FIBRE REINFORCED POLYMERS – STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS

Chris BURGOYNE

Department of Engineering, University of Cambridge, UK

Keywords: economics, strengths, weakness, applications, design

Oh wad some power the Giftie gie us
To see oursels as others see us!
It wad frae monie a blunder free us
An' foolish notion
What airs in dress an' gait wad lea'e us!
(Robert Burns, To a Louse, 1786)

1 INTRODUCTION

Robert Burns watched a louse crawling over a lady's hat in church, and during the sermon wrote a poem wondering what she would have thought if only she could see what everyone else could see. When we see ourselves as others see us, we don't always like the view, but it is probably a good idea to periodically ask ourselves what the rest of the world thinks of us. In business, this is often referred to as a SWOT analysis, which aims to identify the Strengths and Weaknesses of products and to consider the Opportunities and Threats that face the enterprise. Such analyses need to be conducted with an open mind, and are usually conducted in private, but an FRPRCS conference is as close as we are going to get to an industry-wide private discussion. We have to be open-minded and willing to think the unthinkable; fooling ourselves is like cheating at Patience (Solitaire). This is very much a personal view so, unusually, it has been written in the first person.

Every so often the popular press carries stories about some new wonder material, "stronger than steel" from which we are going to build bridges as "light as a spider's web". But we are still waiting. When glass fibres came along in the 1950s there were proposals to make reinforcing bars and prestressing tendons from them, but that came to nothing. Later, aramid and carbon fibres were developed. Corrosion of steel rebar, which usually leads to disfigurement of the structure, or worse of prestressing tendons which can lead to collapse, meant that engineers looked to these materials as non-corrodable reinforcement for concrete. The early work was done in the 1980s, and there were high hopes that these materials would take over a significant share of the market from steel. But it hasn't happened; the steel manufacturers don't seem to be losing sleep over FRP; our market share is very small and concentrated in very specialist areas. Cynics might say that FRPs have provided a lucrative area for study that can attract research funding, and some very good work has indeed been carried out, but they will never be adopted. Why not?

In what follows I will concentrate on the three core fibres with which we are involved for applications in concrete; carbon, aramid and glass. Other materials are excluded; PBO because it is too expensive, polyester because it has too low a modulus, and HMPE because of creep, but all are very interesting fibres and have definite specialist engineering uses.

2 STRENGTHS

The strengths of FRP are well-known; we rehearse them every time we write a paper.

2.1 Fibres are strong

Carbon, aramid and glass fibres are strong; they have strengths as fibres of the order of 3000 MPa and slightly less than this as bundles or as pultrusions. These strengths are higher even than prestressing steels and there is no doubt that they are attractive to structural engineers.

2.2 Fibres are stiff

The stiffnesses of our fibres are high enough to make them attractive; they vary depending on grade but they are at least as stiff as aluminium and in certain cases they are as stiff as steel.

2.3 Fibres are durable

We know that our fibres do not rust, at least in the same way as steel. So they are not going to give us expanding rust that bursts the cover and leads to staining on the outside of our concrete. In particular, they are resistant to attack by chlorides, which are the bane of any structural engineer's life when designing near roads or the sea coast. We are all familiar with boats and ships with GRP hulls. So they are attractive as non-corroding reinforcement and prestressing tendons. But it is not all good news; durability issues are going to appear amongst the weaknesses as well.

2.4 Creep properties

All these materials creep, but studies have shown that the amount of creep is negligible for reinforced concrete and gives losses of force for prestressed concrete that is similar to that in structures with steel tendons. Creep to failure though will appear as a weakness.

2.5 Light weight

The light weight of FRPs makes little difference to internal reinforcement or prestressing tendons, but it does make a significant contribution to the one successful application of FRPs as Externally Bonded Reinforcement (EBR). The low weight could make a significant difference to the costs of installing the reinforcement.

2.6 Other benefits

The materials are non-magnetic and non-toxic, which can be regarded as "good things", although they might be factors only in a limited number of cases.

So much for the good things; much more could be written here but we all know these arguments. What we have to spend time thinking about is the other side of the coin.

3 WEAKNESSES

3.1 Cost

The cost of FRPs is the killer disadvantage in almost all cases. The cost of delivering a kN of force varies depending on where you are in the world, how much material you are ordering and the form in which it is being supplied. The cost of steel has fluctuated wildly in recent years so the relative cost also varies. But in rough terms you would expect to pay three times as much for glass FRP reinforcing bars, and up to 10 times as much for aramid fibre or carbon fibre for prestressing tendons.

When we started working with these materials, we believed that we were paying "prototype" prices, and that these prices would drop as demand increased, but that has not happened; the relative differential between the cost of FRP and the cost of steel has remained largely unaltered. It is likely to remain so; when I explained to one manufacturer that I knew how much he was selling his fibre for into one particular market segment, and asked why he couldn't make that price available to the Civil Engineering community, he said "I will sell it at that price to use up spare capacity in my plant, but I wouldn't build another plant if I could only sell it at that price". The high strength fibre manufacturers have decided to pursue the low-volume high-cost aerospace industry, rather than our low-cost high-volume business.

The result is that almost all applications of FRP in concrete structures are uneconomic when considered on a "first cost" basis. Even if the cost of prestressing in a bridge represents only a few percent of the total cost of that bridge, multiplying that small percentage by 10 makes a significant difference to the overall cost and is one that it is difficult to justify to an accountant. Most of our clients are public servants; they are legally obliged to accept the lowest tender or they can be accused of colluding against the public interest.

Our answer to this has to be that we should look at the "whole-life" costs for our structures, but this is fraught with difficulties. The benefits of using FRPs come from the problems associated with the use of steel, and few of these costs occur within 30 years of the structure being built; many will not occur for 60 years. It is thus not a problem for the designers of the bridge; they will retire long before the costs are incurred – leave it to the children to sort out! It is also very difficult for current designers to admit to their paymasters that the structure they are paying so much for is not durable. "Structures designed in "the olden days" (i.e. the 1960s) may have been inadequate, but now (we think) we know what we are doing".

Even if we do try to allow for long term costs, we have to allow for the effects of inflation. This is done by means of a “discount rate”, which ought to be the real rate of interest that accrues for money on deposit, allowing for inflation. But it is usually set far too high by decision makers, which means that the cost-benefit equation is biased towards choosing immediate certain cost savings over nebulous benefits at some time in the future. When this is added to the inherent uncertainty about what the world will be like in 50 years time, it is perhaps not surprising that sensible decisions are not made to adopt FRPs for new construction. How many papers at this conference are addressing the key reason why people do not use FRPs …?

3.2 Flexibility

All the new fibres have stiffnesses that are comparable to those of metals, while showing much higher strengths. The result is that strains in these materials will be much higher if they are used at a reasonable fraction of the strength that one is paying so much for. Elastic strain capacities of the order of 1.5% - 2% are not uncommon, which compares with cracking strains in concrete of 0.01% and working strains in compression of about 0.1%. (The working strain capacity of steel rebar is about 0.2%.) So we have a bind; either we use the material at strains that are well below their capacity, in which case we are even more uneconomic, or we accept much higher curvatures, which is generally deemed to be unacceptable, if only to stop the public worrying about our structures.

The logical solution is to prestress the FRP, and although this was one of the markets first envisaged for FRPs, there is a general feeling amongst most clients that we should master reinforcing before we tackle prestressing. But if reinforcing isn’t a sensible application …?

3.3 Brittleness

Not only do the fibres have high strain capacities, but when they do fail they are brittle. This has several corollaries. An assemblage of brittle materials is not as strong as the sum of its parts; when one element fails it sheds load to its neighbours, which can become overloaded in their turn. This is in marked contrast to an assembly of steel wires; when the weakest one reaches its capacity it yields and continues to carry some load, sometimes even strain hardening. The failure stress of a bundle of steel wires is pretty close to the average of its constituent parts, whereas the strength of an assemblage of brittle fibres is only a little above the strength of the weakest element. So what is important to the designers of FRPs is the *variability* of strength *between* fibres, and also *along* the fibres. The higher capacity of FRP pultrusions as compared with ropes is because the resin bridges the flaws in the fibres, but it doesn’t bridge all of them. Where is the research looking at the length and variability effects on FRPs …?

Brittle elements cannot be allowed to fail. A ductile structure taken close to failure can redistribute loads to other elements; in brittle structures they snap. Thus, we have to apply larger factors of safety to brittle materials because the consequence of overstressing is more severe. So once again we are being forced to be less economic than we otherwise would. We are often saved by the fact that structures with FRP are usually governed by stiffness rather than strength, but there are major exceptions (see 3.7).

The other corollary of brittleness is the inapplicability of plasticity theory. These theories were developed back in the 1930s because strain gauge measurements on real buildings showed that the stresses were wildly different from those predicted by elastic theory. In part that was because structures were being designed by simplified hand methods, but the same problems still occur when we use finite element programs. The calculations are more detailed than they were before, and the pictures produced by the programs are prettier, but the numbers are still only as accurate as the assumptions made by the *author* of the program. That is usually not the *user* of the program, who is the designer. What saves the designer in most cases with conventional materials is the Lower Bound Theorem, but that relies on the structure being ductile. Virtually all current codes of practice for design of structures with conventional materials assume, explicitly or implicitly, that the materials can deform plastically. There have been many papers looking at the stress-strain curves of FRP bars or the moment-curvature relations of beams reinforced with FRP. But having a plateau on these curves does not mean they are ductile. The *unloading* curves need to be studied to see if energy is actually being dissipated (in which case plastic theory could be used) or merely being stored so it can be released back into the structure when something fails. Where is the research that says that plastic theory can be used for design …?

3.4 Anchorage

In order to get the forces into and out of FRP bars we have to be able to grip them. In the early days there was a huge literature dealing with bond, much of which proved a waste of time since too much bond is as bad as too little. It leads to localization of failure at concrete cracks; steel rebars rely on yield of the steel at critical cracks followed by debonding along the bar to reduce stress concentrations, but FRPs can't yield so they snap. That can and has been quantified, but we still have problems gripping fibres for prestressing applications. Very often, the cost of a prestressing anchorage is more expensive than the FRP tendon to which it is being attached, and we have seen that they are already very expensive. Doesn't it make you wish for a nice strong isotropic metal that you can grip with wedges …?

3.4 Bendability (lack of)

When a delivery of steel rebars arrives at a building site, how many of the bars are straight? How have we ended up in the situation where we take eminently flexible, very strong fibres, and turn them into a material which is almost impossible to bend or which, if formed (as in shear links) tends to have a strength that is no more than half that of straight pultrusions. Where are the proposals for novel techniques such as filament arranging, three-dimensional knitting machines, and the tests to show how much of the strength of the fibres is available around the corners. Why do we persist in trying to make FRP bars look like rebars, and where are the papers that show the alternatives …?

3.5 Durability

The resistance of fibres to corrosion has been mentioned as a benefit, but they are not perfect. The fibres don't "rust", but glass and aramid can hydrolyse, especially in the presence of the high alkalinity in concrete. The resins in FRPs are also liable to various mechanisms for degradation. Unlike corrosion in steel, it will not be apparent on the surface, which is a concern. There are many papers about durability, but how will structures with corroded FRPs be checked …?

3.6 Creep and stress-rupture

Structural engineers like materials that are constant. They accept that concrete creeps, but it only seriously affects deflections; there is very little chance that it affects the strength. But fibres have this annoying problem called stress rupture, in which the fibres can creep to failure. It isn't a durability issue but the plots to show its importance look like plots showing reducing strength with time. By the time the engineer reads the accompanying text the damage has been done. No matter that the retained strength, for short term loads, in almost all cases is close to 100%. Where are the papers that make this clear …?

3.7 Shear

Shear isn't properly understood, even in structures with steel reinforcement. There are at least three competing theories and many more interpretations. But we have evolved techniques for dealing with shear that are safe in most circumstances; these all rely on plasticity theory. We have already noted that FRPs aren't ductile, and yet we persist in using formulae for FRP reinforcement that look like the plastic theories for steel with "adjustment" factors added that try to limit the strains in the FRP to those that would have been present in elastic steel structures. The argument being that if plasticity theory can be applied to steel at these strains it must also be applicable to FRPs at these strains, and we have to have *some* formula or people won't use FRP as shear reinforcement. They aren't using it anyway because of the difficulty of making bent bars (see above), but meanwhile the founders of plasticity theory must be spinning in their graves!

There are also problems associated with the use of EBR as shear reinforcement. As young engineers, being taught how to detail reinforcement, we were all told that the laps in shear links must occur within the compression zone to ensure that the concrete is properly bonded to the steel. Yet with FRP there are many test programs that show the FRP either not being properly anchored in the compression zone, or anchored in the vicinity of the neutral axis.

It can be argued that I have overstated the problems. Not all the difficulties occur for all applications, and many do not apply to all types of fibre. But the problem is that the engineers in client's offices know some or all of these problems, and accountants can add up the first cost easily. What we have to do now is see when we can use the materials to their best advantage. We should look at the Opportunities.

4 OPPORTUNITIES

What applications are there for uses of FRP that minimise the problems and maximise the benefits? It makes sense to look at cases where they are already being used first and then to move on to cases where they might be used.

4.1 Externally bonded reinforcement for flexure

The use of EBR to enhance the capacity of structures in flexure has been an undoubted commercial success. Following the early work in Switzerland, there have been many applications. The amount of material used is relatively small, while the installation costs are large, so the benefit of light weight reduces the costs of providing access, and the relatively small amount of material involved means the disbenefit of expensive fibres is low. The risk to the client is also low. Because the structure is already in place, it must by definition be already carrying its own dead load. Most structures are actually significantly stronger than the values given in codes of practice, which are designed to be conservative. So the FRP probably isn't doing much anyway and even if it did fail it would be unlikely that the structure would actually collapse. Our clients are happy because they are seen to be doing something, and to be using innovative materials.

4.2 Externally bonded reinforcement for extreme loads

This category includes the strengthening of structures against exceptional loads, such as earthquake, impact and terrorism. This has clearly also been a successful application; it is real, in that unstrengthened structures have collapsed in the past, but even more than in the previous case, the FRP will be unloaded most of the time. The risk to the engineer is also low, since the loading cases are so difficult to quantify that even if a structure does subsequently fail, it can always be put down to exceptional circumstances. The associated potential threat is discussed in 5.2 below.

4.3 Internal reinforcement with GFRP

The use of FRP as main reinforcement in reinforced concrete structures is usually precluded by their low stiffness, which leads to larger deflections and excessive cracking. But there are applications for which deflections are not really an issue, and where the benefits of lack of corrosion are important. External balcony walls in buildings, or barrier walls next to salted rods are obvious examples. Fence posts, noise barriers and many other structures where long-term corrosion is a known issue, but the day-to-day loadings are small, would be obvious candidates, although whether the extra cost could be justified is open to question. There are other examples where other properties of the FRP are important; non-magnetic properties in MRI facilities in hospitals, or the ability of the bars to be cut through in break-out panels, also offers potential, and in these cases they are already being exploited.

4.4 Textile Reinforcement

One feature of FRPs that has not yet been fully exploited is to make use of the fibre flexibility. It ought to be possible to make use of the principles of textile machinery to work with the flexibility of the fibres to make products that are bespoke. In conventional clothing, knitted stitches are typically a few millimetres apart, but larger versions of the same machinery could give stitches that are 50 mm apart. Three-dimensional (Raschel) knitting machines exist, which could lead to cellular structures, which would give significantly enhanced concrete properties. Exciting prospects exist for a new type of "FRPcrete" that is more than simply a combination of two existing materials.

4.5 Special details

The possibility of using advanced techniques to arrange the fibres in optimal patterns offers other possibilities for the future. The yarns, possibly in the form of prepregs, could be arranged in 3D jigs by robots and then coated in resin and cured for standard details such as bursting reinforcement in prestressing anchorages, or special details for halved joints and corbels. In such cases the length of the FRP pieces is small (so the higher strains do not translate into significant displacements), and the difficulty of making complex geometries out of straight pultrusions, or even of bending steel bars, can be eliminated. The light weight of the assemblies would mean that transport from a central facility to where they are to be used would not be difficult.

4.6 Prestressing

Prestressing tendons were seen as the first, and most logical, application of high strength fibres, in either rope or pultrusion form, and that argument is still valid. The problem is still the cost, coupled with reliable data for stress-rupture and strength retention. There have been demonstration projects, but few commercial applications. It is also held back by the argument that we have to get applications in reinforcement first. This remains a largely untapped market for FRPs.

5 THREATS

5.1 From the steel industry

It is a sad reflection on our subject that the steel industry no longer sees us as a threat. When FRPs were first introduced, there were attempts to show that FRPs wouldn't work, but these have largely ceased. This is perhaps the most telling criticism of all. We are being ignored! The steel industry will allow us a few niche markets, where magnetic properties or extreme corrosion means that FRP is a clear winner. But they know we will never take over their core business. Steel and concrete work so well together that it is difficult to see us getting much market share.

5.2 Earthquakes

At the time of writing (January 2009), there have been no major earthquakes in parts of the world such as Japan or California where there are a significant number of structures that have been retrofitted with FRP to resist seismic loads, but such an event will certainly occur sooner or later. When it does, the performance of the repaired structures will be critical. If all the structures with FRP survive it will be a triumph and we will thrive; if none survive it will be a disaster and we will be out of work. The most likely scenario lies between the two extremes, and we must then be very careful to see which details worked, and which didn't. All earthquakes are different and we must be careful to learn from both our successes and failures.

5.3 Early development of Codes

It has long been argued that one of the problems holding back the development of FRPs has been the lack of codes of practice. I disagree. Codes should be written by those who have developed systems and made them work for the benefit of those who come later. They have a tendency to fossilize development; it is much harder to rationalize an improvement if it differs from the assumptions in an existing code. Inevitably, most codes make implicit assumptions that are not obvious. If codes are written too early, they prevent the development of completely novel uses of new materials.

5.4 Ourselves

The biggest threat to our industry comes from the inappropriate use of our materials, and if that happens we have only ourselves to blame. The commercial pressures to sell more product means that the temptation to use materials in the wrong way, or to ignore fundamental principles, means that the products can often be specified for the wrong reason or in the wrong application. This will be seriously damaging, because one failure, such as an externally bonded plate debonding under a lower than expected load in a real application, will set the industry back for a long time. This has already happened in the oil industry; the first attempts to use fibre ropes for mooring lines were badly specified; the rig broke loose and the industry decided that "fibre ropes don't work at sea". It took twenty years for better counsel to prevail. We all know of examples where structures are "wall-papered" with CFRP to strengthen them, even in re-entrant corners. There are masonry domes "reinforced" by carbon fibre stays attached at discrete points to the dome surface: What is the worst type of load that can be applied to a dome? Bad applications of FRP really do have to be stopped.

6 CONCLUSIONS

The fundamental problem for the use of FRP in concrete remains the fact that it cannot be used as a direct replacement for steel. We will never see a significant amount of concrete in which an original design using steel bars or tendons has simply had them replaced by the equivalent amount of FRP. For reasons outlined above, it will either be uneconomic, technically infeasible, or both. The future for our industry remains in the development of new combinations of materials, making use of the good properties of FRP and the good properties of concrete, to produce a durable, economic and useful material that will justify the very large amounts that have been spent on research in the last 30 years. This is the 9th FRPRCS conference, and I have been to them all. I am yet to see the developments that we need.