ADVANCED COMPOSITES - THE CHALLENGE TO BRIDGE DESIGNERS

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Summary

The paper considers why advanced composites have not yet established themselves for bridge construction. It looks at the material properties, and considers how they might most sensibly be used. It is concluded that bridges should be post-tensioned with resin-free rope systems, or pretensioned with partially-bonded rod systems. The compression zone of the beam can be enhanced by the use of composite hoops, but our current level of understanding does not permit proper use of shear reinforcement with these materials.

Some remarks are made about the cost implications of using new materials, before a number of successful applications are considered, and the reasons why they are successful is discussed.

1. INTRODUCTION

Advanced composites offers great potential for bridge designers. They offer resistance to corrosion which would lead to great reductions in maintenance costs in future years. But, despite being available in many different forms for at least 10 years, such materials have only been used in a few demonstration structures world-wide. Is this because the technology is wrong? Are the economics wrong? Are engineers too conservative? Are code writers at fault? Is it the fault of the educators?

2. ADVANCED COMPOSITES

The advanced composites in question are made from fibres. These must have high strength, reasonable stiffness, good resistance to corrosion, reasonable cost and resistance to creep and stress-rupture. The three fibres which match these properties at the moment are glass, aramid and carbon. There are many others which offer good performance in some of the above areas, but fail in others; ultra-high modulus polyethylenes would be attractive if it were not for their poor creep performance. PBO (poly(p-phenylene-2,6-benzobisoxazole)) would be attractive if it were manufactured in reasonable quantities at a reasonable price.

All of these materials have to be aggregated in some way to form structural elements. The fibres have diameters measured in microns, and with properties which are highly axially oriented. There are various ways of doing this, including pultrusion, filament winding, and the various forms of rope production.

Pultrusion is ideally suited to producing long, thin elements with fibres running the length of the pultrusion. It is less suited to producing elements where the fibres are inclined to the axis, although this can be done by the inclusion of tapes, sheets or mats of fibres. It is, however, difficult to achieve a high strength normal to the axis.

Filament winding, on the other hand, in which fibres are wrapped around a rotating mandrill, can give elements which have a large proportion of their fibres with a high inclination to the axis. They thus have high transverse strength, but relatively low axial strength.

Combinations of pultrusion and filament winding offer some interesting possibilities for bridge engineering. The use of a filament-wound core, with external pultrusions to form flanges, and a second filament winding on the outside to give the whole thing coherence, is a technology which has not yet been fully exploited.

Rope technology has been revolutionised by modern fibres. Whereas traditional rope constructions were designed for use with short natural fibres which had to be highly twisted together to give an element with coherence, the use of (effectively) endless fibres has allowed the degree of twist to be reduced. Thus, the use of low lay-angle fibre orientations, together with a braided cover, or the use of parallel-lay fibres with a continuous sheath, allows the rope to have virtually the full strength and stiffness of the parent fibres. It also obviates the need for expensive resins.

Ropes also have another major advantage, which will be important later. They are already made in considerable quantities for traditional applications, such as mooring lines and guy ropes, and the termination systems, such as the barrel and spike system illustrated in Figure 1, are tried and tested. They are available in large sizes (breaking loads of several thousand tonnes), and are relatively flexible and thus transportable. So one of the most important disadvantages of composites (small size, difficulty of transportation of long elements, and small volumes of production), do not apply so badly to ropes.

Various other technologies, such as filament arranging and three dimensional textile fabrication, allow the use of more complex structures. Filament arranging is the name given to the laying up of fibres on a jig, often by robot, followed by fixing in place by means of resins. This process allows the fibres to be arranged to follow the lines of maximum stress in components, while making use of the flexibility of the fibres before resin coating. Such techniques are well-suited to component manufacture, such as the end caps for ground anchors, where the stress paths are well-defined. Traditional textile techniques, such as braiding and knitting (particularly techniques such as Raschel knitting, which produces multiple layer structures), open the possibility of automated production of reinforcement cages. Just because the knitting industry measures its machines in "stitches per inch" and works with very fine needles, does not mean that we cannot think of "inches per stitch" with a corresponding increase in the size of the components.

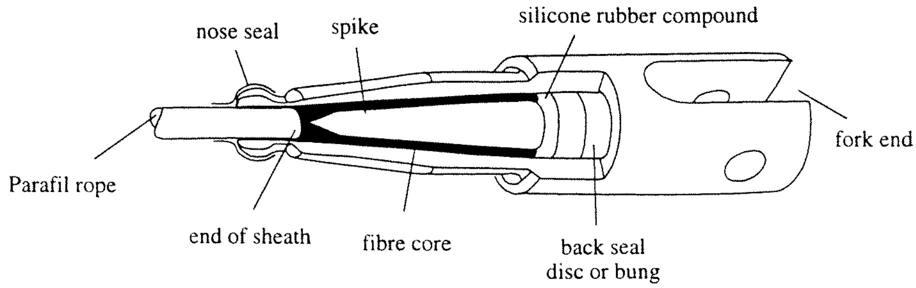

Figure 1. Physical anchorage for a parallel-lay rope [1]

2.1 Stiffness

It is not difficult to think of giving bridges sufficient strength from fibrous elements. But the public also demands structures which have no perceptible motion; engineers may know they are safe, but the client is always right. So bridges also have to have sufficient stiffness, and providing this solely with fibres is difficult. It may be possible, but it will not be cheap, since a sufficiently large number of fibres would need to be provided, and these would almost certainly not be using all their strength. So an expensive element would be provided which would not be used to its full potential.

A much more logical approach is to use a cheap, bulk material, like concrete or masonry, to provide the stiffness, with the fibres providing the strength in the form of reinforcement, or a prestressing force in the form of tendons. So the assumption must be that the major use of composites in bridges will be as tension elements in concrete.

3. LOGICAL USE OF COMPOSITES IN CONCRETE

In another paper [2], the properties of composites and their logical use in concrete were considered. Only the most important argument will be rehearsed here, that relating to the distinction between reinforcement and prestressing.

1. To be economic, advanced composites will be used for prestressing tendons, but not for reinforcement; this allows the full strength of the fibres to be used without inducing unacceptable strains in the concrete. If a section is reinforced with fibres, the strains at the economic working load are so high that the curvatures would be unacceptable, as shown in Figure 2. By prestressing the tendon, it is also prestrained, so that the curvatures are reduced while still allowing a sensible moment capacity to be used. (as in Figure 3).

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 bad as too little, and a greater understanding of the interaction between the tendon and the concrete is required. The object must be to prevent premature snapping of the brittle tendons at crack locations [3].

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

4. Post-tensioning systems should be provided by resin-free rope systems with mechanical anchorages. There is no advantage to be achieved by using resin-based systems for post-tensioning.

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

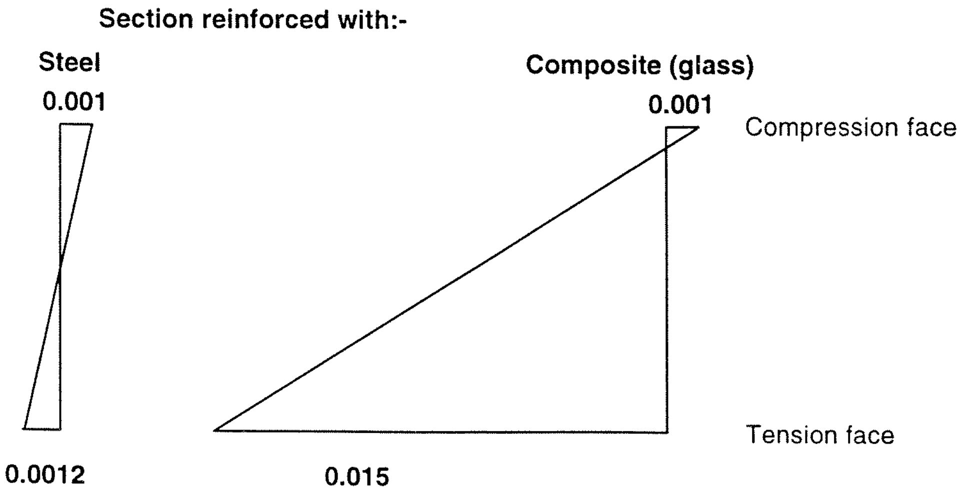

Figure 2. Strains in reinforced sections, at the maximum working load.

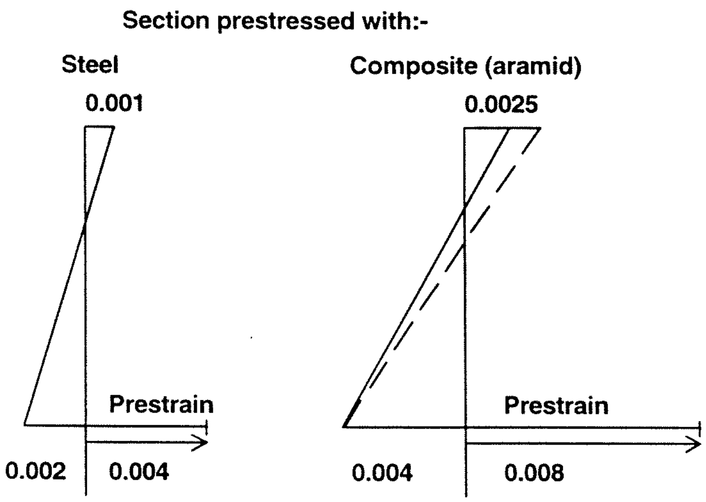

Figure 3. Strains in sections prestressed with steel or composite (here aramid), at the maximum working load.

6. Structures must be designed as over-reinforced. The traditional approach to design for concrete reinforced with steel assumes that the steel is ductile (although even that is now coming into question [4]), while the concrete is brittle. But the fibres in composites are brittle, so this principle no longer applies. It is thus more important to stop the tendons snapping.

7. The strain capacity of concrete in compression can be enhanced by providing hoop reinforcement made from fibres (see below).

8. Fundamental work remains to be done on the shear behaviour of compositely reinforced sections. The fibres remain elastic to failure, so the plasticity theorems - in particular the lower bound theorem - no longer apply.

9. Novel reinforcement layouts, such as those made by textile technology, are possible and should not be ignored simply because they are new.

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

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

3.1 Eventual form of construction

These ideas lead to a logical use of composites in bridge structures which can be idealised as shown in Figure 4. A concrete beam has internal, partially bonded, pre-tensioning tendons, and/or external post-tensioned resin-free tendons. There will be some form of three-dimensional shear reinforcement, probably prefabricated or made on site by robot, and spiral hoops of compression reinforcement to add to the compressive strain capacity of the top flange.

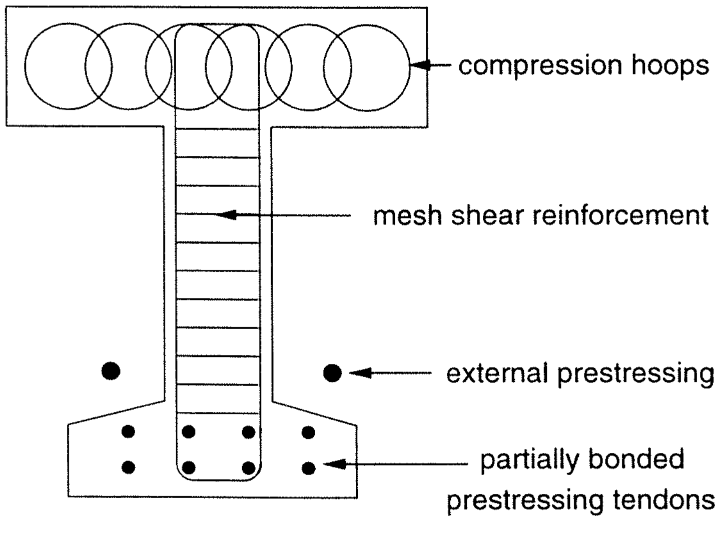

Figure 4. Possible future beam structure.

No one would build structures like this yet, if only because we do not yet have all the information we require to be able to complete the design (especially of the shear and compression reinforcement). Instead, we must work towards this type of structure in stages. But the form of construction could be killed off by ill-judged attempts to use composites in construction.

3.2 Bad applications of composites

The easiest approach to the design of concrete bridges with advanced composites is not necessarily the correct one, and it is almost certainly counter-productive. The false logic goes something like this:-

> *"Composites are a new material which I do not properly understand. I will therefore use them in the simplest application I can think of, which is as reinforcement. I will take a traditional design, and I will replace the steel by an area of fibre with the same strength or to give the same overall stiffness. I will use the cheapest fibres I can find, combined with the cheapest resin. I will detail the section in the same way as I did before, but since the object of the exercise is to produce a bridge with no corrosion problems, all the reinforcement must be non-metallic. I will compare the costs of the new structure with the equivalent traditional structure."*

Such an approach is doomed to failure. It certainly violates four of the conclusions given above, and the spirit of several of the others. The resulting section will be under-reinforced, and have too much bond. If tested, it would fail by the fibres snapping, although this may be deemed not to be a problem since the section will almost certainly be controlled by deflection, rather than strength. Its behaviour in shear would be unpredictable and it will almost certainly cost a great deal more than the equivalent structure made with steel reinforcement.

After construction, a report would be written, doubtless by an eminent engineer who claimed to have investigated new technologies, concluding that they were not cost-effective. This would then be reproduced by sceptics whenever proposals were being made for the use of the new technology, and the technology of composites

4. SEQUENTIAL APPLICATION OF COMPOSITES

How can things be done better? There is an old adage "*change only one thing at a time*". So we should include elements of new techniques in stages - introducing one new technology at a time until we are happy with it.

4.1 Tension elements

At the present moment, the techniques for making tension elements in composites have been established. There are a variety of products commercially available both for use as bonded pre-tensioning tendons, and also as resin-free post-tensioning tendons. The use of external post-tensioning steel tendons is also a known technology, and applying the force from a carbon or aramid fibre tendon will not alter the response of the concrete in any way, once a small allowance is made for the slightly lower Young's Modulus. Anchorage systems for ropes and pultrusions are available and can easily be proof-tested. So the first stage is to build bridges with these tendons as external tendons.

The use of internal, partially-bonded, tendons could also be accomplished quite easily. The theory is known, and the practice has been demonstrated. Some techniques for establishing partial bond can easily be tested on small scale samples, such as wrapping with tape, so transferring knowledge from laboratory to practice will not be difficult. These techniques are ideally suited to precast construction, so that will be the next stage in the procedure - build precast bridge beams with internal, partially bonded pretensioning tendons.

Neither of these beams would have composite secondary reinforcement. The technology for producing shear links are not yet ready, and our knowledge of the underlying theory is not sufficient. It does not matter that we are not building completely non-metallic bridges yet - we are making sure that we can provide the prestress for them with non-corroding tendons.

4.2 Compression hoops

The next stage in the process would be to enhance the ductility of the section by improving its rotation capacity by the inclusion of hoops of composites to confine the concrete, as in Figures 5 and 6. If a section is made with an unreinforced compression zone, the strain capacity of the concrete limits the depth of the neutral axis, which in turn limits the tensile force on the section, and thus lowers the moment capacity. The section also has no element which can absorb energy, and this can cause concern about ductility. However, tests have shown that a three-fold increase in strain capacity of concrete can be achieved by confining the concrete in this way. This will allow much more of the depth of the section to be above the neutral axis at failure; this will increase the force in the compression zone, and hence also the force in the tension zone, which in turn will lead to an increased moment capacity. It will also have the effect of dissipating energy before the section fails. The result will be higher moment capacity *and* higher ductility than could be obtained without such hoops.

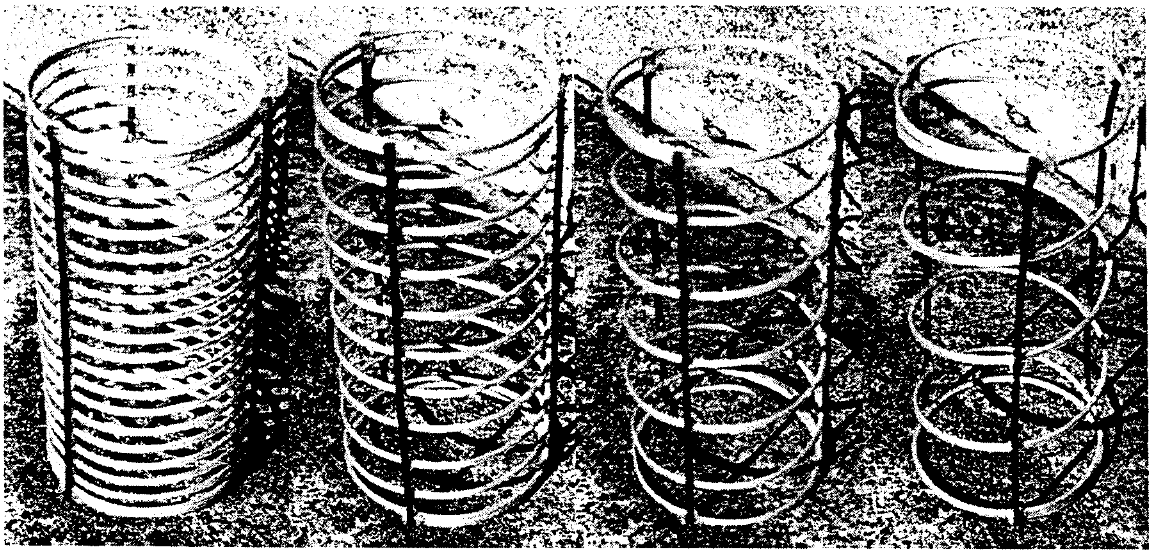

Figure 5. Spirals of aramid fibres for confinement reinforcement

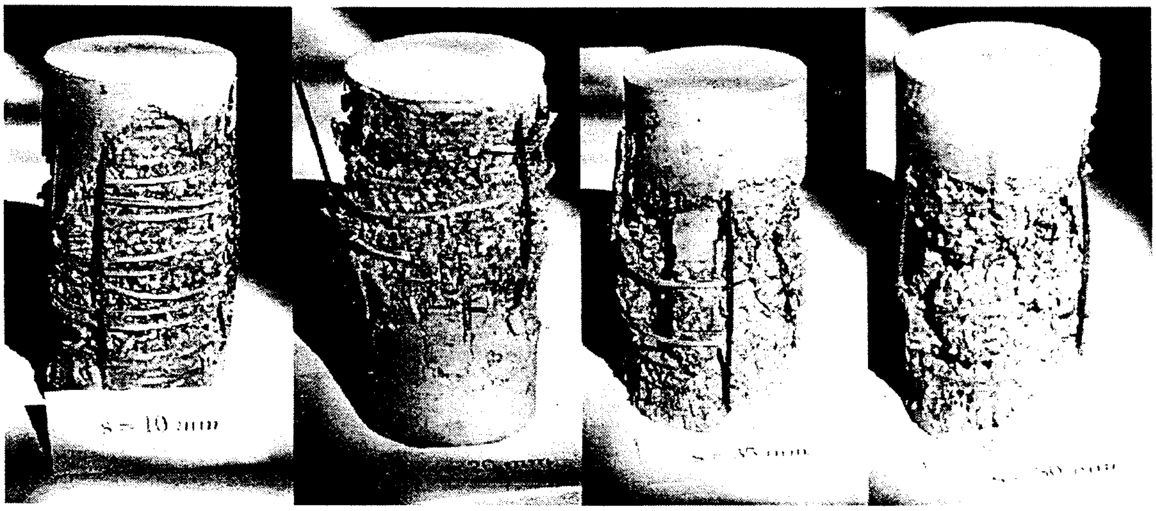

Figure 6. Compression samples with confinement reinforcement.
The samples on the left have more confinement.

Hoops of composite reinforcement are not routinely made at present, although the procedure is not significantly different from pultrusion - all that is required is that the partly-cured pultrusion is wound onto a mandrel to form the spiral shape. It is also likely that the fabrication of multiple spirals to form rigid cages can also be automated, so the cost of the spirals will then not be much higher than the cost of the fibre and resin.

Thus, the way would be open for the next stage of the move towards a completely composite section. These sections would still have shear links from steel, but the technology could again be demonstrated and many more of the economic benefits of composites could be realised.

4.3 Shear links

The final stage would be to move towards replacement of shear links. This requires more work by researchers. Present theories for shear rely, implicitly, on plasticity theory. The links are assumed to yield, and a distribution of forces is sought which satisfies equilibrium and does not violate the yield condition. Compatibility conditions are not satisfied, and the whole process relies on the Lower Bound Theorem of plasticity.

There are serious problems of translating this process to work with composites. The composites do not yield, which means that plasticity theory no longer applies. The most obvious fabrication technique, pultrusion, produces straight elements, and even if they are made with thermo-plastic resins so they can be heated and bent to shape, the alignment of the fibres is seriously disturbed at the corners, and many tests have been reported where the links fail in the corners. It has also been reported that it is the shape of the links [5], and the amount by which they can move relative to the concrete, that controls the post-cracking behaviour.

All of these points mean that a considerable amount of fundamental work needs to be done to understand the behaviour of shear with elastic links. This can be split into two, inter-related areas.

The first relates to the manufacturing process. It is intrinsically wrong to take something flexible, in the form of a fibre, and then to make a rigid element from it which subsequently has to be bent to the required shape. It is much better to use the fibre flexibility to form the element that is required and only subsequently fix the shape. This may well mean adopting textile technologies, such as knitting, weaving and braiding, to achieve the required shapes. There will need to be studies both of the type of elements that can be formed, and their strength.

The second relates to the behaviour of the shear elements within concrete. Since plasticity theory is no longer valid, new theories for the behaviour of elements that are elastic but with concrete cracked in tension will be needed. This is not a trivial task. The models must account for the elasticity of the fibres, their bond characteristics with the concrete, the lack of tensile strength in the concrete, and the variability of the brittle fibres [6] which has a significant effect on their strength.

4.4 Bursting Reinforcement.

Very little work has been done on the use of composite reinforcement to resist bursting forces behind anchorages. As with shear reinforcement, the principles used for design of this reinforcement rely implicitly on plasticity ideas [7], so they will need to be rethought for use with composites. There will thus need to be research before economic design rules can be introduced.

Only when all of this work has been completed can we move towards the final stage of making bridges with completely non-metallic reinforcement.

5. COSTS

The economics of the use of composites cannot be ignored. It must be accepted that, at the moment, 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 AFRP seem to be about 3-4 times the cost of basic prestressing strand, while CFRP is even dearer and GFRP is slightly cheaper, on the basis of cost/unit of force delivered [8]. 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.

There is a very grave danger that the use of composites in bridge engineering will not take off because of a vicious spiral in terms of costs. The elements required for bridges are made in small batches, and are thus expensive. Manufacturers, although aware that civil engineering might eventually be a very lucrative market for composites, are not geared up to large-scale production. Even if bridge engineers recognise the potential long-term benefits of composites, they find it very difficult to justify to clients the spending of additional money even on prototype demonstration projects. Virtually all the structures built to date have received substantial discounts from the fibre producers, which are normally large multi-national companies and thus can cover these costs for a *few* projects. But they will not continue with this policy indefinitely. The result is "*small volume of production = high cost of production = low perceived demand = smaller volume of production*". If we are not careful, a potentially beneficial technology will wither and die.

Advanced composites do 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 to use? If a discount rate of 8% is used, as in the UK, then savings in 30 years time have no value now. 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.

6. IMPLICATIONS FOR BRIDGE DESIGNERS

So what do these ideas mean for Bridge Designers now? The new techniques will not be successfully used if existing designs using steel reinforcement are simply translated into design with composites. No attempt should yet be made to replace the shear reinforcement, as this technology is not yet fully understood. Instead, bridges should be designed with external rope post-tensioning tendons, or internal rod pretensioning tendons.

The best applications of composites are to be found by the application of "lateral thinking". Do not consider the most immediately obvious ideas as exemplified by the false logic given earlier. Rather, think around the problem:-

> *"What are the strengths of composites? What are their weaknesses? Why do we build structures with steel reinforcement they way we do? How might I best utilise the strengths of the new materials, and minimise their weaknesses?"*

Consider some good examples of the structural use of composites in recent years to see why they are successful.

7. APPLICATIONS

7.1 Cooling Towers at Thorpe Marsh

Although this is not a bridge structure, it illustrates some of the ideas that are being considered here. Thorpe Marsh Electricity Generating Station in the United Kingdom had six cooling towers, approximately 80 m tall. They were built in the 1960s to a design similar to that of the Ferrybridge Power Station, where 3 towers blew down in a gale. The towers at Thorpe Marsh were subsequently strengthened by an additional layer of sprayed concrete, primarily to add weight. Early in the 1980s, the towers were inspected during routine maintenance, and three were found to have major cracks.

The cure was to circumferentially prestress the towers, with straps made from aramid ropes. These were erected by steeplejacks (Figure 7), in some cases sitting in bosun's chairs suspended from cranes. Although aramids were more expensive than steel, they were light enough to be carried up by one man. The alternative would have been to form a steel cable net at ground level, haul it to the top, and then adjust the geometry in-situ to match the tower's profile. There was some difficulty in stressing the tendons evenly around the towers, but when they returned 6 months later to retension the cables after the initial relaxation, it was found that friction, coupled with the heating and cooling cycles, had equalised the stresses.

The generating station has now been demolished, but this simple application of composites allowed the station to continue to function right up to its scheduled replacement date.

Figure 7. Erection of prestressing cables on cooling towers

7.2 External prestress

Bridges with external cables have had a chequered history. The absence of ducts and grouting means thinner webs and a lighter section, which has made engineers want to use them, but there are problems caused by corrosion of the steel. The manufacturers of steel prestressing systems have gone to great lengths to ensure that their systems are waterproof.

The steel strands are greased, placed into plastic tubes, then put into hermetically sealed ducts filled with special grouts, resins or bituminous compounds. External tendons potentially allow the tendons to be inspected, and replaced if necessary, and following the ban on the use of internal bonded post-tensioning in the UK, for example, they suddenly came back into vogue. However, the techniques used to prevent corrosion also prevent anything other than superficial inspection, and there will always be problems of inspection at deviators.

It is clearly much better to use a tendon that will inherently not corrode. The benefits from optimising the concrete section can be realised, the tendon does not need to be coated, so really will be inspectable, and it is anyway an advantage not to bond it. Figure 8 shows a test beam with two external posttensioning cables. Hamamatsu Bridge in Japan has been effectively strengthened with a system very similar to this.

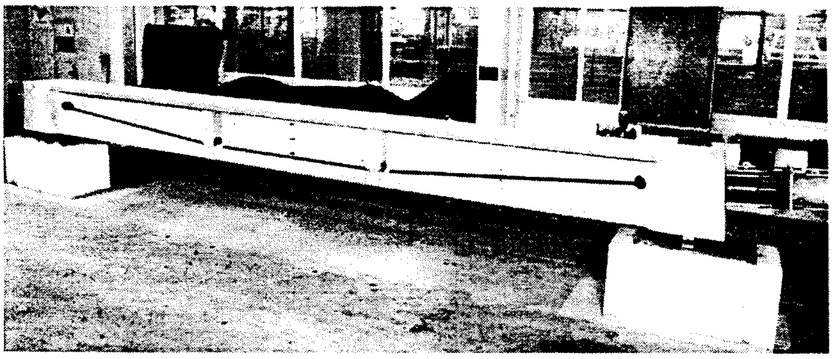

Figure 8 Test beam with external aramid cables

7.3 Masonry Bridge at Tring

Masonry is a traditional material for building bridges, but usually in the form of arches. The absence of tensile strength means that masonry is not regarded as a sensible material for use in flexure. However, considerable use has been made of prestressed brickwork in buildings, particularly in the walls of school sports halls where the high ceiling means that conventional brickwork would otherwise be unsuitable. The walls are cellular, with a prestressing tendon passing through the cells. This makes use of the fact that the horizontal bedding joint in brickwork is inherently strong, while the vertical "perpend" joint is much weaker, given the difficulty of filling it evenly with mortar.

A footbridge was recently constructed at Tring, in the UK by the firm (Curtins) which specialises in masonry walls. This was made from a brick box structure (Figure 9), with the aramid tendons passing along the centre of the box. To overcome the problem with the lack of strength of the vertical joints, which of course are the most important ones in a bridge, the structure was built on end, and then rotated to its final position by crane after prestressing. The bricklayer built it as though building a multi-flue chimney. Figure 10 shows the completed structure.

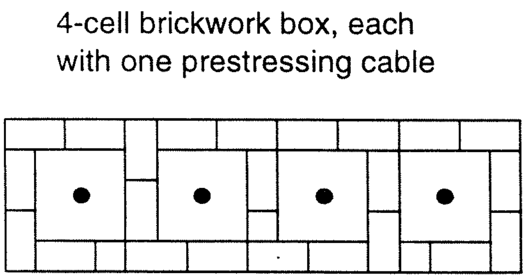

Figure 9. Section through deck of Tring Bridge

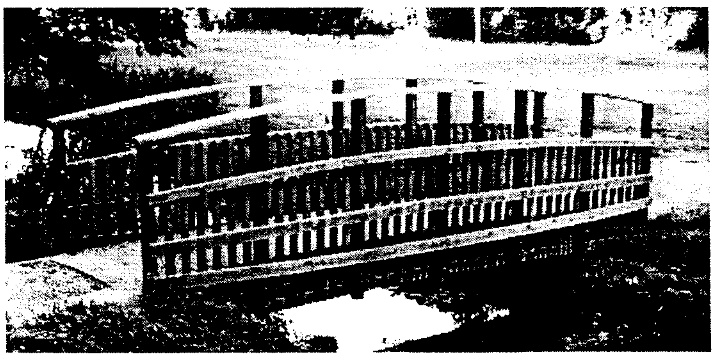

Figure 10. Bridge after addition of handrails

7.4 Aberfeldy Bridge

The Aberfeldy Bridge (Figures 11 and 12) in Scotland is well-known as one of the first applications of composites in bridge engineering. It is successful since it takes the use of composites as deck and tower elements to a logical conclusion, using the system developed by Maunsells, and also incorporates fibrous ropes as stay cables [9]. The method of erection took advantage of the low weight of the deck to do away with expensive equipment.

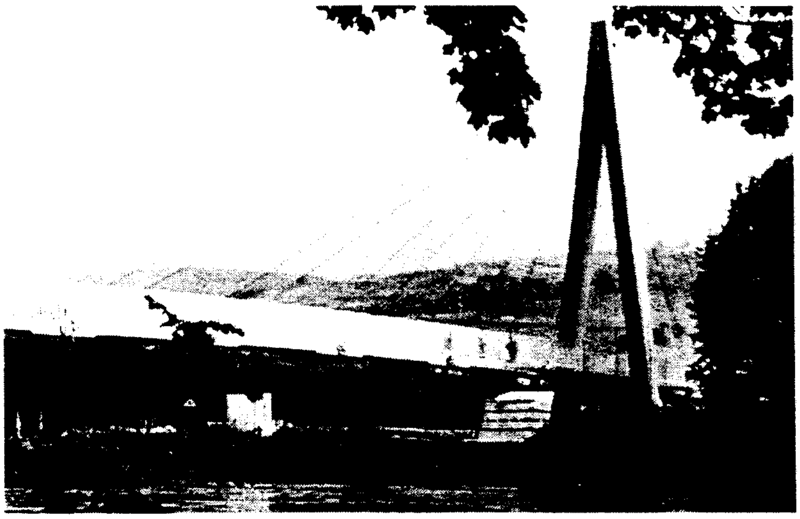

Figure 11. Aberfeldy Bridge

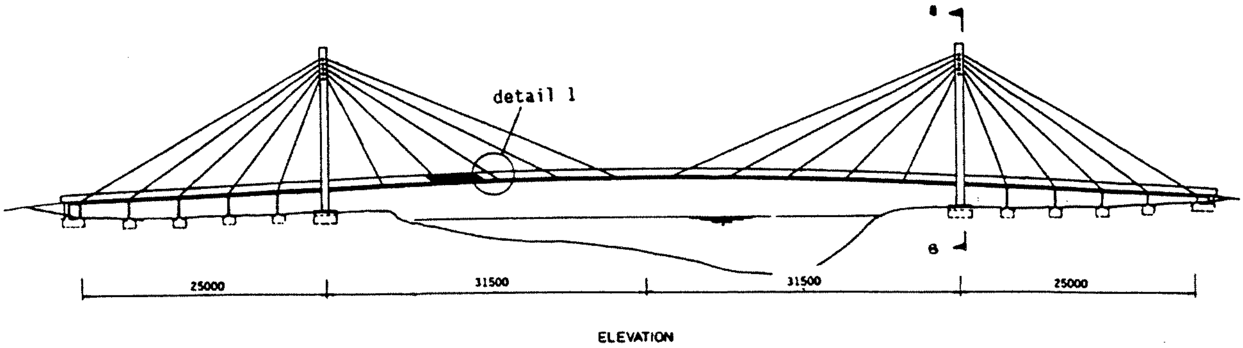

Figure 12. Elevation of Aberfeldy Bridge

7.5 Prestressed Timber

The use of transversely prestressed timber decks was pioneered in Canada, combining cheap but plentiful waste timber, which would otherwise be difficult to dispose of because of the chemical treatment, to form a useful bridge deck. This relies for its integrity on the transverse prestress from non-metallic tendons.

7.6 Repair with composite sheets

There are now many applications around the world of carbon fibre sheets to reinforce bridge decks for both flexure and shear [10]. This is one case where the use of these materials as reinforcement is justified. There are some benefits from prestressing the tendons, but the additional complication during erection and the requirements for secure anchorages may make this extension uneconomic.

8. FUTURE APPLICATIONS

Future applications are limited only by our ingenuity. Consider the following possibility.

Concrete is very good for making arches, and arching action is known to develop even in fairly thin slabs. Tied arches also work well, so why not build solid slab with a rope system acting as the tensioned tie? The bridge's dead load 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. So a long section would look like the system shown in Figure 13(a). There would be no need for shear reinforcement, as all the loads would be carried by arching action.

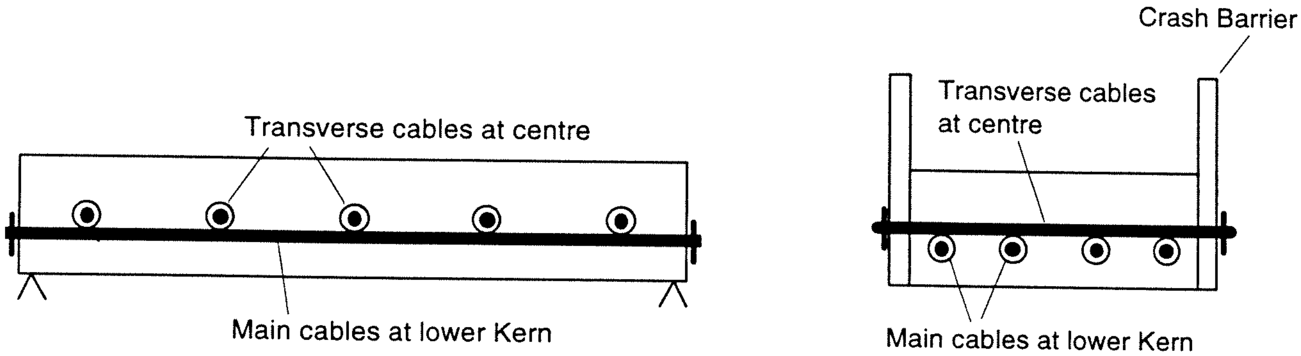

Figure 13 (a) Long section showing primary tie cables (b) Cross-section showing transverse cables

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 (Figure 13(b)).

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 it be economic? It would be 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 there would only need to be a small amount of reinforcement around the anchorages, so there would not be much site labour. It might possibly be a little expensive in concrete, but void formers could be used for larger spans to reduce this. There is nothing to corrode, and it would be easy to inspect.

9. CONCLUSION

The successful applications of new materials in the field of bridge engineering have come about by intelligent use of knowledge of the material properties. The engineers concerned have learnt about the materials, and have understood the principles which underlie our codes of practice. This has allowed them to make sensible changes from established custom and practice. It is now up to other bridge engineers to take up the challenge that new materials offer, and to use them in logical ways that will benefit future generations which will have to maintain our bridges.

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