ADVANCED COMPOSITE MATERIALS IN BRIDGES AND STRUCTURES
MATÉRIAUX COMPOSITES D'AVANT-GARDE POUR PONTS ET CHARPENTES
Calgary, Alberta, July 20 – 23, 2004 / 20 – 23 juillet 2004

DOES FRP HAVE AN ECONOMIC FUTURE?

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ABSTRACT: Fibre reinforced polymers offer high strength, high stiffness and good durability. When they were introduced 25 years ago they appeared to offer a solution to the durability problems of reinforced and prestressed concrete structures. They also offered light-weight bridges. They were slightly more expensive than steel but it was expected that these costs would drop rapidly and a premium would be paid for the higher durability. The market has not lived up to these expectations; even though the technical problems have been overcome, there is little adoption of these materials and the future looks bleak. The paper discusses why this might be so and considers some of the technical, economic and organizational aspects which have led to the current situation. It is concluded that we will never build the world's longest span using FRPs and that, with the possible exception of externally prestressed concrete, the market is restricted to repair of existing structures or certain niche applications where the corrosion risk is very high.

1. INTRODUCTION – THE DREAM

Over twenty years ago the author was asked "*Do you want to do some work with plastic prestressing tendons?*" The initial reaction was scepticism; 21 gm/denier for aramid fibres sounded like a very small strength, although it turned out to be in excess of 2000 MPa. When the manufacturers were asked for long-term strength data they supplied a chart that went up to 4 hours duration; "*I want the long-term data not the short-term data*"; "*Buddy – our fibres are used for bullet-proof vests and rocket nozzles – 4 hours is an eternity*."

Contact was quickly made with others working in similar fields; Rostasy in Germany was working on glass fibre tendons; Meier in Switzerland was working on CFRP, and Gerritse in Holland was working on a competing aramid product. Head in England was developing FRP pultrusions for structural applications. The term "Advanced Composites" was adopted to describe the materials although "FRPs" has since become the generally accepted term.

All the researchers came to very similar conclusions after carrying out strength, stiffness and cost comparisons. The various materials were potentially stronger than steel, but usually less stiff. They had higher strain capacities, so if they were going to be used to their full potential they would have to be prestrained – prestressing tendons were clearly a better idea than reinforcing bars. Costs were calculated that were, typically, 5 or 6 times the cost of steel on a cost/unit-force/unit-length basis [1] but, it was argued, those costs applied to materials in development and they would surely fall rapidly as manufacturing technology and the competitive market developed. The light weight of the materials was only of marginal interest; there may be military bridging applications in which soldiers have to carry tension members in hostile environments where the cost can be justified [2], and there are some temporary bridging examples where access is difficult and components have to be carried or helicoptered into place [3]. Only for very-long-span bridges is light weight such a significant advantage that it is likely to change the economic solution.

So much for dreams; what of reality?

2. PRESENT REALITY

Twenty years later, has the situation changed markedly? This is the fourth ACMBS conference, and there have been six FRPRCS conferences. On the web pages of most university civil engineering departments and there will be someone researching the applications of FRPs, usually to concrete. There have been a significant number of demonstration projects – some use FRPs in association with steel as a back-up, but many rely on FRPs – the technology works. But it is not selling; the key questions are these:-

- How many structures have been built where FRP reinforcing bars or FRP prestressing tendons have been supplied as the material of first choice without subsidy either by the material supplier trying to develop the market or as part of a national research programme?
- Would clients specify FRPs in normal circumstances?

It was long argued that the reason these materials were slow to take off was that there were no codes that could be applied. This should have been a warning sign – if a new material or a new technique offers significant advantages it forces its way onto the market without a code. Codes follow technology, they do not lead it. Those who understand its potential make it work – the code allows others access to the technology. ACI 440, Ontario Highways, FIB TG9.3, the Institution of Structural Engineers and various groups in Japan, amongst others, have all produced documents or are in the process of doing so; despite the genuine efforts of their authors they are all to some extent flawed, since test data is not available, particularly on the long-term properties, and the products are not yet standardized. Fibres, resins and production techniques are all changing – in the case of proprietary products, sometimes without the knowledge of the end user. Manufacturers will offer some sort of guaranteed minimum property, usually short-term strength, rather than compliance with some not-yet-written standard. But was it really the absence of the codes that meant the materials were not being adopted?

There have been a number of other factors that have affected the adoption of FRP. Reinforcement is seen as simpler to use than prestressing; "*we must learn to walk before we learn to run*". There is more reinforced concrete made than prestressed concrete, and more engineers who feel confident to design in reinforced concrete. Some clients say that once FRPs have been established as reinforcement they would consider them for prestressing, which ignores the fact that rebar is not a sensible application of FRP so this will never happen. Several manufacturers have produced rebar, generally using the cheapest fibre with the cheapest resin in order to keep costs down, even though that may not be the best product. Much of the literature produced by rebar manufacturers emphasizes strength, not stiffness. "*Information will be provided if designers ask for it.*"

There have also been changes in clients' procurement processes. In many countries the days are gone when a government department would be willing to have a programme of innovation, with one structure being experimental; if it did not work, the loss would not be too severe, but if it did work, the innovation could be adopted and the next structure could try other innovations. Nowadays, most client authorities employ very few engineers and even they are employed primarily to administer competitive contracts rather than to take technical decisions. Each structure must be the cheapest possible; if the government official rejects a tender that conforms to the specification in favour of a higher priced tender he can be personally liable for the cost difference and, in some countries, may have committed a criminal act. Designers are free to propose innovations, provided they are cheaper than the conventional alternative and the designer assumes all risk. It is little wonder that there is little innovation.

2.1 Repair market

The one success of the FRP industry has been its use for repair and strengthening. It now seems *de rigeur* to assess an existing structure, find it is deficient, and then stick on some CFRP. This was not one of the markets originally envisaged for FRP, but it is the one which has been successful. There are undoubtedly cases where repair with CFRP is both necessary and successful. But it is worth asking why this market has taken off when others have not?

One reason for the success is the light weight of the material. A moderate saving in weight is not normally a benefit to civil engineering structures; the public's perception of solidity goes with mass and lack of movement and in most cases we have robust ground to take the additional weight. For repair, however, the benefit comes from the reduction in handling costs; cheaper scaffolding, no craneage required and man-handleable products mean that, despite additional material costs, FRPs are easier to install. So the cost benefit comes up-front – it is cheaper *now*, not at some undefined time in the future.

Secondly, the client has reassurance that the structure will not be made worse by the repair. The structure is clearly there; it may have problems; the steel may be rusting and it may not be able to carry the intended load, but it can certainly carry its own dead weight. Even if these fancy new materials turn out not to be as good as they claim, the structure will be no worse than it is now. The client's engineers and the local politicians are seen to be "*doing something*". They can put the blame on previous generations of engineers ("*if only they had allowed for deterioration of the materials/increased truck weights*") and politicians ("*those cheapskates wouldn't spend a few percent more to get a properly-built structure*") and show that they are helping society now ("*we are building a better Britain/Canada/France* (delete as applicable)"). By reinforcing the structure the engineer is seen to have done something and it is certainly going to be better than it was before. It is a "*safe*" decision in the sense that it is very difficult to criticize.

The structure may not have needed repair in the first place, but that does not matter. Many structures that are being repaired were designed in the 1960s using hand methods of design. The stress distribution was assumed and satisfied the lower bound theorem of plasticity, on which all designers rely, even if they can't remember what it says. Nowadays, structures are checked using finite element analyses, which make a host of assumptions of which the checker is unaware (relative stiffness of the structure, articulation of joints, etc) and come up with a different stress distribution that the existing reinforcement cannot carry. The stress distribution found by the finite element analysis is only one of the distributions which satisfies equilibrium, so it does not mean that the original design was unsatisfactory, only that the modern checker cannot prove that it is OK [4]. This is a major problem for slab bridges but an even worse problem for masonry arches [5].

Even if the structure failed its assessment, would it have fallen down? In most countries, structures are assessed against the design code [6], which makes assumptions about the materials that *will* be used in a structure yet to be built; in the UK there is an assessment code which takes account of the prior knowledge of the structure as-built [7]. In reality, the average structure is between two and three times as strong as the load for which it was designed; codes require pessimistic assumptions about the variability of loads and the strength of materials, and then add factors of safety to allow for uncertainty about the methods of analysis and to protect the engineer's professional indemnity insurance. How many highway authorities really design their bridges to fall down if a truck marginally over the 44 tonne limit (or whatever the design load is) crosses the bridge. The codes assume that some trucks will be overloaded and the real design load is considerably higher. Anyone running a testing laboratory has learnt to beware of the client who wants a structure tested; "*The structure will fail at 100 tonnes*" usually means that this is what the code formulae say. The tester must ask "*what is the greatest possible strength of the structure?*" when designing the strength of the test frame; the forces are typically many times the client's original estimate, and the mean strength of the structure is probably at least three times its notional strength.

The repair market has reached the stage where adding CFRP is seen as the logical thing to do [8]. It has even been described as wall-papering, with clearly bad examples, such as re-entrant corners, being repaired. Structures are now being repaired in many ways that defy our standard procedures. Student engineers are taught that steel links have to be properly anchored; the lap in a steel link must be detailed so that it occurs in the compression zone of the beam to ensure adequate anchorage. Most beam and slab structures are detailed so that the neutral axis is at, or just above, the beam/slab interface. If CFRP shear reinforcement is placed on the outside of the web, how can it possibly be properly anchored? There are clever techniques using longitudinal rods [9], or drilling into the concrete, but even so the anchorage would normally be regarded as inadequate using the rules that apply to steel. They are often anchored into the cover, which is presumably suspect because of corrosion of the shear steel and which is presumably cracked in tension. The use of self-anchored prestressed external strips is possible [10], although the required saddles can be a disadvantage.

By far the largest component of the repair market has been the reinforcement of columns against seismic action, with the reinforcement in the hoop direction at the ends of the columns [11]. In the UK, where large earthquakes are not expected, there has been considerable use of these techniques to reinforce bridge columns against vehicle impact, which is believed to be a significant danger [12]; this requires axial reinforcement at mid-height. FRPs have also been used for the reinforcement of old masonry structures, most typically in Italy and Greece. The collapse of the roof of the cathedral of St Francis at Assissi [13] is the sort of thing that must be prevented, but some of these techniques involve the application of point loads to domes, which seems to be a highly suspect technique. There is also considerable research in the US and elsewhere on the use of FRP to protect buildings from explosive damage.

To the best of the author's knowledge, at the time of writing (May 2004), there has not yet been a major earthquake affecting structures that have been reinforced with CFRP. This market will depend critically on the first such event to occur. If the CFRP does protect the structures, the market is secure, but if *any* of them fail, even if the earthquake were much stronger than expected, the market will be killed overnight. This puts an extra onus onto designers working with the material today. One badly designed or shoddily constructed application can ruin, not just the people involved, but the whole industry.

3. COST OF FRP

Table 1 gives costs being charged in the UK in 2004 for various materials, in commercial quantities, based on the ultimate strength of the element concerned. Anchorage costs are not included, nor are labour costs or profits. Table 2 shows the same materials, but based on the cost of providing a stiffness of 1 kN/mm of extension/m of length. These figures should be taken as approximate in all cases.

Table 1. Cost of materials per unit force

Material	Strength (MPa)	Cost (£/kN/m)	Cost ratio	Notes
Prestressing steel	1700	0.002	1	7-wire strand on coil
Reinforcing steel	460	0.006	3	Includes bending
GFRP	580	0.013	6.5	Excludes bending
Aramid fibre	2600	0.009	4.5	Fibre only
Aramid rope	2000	0.025	12.5	As a rope
AFRP	2000	0.025	12.5	As a pultrusion
CFRP	2000	0.025	12.5	As a pultrusion
PBO	4000	0.030	15	Fibre only

(based on £1 = US$1.77 = Can$2.47 = €1.50)

Steel costs have recently risen by about 30%, supposedly because of significantly increased demand in the burgeoning Chinese economy. That should have improved the market for FRP, but it is clear from this table that the costs of new materials are higher in comparison to the costs of steel than they were 20 years ago and they are significantly higher than they were expected to be; the assumption in 1984 that FRP costs would come down significantly has not been borne out. It is widely believed that the aramid and carbon fibre manufacturers have decided to concentrate on the small-volume, high-price, high-technology markets such as aerospace, rather than go for the high-volume, low-price, basic-technology civil engineering market. It may occasionally be possible to buy products slightly cheaper than this, but this is normally to use up surplus stocks; manufacturers would not build another production plant if the product had to be sold at the reduced prices.

The figures for PBO have been included because, although this is a very exotic material which is far too expensive for use in civil engineering structures, it is gaining a market in areas such as racing-yacht rigging, where the expense is outweighed by the reduced area and the transportation costs for the steel alternative, which has to be supplied as a bar. Using the right product for the right market can be cost-effective, whereas trying to apply it to the wrong market can be counter-productive.

Table 2. Cost of materials per unit stiffness

Material	Stiffness (GPa)	Cost (£/kN/(mm/m)/m)	Cost ratio	Notes
Prestressing steel	200	0.016	1	7-wire strand on coil
Reinforcing steel	200	0.014	0.9	
GFRP	40	0.150	9	
Aramid fibre	124	0.190	12	Fibre only
Aramid rope	124	0.480	30	As a rope
AFRP	80	0.500	31	As a pultrusion
CFRP	124	0.480	30	As a pultrusion
PBO	270	0.440	27	Fibre only

With these cost figures in mind, it is worth looking again at the FRP market.

4. FRP CONCRETE MARKET

4.1 Internal reinforcement for flexure

GFRP will always suffer from its low stiffness and it is very unlikely to find a serious market where the deflections of the structure matter. Structures under any significant load would crack, so to keep the deflections to acceptable limits the structure would have to be much deeper than normal, or the structure over-designed to an unreasonable extent. There are, however, applications, where corrosion risk is very high but deflections would not be a problem, such as retaining structures or fenders in the splash zone. Structures that have to resist occasional loads, such as balustrades, or wind loads (such as sign gantries) might also be suitable, but it is doubtful if the extensive cracking that will occur in GFRP-reinforced concrete will make it robust enough for structures carrying heavy wheel loads, such as bridge decks.

It is also unlikely that AFRP or CFRP will be economic for flexure. At the strains at which concrete cracks the AFRP or CFRP will not be carrying significant load. The client is therefore paying for strength which is not being utilized. The additional stiffness relative to GFRP will make no difference and the additional cost cannot be justified, so it is difficult to foresee even a niche market for which these materials are the logical choice.

4.2 Internal prestressing for flexure

Beams pretensioned with steel tendons do not have problems with corrosion, provided there is adequate cover to the concrete and the beams are made under factory conditions to sensible designs. In the UK alone there are tens of thousands of bridge beams and millions of railway sleepers (ties) made in this way, and in France most electricity and telephone poles are precast. Although it is possible to replace the steel in them with FRP tendons, probably partially-bonded to achieve good moment-curvature responses [14], there appears to be little economic justification for so doing.

4.3 Internal reinforcement for shear

The situation regarding internal shear reinforcement is more complex. Shear reinforcement is always closer to the surface of concrete than the flexural reinforcement and is much harder to fix in the correct location. Unless every link is provided with spacers the chances are that some links will have inadequate cover, so it is always this element that corrodes first. Logically, therefore, there might be a stronger case for replacing the shear reinforcement than the flexural reinforcement.

However, theories for the mechanics of shear transfer with elastic reinforcement are inadequate [15]. Although beams can be analysed with elastic reinforcement the behaviour remains complex, so most formulae rely on analogues with the steel codes [16]. Because of the lack of ductility, it is assumed that limiting the strain in the FRP to the strain that the steel would have at yield allows plastic truss models to be used. The logic is false but it introduces a large factor of safety that appears to work! So the cost that matters is the cost per unit stiffness, which is shown in Table 2; note however that these figures exclude bending costs for FRP, or other costs associated with making links, so the true cost would be much higher.

The stiffer fibres, like carbon, might be expected to have an advantage in this situation and if they have to be used it seems most logical to consider CFRP shear links. But none of the existing techniques make full use of the properties of the material that is being provided so expensively. By limiting the fibre to the yield strain of steel, 90% of the fibre strength is not being utilized. It is difficult to fabricate FRPs as links and the conversion efficiency between yarn and composite properties is badly affected by the bend. This is a field in which a novel form of fabrication, perhaps involving a process such as knitting technology [17], could have clear financial advantages. A technique that went from yarn to reinforcing cage in one operation, and got more out of the concrete by making use of its triaxial strength, would definitely be an advantage. If the concrete can be made to work harder and the fabrication costs of the shear reinforcement could be reduced, it may be possible to see an economic future for advanced composites in concrete structures. Bent pultrusions, however, will never be economic.

4.4 Internal confinement for compression

Engineers are used to the idea that concrete is brittle and steel is ductile, so structures must be underreinforced. The steel fails first and the concrete only has to have sufficient strength; the actual mechanism of failure is not important, and although it is generally regarded as “a good thing” to confine the compression zone.

The situation changes if the tensile elements are provided by FRP. These elements are brittle and will snap if their strength is exceeded. If energy is to be absorbed in the section this must occur in the compression zone. The use of spirals of FRP to contain the concrete can be remarkably cost effective. By confining the concrete in the compression zone with spirals of aramid fibre the strength can be increased marginally, but the strain capacity can be increased three- or four-fold. Remarkably little confining stress is needed for this; 2 MPa is sufficient. The amount of fibre needed to achieve this is small; if about one-sixth of the volume of the material used to provide tension capacity is used to provide spiral confinement, the strain (and hence curvature) capacity is tripled. These results were obtained from very simple tests on cylinders and rectangular beams [18] and it is probable that with more sophisticated fibre geometries, such as spirals of different sizes to reduce the amount of unreinforced cover concrete, even better results can be achieved.

This is an example of using FRPs for what they are good at, rather than trying to make them behave like very expensive and rather inadequate versions of the steel reinforcement that they are replacing.

4.5 Internal reinforcement for local effects

A field that has largely been ignored for FRPs relates to the reinforcement that is required in the vicinity of concentrated loads. Such reinforcement is often close to the surface and the concrete is frequently cracked nearby. The anchorage zones for prestressing tendons are a classic case where the concrete is almost certainly cracked in the vicinity of the bursting reinforcement (otherwise it can't be doing very much) or the reinforcement is placed close to the surface [19]. The lack of stiffness is not of itself a problem, although its effect on the stress distribution needs to be properly considered.

Other cases where problems occur with steel reinforcement are in half-joints, corbels or beam seats. These structures are invariably cracked and often very difficult to inspect. They are also often exposed to water which may, in the case of bridges, be contaminated with de-icing salts. Any reinforcing bars would be short, so additional deflections would be negligible. Ground slabs are also a field in which strength is required but the strains are low, although, as with bridge decks, the effect of concentrated wheel loads on the fatigue strength of cracked concrete would need to be studied.

4.6 External prestressing tendons

External prestressing tendons were one of the first applications envisaged for advanced composites [20] and remain the major application for which FRPs are most suitable. The ability to inspect, and if necessary replace, the prestressing tendons is attractive to specifying authorities. This has been recognized even with steel tendons where it is known (although perhaps not acknowledged) that the exposure will shorten the lifetime of the tendon. Steel can be protected by wrapping the tendons in grease-filled plastic sheaths, but this typically triples the cost and removes the ability to inspect the tendons in detail. By prestretching the aramid or carbon fibre tendons the additional strain capacity can be utilized. One disadvantage is the requirement for anchorages, but systems are available for aramid ropes that can anchor the full strength of the rope [21], and systems that are almost as effective are available for CFRP [22].

The arguments that, twenty years ago, identified these tendons as the most logical application of advanced composite tendons remain valid today.

5. VERY-LONG-SPAN BRIDGES

Head and Richmond [23] showed that historically it took 30 years from the invention of a new material before it was used to build the world's longest span. They also showed that the break-even span, where materials like carbon or aramid fibres would replace steel in the suspension cables of bridges is about 5 km. The longest span at present is the Akashi-Kaikyo bridge at 2 km and the main span of the Messina Bridge on which work is to start soon is "only" 3.5 km. To the best of the author's knowledge, no structures longer than 4 km are being seriously contemplated, although Meier proposed a cable-stayed bridge linking Europe and Africa across the Straits of Gibraltar using CFRP cables [24]. The main span would have been 8.4 km supported from a tower 1.4 km high founded in water 700 m deep. One of the four shortlisted proposals for the crossing between England and France envisaged a series of 4.5 km spans using aramid cables [25], but none of the associated technical problems such as aerodynamics was seriously addressed and a railway tunnel was built instead.

The Channel Tunnel is itself instructive. In most cases, when a major new crossing is built, the existing ferries go out of business. They are unable to compete in terms of cost and convenience with the new structure. That has not happened between England and France; the tunnel naturally carries all railway traffic, but cars and trucks have to travel on special trains. The costs of the fixed link are so large that the charges for its use are too high; two ferry companies still offer extensive services across the Channel that compete in time and cost with the tunnel. There is now widespread dissatisfaction from the investors in the tunnel who realize that they will never see a return on their investment. The same can be expected of other major crossings; once the cost of the structure becomes so high that the alternatives are still cheaper, it will never be economic to build a major structure in FRP.

6. WHOLE-LIFE COSTING

There is widespread criticism in the UK (and elsewhere) of construction standards in the past. Many structures are being repaired because of deficiencies, often related to durability. As discussed above, engineers of the past are being criticized for not paying sufficient attention to durability; an apparently small amount of money and an ability to see into the future would supposedly have led to more sensible decisions. But are better decisions being made now? If structures are designed today and it takes 35 years before they need attention, who cares? Who can foresee what they will be doing in 2040? The chances are that the senior engineers (who presumably take the decisions) will be dead, and their children will have retired; the problem will fall to their grandchildren to deal with. Is it possible to make sensible decisions on that time-scale? An often-quoted, but apocryphal, statistic is that London office buildings are designed with a structural lifetime of 20 years; the cladding is expected to last 10 years; the internal partitions 5 years, and the internal wiring 2 years. If refurbishment is not undertaken on this time-scale the building is seen as old-fashioned and is unlettable at economic rents. What price durability for this type of structure?

The only other industry that makes decisions on a comparable time-scale is forestry; sustainable forest management assumes that fast-growing species can be cropped after 30 years but accepts that some trees will take 100 years or longer before they make a return. Planting decisions are made in the knowledge that it is future generations who will benefit, but they are also taken as part of a continuing cycle; trees planted by previous generations are reaching maturity and generating returns. It is only when the industry gets too greedy and tries to crop too quickly without planting replacements that the system breaks down and attracts criticism from environmental groups.

6.1 Discount rates

It is commonly stated that structural options are determined on the basis of whole-life costing [26], but the impression is often gained that only lip-service is being paid to these ideas. In theory, designers can choose between the cheapest first-cost option or the cheapest whole-life-cost option. To make that choice, an assumption has to be made about the discount rate to be used. If money is invested now, it will accrue value; that added value can be used to pay for future maintenance costs. If a high rate of return is used, not much money has to be invested to pay for future maintenance, so the present value of future maintenance costs is low and it is not worth spending much money now to prevent future maintenance. Conversely, if discount rates are low, a lot of money has to be invested to pay for maintenance, and a durable structure is a valuable asset. In the UK, at present, one can earn about 4% return on investment income, with inflation running at about 2.5% per annum. So the true discount rate that should be used is about 1.5%, and calculations performed this way can compare building costs and future maintenance costs at 2004 prices. Historically, discount rates have been set as high as 6%; $1.06^{35} = 7.7$, whereas $1.015^{35} = 1.7$. The present value of a repair to be undertaken in 35 years time is more than 4 times higher if a low discount rate is used than if a high discount rate were used. The choice of the discount rate to be used in these calculations is of crucial importance to the decisions that are made; the temptation is to use a high rate which conveniently means that the best whole-life solution just happens to be the best first-cost solution as well. Future maintenance remains the problem of future generations and new structures are built cheaply.

The form of ownership of the asset is also significant. Until about 10 years ago, in the UK, most public buildings and highways were the property of the government, either directly or owned by local councils, the military or (in the case of hospitals) by the National Health Service. All of these bodies were expected to be run efficiently but they could not go bankrupt. They would continue to own the assets and be responsible for them in perpetuity but this has been deemed to be anti-competitive. Major assets are now constructed by private companies who design, build, operate and maintain the facility for a fixed period; they are paid a fee each year for supplying the service. At the end of the period the assets are to be returned, supposedly in good order, to the government body that commissioned them. It has been assumed that the continuing responsibility for the assets will mean that the private companies will maintain them in good order. However, with maintenance intervals due to reinforcement corrosion of the order of 30 or 40 years, it seems likely that the maintenance regime will not keep the assets in peak condition but will aim to return them in the minimum acceptable state. It is very likely that major maintenance will be required on assets soon after they have been returned to government ownership; the politicians of the day will blame the commercial owners. So what future will there be for materials whose main claim to economy is the money that can be saved in 30 years time?

6.2 Delay costs

The question also arises as to what future costs are to be included. In the case of a building the situation is clear; the building is owned and occupied by the same person – even if space in the building is let to a tenant, the tenant is free to move elsewhere so the owner is directly affected by the tenant's costs. But in the case of a highway structure the situation is less clear. In the case of a public highway, to which everyone has free access, the costs borne by the bridge *owner* and the costs borne by the bridge *user* are separated. The bridge owner, usually ultimately the government, has to bear the costs of the actual work carried out on the bridge, but traffic delay costs are borne by the motorists themselves (or by the clients of the haulage companies whose goods are being carried). If there were many alternative routes that could be followed then traffic would simply divert elsewhere, but in practice most highways run at or near capacity for much of the time. So diversion is not possible and traffic is disrupted, causing delays that can be assigned a cost.

As detailed in another paper at this conference [27], these traffic delay costs can be huge and totally overwhelm all other costs. Whereas the cost of using FRPs may be measured in tens of thousands of pounds (or dollars, or euros), and the cost of repairs may be measured in hundreds of thousands, the cost of traffic delay costs are measured in hundreds of thousands *per day*. So the economic viability of a design depends crucially on whose costs are taken into account. If society is building a structure for itself, then the costs incurred by motorists wasting time are a true cost to the national economy; if a company is building an asset, and the consequential costs incurred by others do not impinge on the company itself, then there is no need to take delay costs into account.

The effect of this dichotomy is illustrated by the different strategies imposed until recently by the UK government on road and rail infrastructure (both of which it owned). Roads and railways were both regarded as national assets and investment decisions were funded centrally. The strategy for road building took into account the costs and benefits to road users, including delay costs and accident costs, as well as the construction cost of the project. Railway projects, on the other hand, had to show a return on investment for the railway operation without taking account of indirect benefits to society. It was much easier to show that a new road made economic sense than a new, or improved, railway. It remains a complaint within the railway industry that investment decisions are not made fairly, despite a government pledge to get traffic off the roads and on to the railways.

6.3 Simple result

The effect of these decisions on the FRP market can be summarized simply:-

- If the structure under construction is externally prestressed, *and*
- If realistic whole-life costing is being adopted, *and*
- If a realistic discount rate is being used, *and*
- If traffic delay costs are being included

then the owner *must* use FRPs for an economic structure. If any of these conditions are not satisfied, FRPs will never be an economic solution unless special factors apply, such as exposure to extremely corrosive environments in an application where large sections or large deflections are acceptable, in which case reinforcement with FRP may be an acceptable solution.

Many of the scenarios quoted here reflect practice in the UK, but it is clear that similar considerations, perhaps with different emphasis, apply in most countries throughout the world. The overall conclusions, if not the details, are believed to be generally relevant everywhere.

7. CONCLUSIONS

The effective design of structures using advanced composites cannot be divorced from the economics of the world in which the structures are being built. The market for FRPs has not taken off as had been expected, largely because the FRP market has concentrated on trying to make FRPs look like the steel elements they are replacing. FRPs do not make effective reinforcing bars except in certain niche applications and they are very ineffective in shear. External prestressing with aramid ropes and carbon fibre cables remains a sensible application, as is adding confinement to the compression zone of concrete beams. A useful contribution to the shear capacity of beams will only be provided when a system is developed that allows the fibre to confine the concrete in such a way that the concrete itself becomes more effective.

Structures will rarely be economic unless sensible decisions are made using whole-life costing and taking into account all the costs of repair, including delay costs and loss-of-use, as well as using a realistic discount rate to determine the present value of durability.

The world's longest-span bridge will never be built using advanced composites, because they will only become economic at spans where the costs are so high that ferries will remain as effective commercial competitors.

Has the author wasted his time over the last 20 years working on various problems associated with the use of FRP? No, because the problems tackled have always been those which relate to applications of advanced composites that have economic benefits. It is not always clear that this logic applies to all work carried out on FRPs!

8. ACKNOWLEDGEMENT

The author wishes to thank the various members of the profession who provided the commercial cost information from which Tables 1 and 2 were compiled, but who did not wish to identified.

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