will increase, leading to higher force in the steel. When advanced composites were developed, a considerable amount of work was carried out in an attempt to show that advanced composites can bond to concrete; some of the results show that very high bond strengths are possible.[15] Transmission lengths of a few millimetres have been reported, with bond strengths of the order of 20 N/mm^2.[2,16]

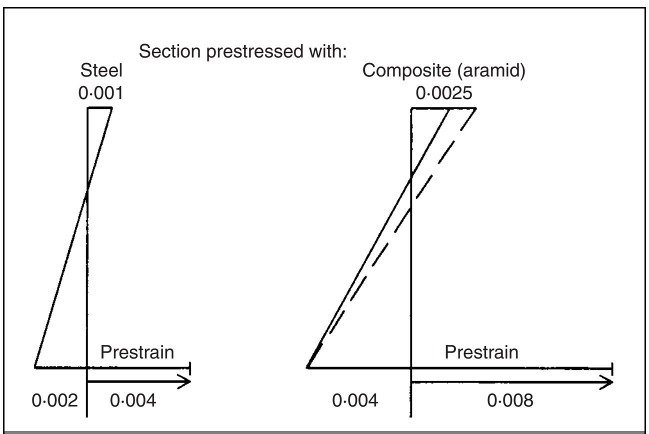

Fig. 4. Strains in sections prestressed with steel or composite (here aramid), at the maximum working load

But is this a good thing? Steel is highly ductile, so increasing the strain in steel will push it onto its yield plateau—maintaining its force while allowing large displacements. But this cannot happen with advanced composites; if the strain is increased too much, the composite can be pushed off the top of its stress–strain curve, leading to rupture of the tendon which would be sudden and catastrophic. Experience with glass fibre reinforced concrete (GFRC) sections used for cladding panels has shown that these become more brittle with age.[17] Continuing hydration leads to increased bond, which leads to strain concentrations at cracks. They can then fail when subject to sudden shock loads without warning. There is a direct analogy here with the use of bonded advanced composites.

However, if too much bond is a problem, so too is absence of bond. Reinforcement must be bonded, at least at its ends, and prestressing tendons must either be bonded at their ends or provided with anchorages, which are themselves a potential source of weakness. In addition, a beam with unbonded tendons will have a lower moment capacity than one with bonded tendons, since the tendon will not pick up as much additional force in the failure zone.

Determination of the bond capacity of the tendons themselves can also be a problem. Lees has produced results, by inferring the shear stress–slip relationship from the measured pull-in when prestress is released, which show that different FRP tendons have very different behaviours.[18] A braided rod seems to slip in the same manner as a steel tendon, with a shear stress that increases as the tendons slips. On the other hand, a circular pultrusion with a wrapping fibre appears to show very high initial bond strengths which then decrease as the tendon slips (Fig. 5).

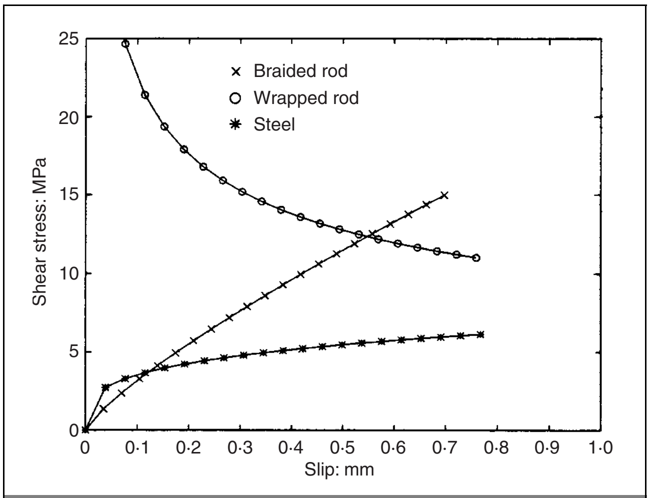

Fig. 5. Bond stress/slip relationships for small aramid or steel tendons

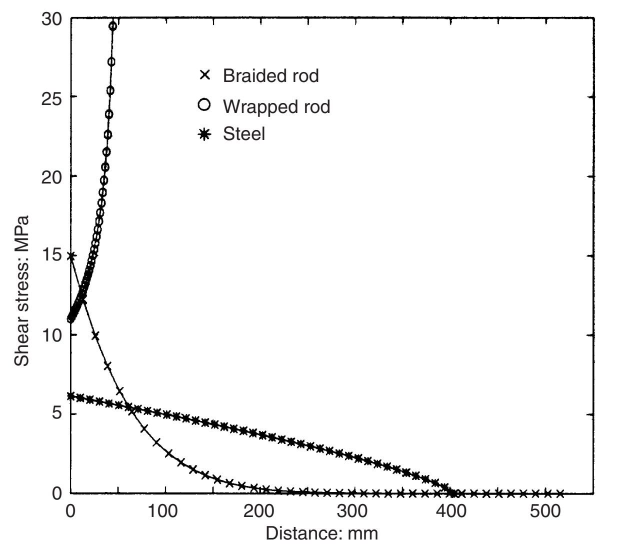

Fig. 6. Shear stress in a pretensioning tendon against position in the beam

When these stress–slip relationships are used to predict the shear stresses inside a pretensioned beam, a very different behaviour is observed for the three types of tendon (Fig. 6). The braided rod transfers most of its force at the surface, the steel tendon has a much more even distribution of force, while the wrapped tendon appears to lock against the concrete a small distance into the beam. These very different behaviours must produce very different structural responses.

The idea that some intermediate level of bond may be desirable has been backed up by Lees' results, which show that both high moment capacity and high rotation capacity can be achieved by limiting the bond capacity of the tendon away from the anchorage zone.[19] This was achieved either by applying a resin coating of known, low, shear strength, or by intermittently anchoring the tendon (Fig. 7).

3.1. Conclusion 2

Much more attention must be given to the way in which FRP tendons are bonded to the concrete—too much bond can be as

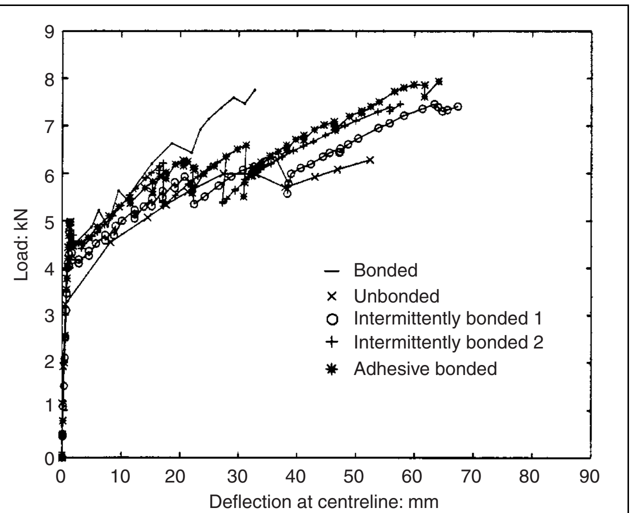

Fig. 7. Load–deflection response of bonded, unbonded and partially bonded beams with aramid pretensioning tendons

bad as too little, and a greater understanding of the interaction between the tendon and the concrete is required.

4. PRE-TENSION OR POST-TENSION?

The choice between pre- and post-tensioned systems is largely dictated by the end use of the product. Pre-tensioned systems are most suitable for mass-production of relatively small components, while post-tensioning is most suitable for *in situ* construction of larger elements, and for repair.

The logical choice between the various types of advanced composites then relates to anchorages; post-tensioned concrete relies on anchoring systems that must remain effective in the long-term, while pre-tensioned concrete requires anchorages only for the stressing operation. With most advanced composites, the forces have to be transmitted to the fibres through the resin. Thus, the long-term integrity of the anchorage relies on the stability of the resin over time and its resistance to heat and chemicals. The anchorages are in the most exposed position. Resin-based systems are, thus, most suited for use as pre-tensioning tendons, where anchorage, by bond, is distributed and the resin is protected by the surrounding concrete, to a large degree, from heat and chemicals.

The only systems which do not require resins are those based on ropes, such as the parallel-lay ropes, where there can be a direct physical connection between the anchor block and the fibres themselves (Fig. 8). These systems cannot, in general, be bonded to the concrete. So they are a clear choice for use as unbonded post-tensioning tendons.

Is there any benefit in producing bonded, post-tensioned systems? The answer is 'probably not'. There is no need to provide corrosion protection to the tendon by means of grout, and the uncertainties of grouts, combined with the arguments about bond given above, mean that it is probably an undesirable combination. Such systems would then be both removable and replaceable, which is required by some certifying authorities.[20]

4.1. Conclusion 3

Pre-tensioning systems should be provided by advanced composite bar systems involving resins, with temporary stressing anchorages and permanent anchorage provided by bond.

4.2. Conclusion 4

Post-tensioning systems should be provided by resin-free rope systems with mechanical anchorages.

5. INTERNAL OR EXTERNAL TENDONS?

The justifications *for* internal prestressing and *against* external prestressing that apply to systems prestressed with steel do not apply to composite systems. Composite tendons are not generally affected by environmental conditions, but they can be affected by highly alkaline cements. By definition, externally prestressed systems must be post-tensioned, and since it has been argued above that composite systems should not be bonded to the concrete, there is no need to make them internal for structural purposes.

However, there are other justifications for putting these materials into the concrete, or within some form of protection.

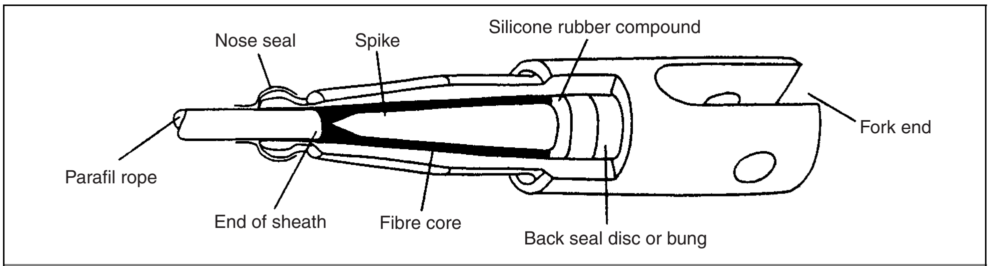

Fig. 8. Physical anchorage for a parallel-lay rope[21]

These relate to fire protection, which is probably more of a problem for advanced composites, or vandalism, which is certainly a more severe problem. Thus, the use of external tendons inside box girders is eminently suitable. But not all the protection needs to be by concrete. Various non-structural elements, which could also allow access for inspection, may be considered more suitable. This opens the way to tendons which penetrate the top or bottom flanges, to lie in slots on the surface, protected by access panels. The use of external cover panels is also possible.

5.1. Conclusion 5

There is no justification for placing tendons inside concrete for structural purposes, although some external protection is necessary.

6. UNDER-REINFORCED OR OVER-REINFORCED?

Failure of advanced composite tendons is undesirable—such failures are sudden, catastrophic, and can release a lot of stored energy. It thus follows that structures should be designed so that the concrete fails first. In conventional terms, structures must be over-reinforced, rather than under-reinforced. All the concrete codes say that this is bad, since it is axiomatic that failure of steel is ductile, while failure of concrete is brittle. However, it has recently been argued that not even steel reinforcement provides as much ductility as had been supposed.[22] Nevertheless, with composites, it must be recognised that structures will be over-reinforced, and suitable measures taken to add some ductility.

The distinction between under- and over-reinforcement has always been more apparent than real; most laboratory tests are carried out by hydraulic loading systems which are, in effect, displacement controlled. Most real structures are under load control, since the loads are applied by gravity. Thus, even structures which have load deflection curves as shown in Fig. 9, which would be typical for under-reinforced structures reinforced or prestressed with steel, are brittle under load control. The driver of a truck of weight A would be safe; another of load B would be in the river.

6.1. Conclusion 6

Structures must be designed as over-reinforced

7. CONFINEMENT REINFORCEMENT

If structures are going to be over-reinforced (6 above), and are going to have high curvatures at failure (2 above), then it follows that it is a good thing if the strain capacity of the concrete in the compression zone is as high as possible. This has never been of major importance hitherto, since with under-reinforced structures, the strain capacity of the concrete has been adequate, and it has only minor influence on the failure load or the mode of failure. Nevertheless, there is work that shows that the strain capacity of concrete in compression can be considerably enhanced either by confining the concrete externally, by putting the concrete in the compression zone into triaxial compression, or by fibre-reinforcing it.[23,24] Increasing the strain capacity by an order of magnitude is certainly feasible. Concrete-filled steel tubes were used in the 1960s,[25] but suffer from Poisson's ratio effects which reduce the effectiveness of the confinement. The use of glass fibre-reinforced plastic (GFRP) tubes, formed by filament winding with a low helix angle, overcomes these problems, and allows very high strain capacity.[26,27] However, compression flanges in the form of circular tubes would be impracticable, but it is feasible to include spirals of composite reinforcement (Fig. 10). These can achieve significant strain capacity increases, albeit of a lower order since the concrete between the spirals is not so effectively confined (Fig. 11). The use of fibres to achieve strain capacity increases is also feasible.[27]

7.1. Conclusion 7

The strain capacity of concrete in compression can be enhanced.

8. SHEAR REINFORCEMENT

Determination of the shear capacity of all types of reinforced concrete structures remains problematical,[28] even sections with steel reinforcement. Understanding of the underlying mechanics is not good—there are truss models,[29] variable truss models,[30] compression field theories,[31] compression force path models[32] etc. The code rules are mostly based on a set of tests carried out in the 1960s and the resulting empirical rules modified to suit the philosophy of the various code committees.[33] Structures are usually conservatively designed, and rely on plasticity theory for safety. This ensures that, if a set of internal forces exists which is in equilibrium with the applied load, and since it is known that steel is ductile, the lower bound (or 'Safe Load') theorem can be used to assert that the structure is safe.

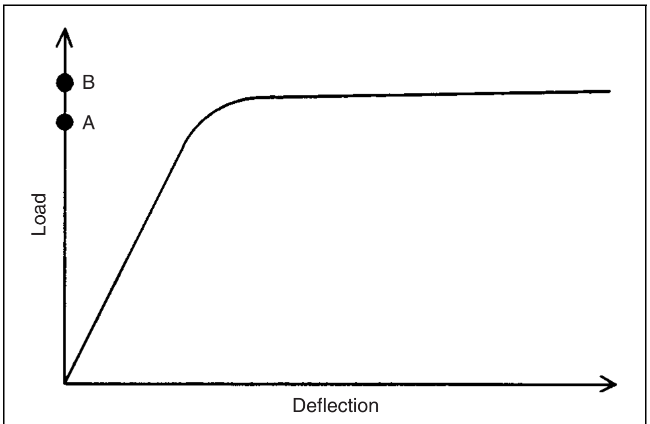

Fig. 9. Load–deflection behaviour of an 'under-reinforced' section

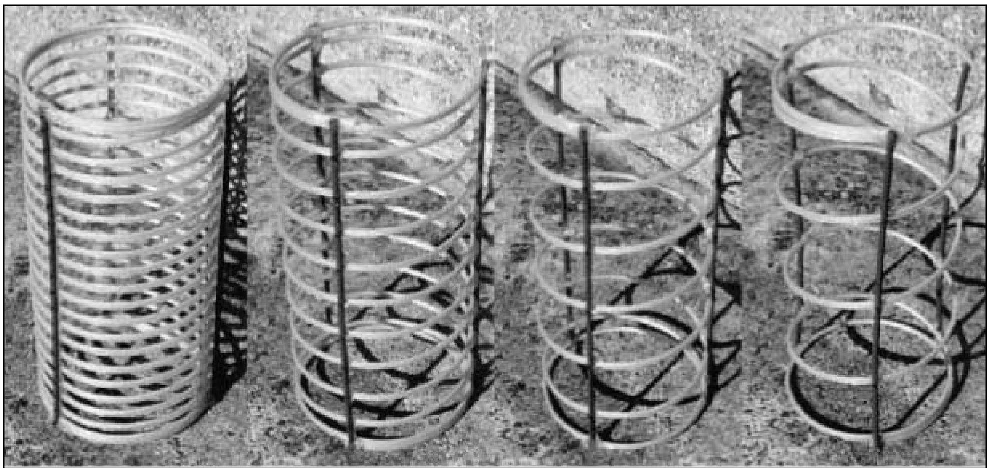

Fig. 10. Spirals of aramid fibres for confinement reinforcement

Fig. 11. Compression samples with confinement reinforcement. The samples on the left have more confinement

monitored, but they should not be used for general structural design.

There is clearly much work to be done in this field—a model is required which satisfies all three of the basic principles of structural mechanics—equilibrium, compatibility and the material stress–strain behaviour.

8.1. Conclusion 8

Fundamental work remains to be done on the shear behaviour of compositely reinforced sections.

9. NOVEL FORMS OF REINFORCEMENT

Why is reinforcement the shape it is? Because it has been this way for 100 years. Steel reinforcement is round as it is an easy shape to roll, and it doesn't matter which way up it is placed in a beam. It is easy to bend in any direction, so shear links and more complex shapes can easily be produced. The surface can be indented to give better bond.

When advanced composites are used, however, the theoretical justification is much less sound; many of the basic assumptions no longer hold. Composites are generally less stiff than steel so, when the concrete cracks, a composite is carrying less force than steel would be. Cracks will, thus, be wider, so there will be less concrete–concrete interaction across the crack; there will thus be less 'aggregate interlock'. Composites also delaminate when placed across shear cracks, so 'dowel action' will be lower and there are problems caused by the bends in the bars.[34] Finally, and most importantly, although composites have high strain capacities, they do not behave plasticly, so the Safe Load theorem cannot be used to hide the lack of knowledge about the deflections.

Taken together, these results mean that care must be taken about producing design guidelines for shear in compositely reinforced structures. Various attempts are being made to limit the strain in the reinforcement to safe load levels,[35] and to use the corresponding forces in a truss model (or a code formula derived from it) to get safe load capacities. But it must be recognised that, although these models satisfy equilibrium, and do not violate the failure criteria for the composites, they do not satisfy the compatibility condition (so may not give the correct elastic distribution of force), nor can they rely on plasticity theories. Such rules may serve as guidelines for experimental structures which will be tested or closely

But do these properties apply to advanced composites? Clearly not. Composites can be pultruded relatively easily, but they cannot then be bent to shape. It is possible to use thermo-plastic resins so that some bending flexibility can be provided when the bars are heated, but the properties of the bundle of fibres in the bent region are very different from the values elsewhere.[36]

The textile industry, on the other hand, has been making three-dimensional structures from fibres for a very long time, but generally on a much smaller scale. Machines exist, of varying complexity, to knit, loop or generally intermingle fibres in a variety of ways. The product would have to be scaled up from what is already made, and it must be given some structure so that it can withstand the forces associated with pouring concrete, but various forms are certainly feasible.[37]

Some forms of textile reinforcement would probably be unsuitable, particularly those involved in knotted structures, where the knots would act as stress concentrators for the fibre. Many fibres are given coatings, however, which improve their resistance to looping or knotting. Bespoke reinforcement arrangements, produced by robots, may also be suitable for the large-scale batch production of special products, where particular reinforcement layouts can be designed that would not be possible using traditional pultrusions, and would also not be feasible with steel due to the bending stiffness of bars.

The type of structure that could be produced might be ideally suited to shear reinforcement. A large-scale, fully three-dimensional geometry, with relatively small yarn bundles at quite close spacings, would have very different properties from steel links, in much the same way that ferrocement is a very different product from reinforced concrete. This should prevent the opening of large cracks, which should make the reinforcement act more effectively.

9.1. Conclusion 9

Novel reinforcement layouts are possible and should not be ignored simply because they are new.

10. ADVANCED BEAM TYPES

The arguments given above imply that novel types of beam could be envisaged. It will still be desirable to have a compression flange as far away as practicable from the tension flange, so I-beams are always going to be the primary option. But the internal structure of those beams might be very different from what is built at present. The beams will be prestressed; if suitable for precasting they will be pre-tensioned with partially bonded tendons, while if built *in situ* they will be post-tensioned with resin-free external ropes. They will have helical reinforcement in the compression flange to improve the ductility of the structure if they fail in an over-reinforced manner, and they are likely to have a novel form of three-dimensional composite reinforcement for shear.

A typical beam is shown in Fig. 12. The overall dimensions will be worked out as for any prestressed concrete beam, but probably without requirements for large amounts of cover concrete to protect against corrosion. There are thus likely to be significant savings in weight of concrete.

Alternatively one can consider a virtually unreinforced bridge.[32] Concrete is very good for making arches, and arching action is well-known to develop even in fairly thin slabs.[38] Extensive use has been made of this effect for making steel-free deck slabs by Bakht and others in Canada, but these still rely on external restraint by steel straps to provide the arching action.[39] So why not extend the process to complete decks? Tied arches work well, so why not build a solid slab with a rope system acting as the tensioned tie? The bridge's dead load

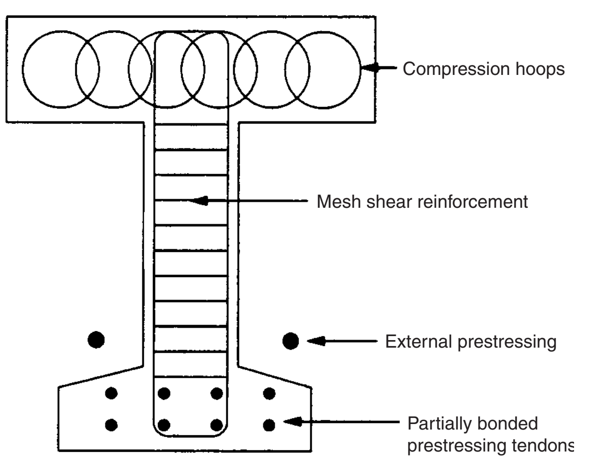

Fig. 12. Possible future beam structure

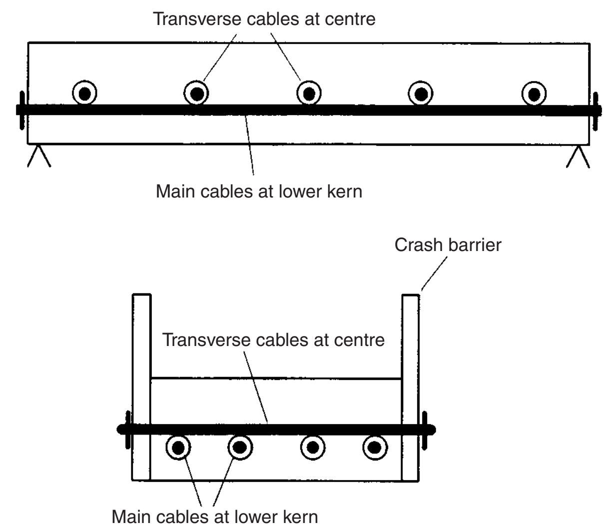

Fig. 13. No-steel bridge

would be fairly low, so the prestress would have to be applied at the lower kern point to avoid cracking the slab in hogging when unloaded. A long section would look like the system shown in Fig. 13. There would be no need for shear reinforcement, as all the loads would be carried by arching action. Although the system looks like a beam, the tendon is not bonded to the concrete and the load would not be carried by flexure.

Consideration should be given to transverse bending. This arises from two causes—the uneven distribution of loads across the structure, which can cause both sagging and hogging effects, and also the impact loads on the crash barriers. These could both be carried by prestressing transversely with tendons that tie in the uprights of the crash barriers and pass right through the deck at mid-height.

Both sets of tendons would be unbonded—there would be no benefit in bonding them—and debonding would allow them to be detensioned and replaced if necessary. The absence of bond would also allow the uprights of the crash barrier to displace a little under load, without overstressing the transverse tendons. If necessary, a snap-off connection could be used to prevent tendon damage.

Since the bridge would be prestressed in both directions, no shrinkage reinforcement would be necessary. Some reinforcement would probably be needed around the anchorages. Would such a bridge be economic? It is made from a rectangular block of concrete, so would be easy to form. A few straight plastic pipes would be needed to form ducts and a small amount of reinforcement would be required around the anchorages, so there would not be much site labour. It might be a little expensive in concrete, but void formers could be used for larger spans. There is nothing to corrode, and it would be easy to inspect. As a novel form of construction, it would be expected that it would need to be checked at intervals, and the cable tensions would probably be kept under observation.

This design is intended to be purely conceptual, to demonstrate the sort of structure which can be envisaged, once we break out of the straightjacket of thinking about concrete decks reinforced or prestressed with steel.

10.1. Conclusion 10

Structures with composites will significantly differ from those with steel reinforcement, particularly in their internal layout.

11. COSTS

It must be accepted that the cost of advanced composites is several times higher than the cost of steel; to ignore this aspect would mean a great deal of wasted effort. Depending on how the calculations are carried out, the costs of aramid fibre-reinforced plastic (AFRP) seem to be about 3–4 times the cost of basic prestressing strand, while carbon fibre-reinforced plastic (CFRP) is even dearer and GFRP is slightly cheaper, on the basis of cost/unit of force delivered.[40] The composites industry will not take off unless these costs can be brought down by volume production; at the moment, most costs for composites are based on the costs of small batch production, and the components are manufactured by small companies with limited resources. The costs of steel are based on large volume production by huge companies with very large resources, often backed by national governments.

Advanced composites hold out the potential for long-term cost savings, but calculation of the net present value of those savings is fraught with difficulty. What discount rate should be used? If a discount rate of 8% is chosen, as in the UK, then savings in 30 years' time have no value now.[41] Which costs get included in the analysis? If only the direct structural costs get included, then the future saving is slight, whereas if the future traffic costs caused by delay and disruption are included, then virtually any cost now can be justified. What proportion of steel reinforced or prestressed bridges are likely to fail? Does data exist yet for the proportion of bridges that have to be replaced due to corrosion after 20 years, 30 years, 40 years, etc.?

However, some immediate cost savings can be made. Structures should be designed to make optimum use of the composites, rather than taking an existing design with steel and replacing the steel with a supposedly equivalent composite, which is bound not to be cost-effective. Even worse, there is a tendency for any real structure, other than a simple demonstration project, to be designed with additional redundancy built-in. Provision is made for spare tendons, or the addition at a later stage of steel tendons 'just in case' there are problems with the composites. Unless care is taken, such structures get penalised four ways; too many composite tendons are provided, too much is paid for them, the economic benefits elsewhere in the structure are not made, and there are additional costs of providing unused steel anchorage positions.

11.1. Conclusion 11

Estimates need to be made of the real cost of large-scale production of composites; the long-term costs of steel corrosion need to be quantified carefully, and design procedures for compositely reinforced or prestressed structures need to be established from first principles.

12. IMPLICATIONS FOR STRUCTURAL DESIGNERS

Various conclusions have been drawn above about the way structures behave and how they should be designed. There is almost enough information to be confident of how this industry will progress. It is now up to designers to look at the way existing structures have been designed, and to say not 'how do I replace steel with composites', but 'what would this structure look like if I designed it with composites from the beginning'. This requires going back to first principles, and asking why particular components are used and what job they are doing. There will thus be a requirement for education of designers in the properties of composites. It will also be important for designers who really understand structural principles to be used for this work, as opposed to those who merely insert numbers into code formulae.

12.1. Conclusion 12

Design firms should get a team of good designers to redesign their products from first principles using composites, having first taught themselves what the underlying material properties are.

13. IMPLICATIONS FOR THE COMPOSITES INDUSTRY

The composites industry must recognise the problems of the structural engineering industry. They should appreciate that, although the market for advanced composites at the moment is fairly small, it has the potential for very large sales. Although small-scale prototype structures will be needed at first, and they will have costs associated with small-scale batch production, the true cost of large-scale production should be determined, so that realistic costs can be assigned when comparisons are being made.

The composites industry should also consider ways in which large-scale novel structural elements can be produced. Cutting and bending of straight pultruded bars is not a sensible long-term solution, but what other methods of production are feasible? It is clear that the surface characteristics of composites are of vital importance—how can this be controlled by intelligent manufacturing techniques?

Fibre manufacturers should also consider their cost base fairly carefully. Most costs are based on the production of a few kilograms of reinforcement—what would they charge if they were selling thousands of tonnes of fibre per year into this industry? What resins could be made available if they were sold at a similar rate?

13.1. Conclusion 13

Composite manufacturers need to become aware of the real problems of the civil engineering industry, and to see how their manufacturing techniques can be adapted to suit.

14. OVERALL CONCLUSIONS

The use of advanced composites in concrete has been shown to be feasible from a structural point of view. The flexural behaviour is well-understood, although shear still has some problems because of the lack of plasticity, and the behaviour in concrete in compression needs to be improved. The bond characteristics between the composite and concrete are crucially important, and it is not always the case that more bond is better.

The emphasis must now move from the engineering to the commercial. Costs must be looked at very carefully, and designs must be optimised for the least use of composites rather than simply replacing the steel. This requires education, of engineers about composites and of the composites industry about engineering.

The stage has been reached where the civil engineering and composites industries must move forward into the exploitation of the technology that has been developed over the last 15 years.

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