Technical Sheet 06/01

Durability of Fibre Reinforced Polymers in Construction

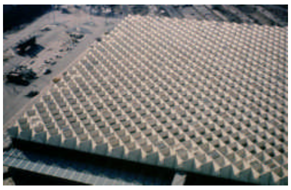
Executive Summary

Fibre reinforced polymers (FRPs) have been used successfully over the past 50 years in a wide range of applications in the marine and civil engineering sectors. These include pipes, tanks, slabs, walkways, bridge decks, gratings, column reinforcing wraps and reinforcing bars for concrete. In many of these applications FRPs are exposed to one or more environmental influences. FRPs can be formulated to meet the durability requirements of even the harshest environment, and all grades are durable inasmuch as they are water resistant, thermally stable and cannot rust. In almost all applications, the durability of an FRP may be enhanced further by imposing a conservative safety factor (2-4) on the design.

FRP components have good durability:

- FRP structures where appropriately designed perform exceptionally well
- several structures in the UK have given over 35 years of service, and are still meeting performance requirements
- where reported, failures are not due to the material, but due to a lack of understanding of material properties at the initial design stage or poor detailing in some prefabricated sections.

Figure1: Structures erected in the early 1970s are still meeting performance requirements


Covent Garden Flower Market roof


School classroom Preston


Mondial House London


Modular Stores Building Wollaston

Any deterioration caused by weathering is restricted to the surface of the FRP component. This does not generally affect the structural performance of the component or building, but may be significant for certain applications where aesthetics is important. Regular inspection and correct cleaning will ensure such effects are spotted at an early stage and treated to restore the FRP.

Improvements in resin and manufacturing technology over the last ten years will lead to improved durability of FRP components enabling design lives of 60-100 years to be realised.

Materials used

Thermosetting resins are most widely used in the construction industry, the most common being the unsaturated polyesters, epoxides and phenolics.

- Polyester resins are relatively inexpensive, easy to process, allow room temperature cure and have a good balance of mechanical properties and environmental/chemical resistance.
- Epoxy resins are used for the majority of high-performance FRP structures. They have excellent environmental and chemical resistance and superior resistance to hot-wet conditions. Compared to polyesters, they are more expensive and require more careful processing, however, they give better mechanical properties and better performance at high temperatures.
- Phenolic resins find specific application in construction due to their flame-retardant properties, low smoke generation, dimensional stability at high temperature and excellent resistance to environmental degradation.

A wide range of amorphous and crystalline materials can be used as the fibre. In the construction industry glass fibre is most widely used, mainly from economic considerations. There are 4 classes of glass fibre: E-glass, AR-glass, A-glass and high strength glass, but E-glass tends to dominates the reinforcement sector. Carbon fibre, of which there are 3 types (Type I, II, III), can be used separately or in conjunction with glass fibre as a hybrid to increase the stiffness of a structural member or the area within a structure. The stiffness obtained exceeds the value possible using only glass fibre. Ultra high modulus (UHM) carbon is used for steel reinforcement. Aramid fibres can be used instead of glass fibres to give increased stiffness to the component.

Performance Requirements

Service Life

Most construction materials have a finite life. Metals can corrode and can suffer from fatigue. Wood can rot, even preservative treated timber can rot eventually in a severe hazard. Concrete can crack or suffer from various chemical degradation processes. Natural rubber can perish as a result of ozone attack. All these materials have been around for long enough for us to know and make allowance for their weaknesses.

Whilst FRPs are no exception to deterioration, they can easily be designed to meet even the most challenging service environment. FRPs are being specified for applications in service environments ranging from the Middle East to Antarctica. In addition, there are continuous improvements in resin technology (new improved varieties of resin tend to be developed around every seven years). FRPs are now being specified for applications designed to last for 40 or even 60 years without loss of functional effectiveness. The accelerating trend towards using FRPs in bridges and buildings means a further extension of the required lifetime, possibly to almost a century.

When does an FRP product have to be replaced?

It is sometimes difficult to determine the end of life of a product. There are three key factors:

- the product must remain safe to use despite the stresses and the external weathering they experience over decades
- it must not become too expensive to maintain
- it must continue to meet performance requirements – structural or aesthetic.

The possibility of repair is an attractive feature of FRPs. Their useful life can often be extended because they are more easily repaired than some other materials. Additionally, they can be used to extend the life of structures originally made from another material, such as concrete or metals.

Performance in Service

Causes of deterioration

All construction materials are subject to deterioration in service due to exposure to certain environmental elements. Material deterioration may begin through one or more of the following influences:

- Mechanical stresses, including static loading, fatigue, repeated minor impact, erosion (including water erosion) and abrasion
- Chemicals (water, solvents, fuels, oils, acids, cleaning liquids, atmospheric oxygen, oxidising agents, caustic alkalis etc)
- Radiation (including sunlight)
- Heat, including high temperatures and large and rapid fluctuations in temperature
- Biological attack from bacteria, fungi, insects and marine borers.

Outdoor weathering can involve all five factors simultaneously. Materials can often survive individual threats such as ultraviolet light or a specific solvent, but they can still succumb to a combination of influences.

Biodegradation through micro-organisms, whilst a major factor for other materials (timber in particular), has very little importance in the degradation of most polymers, whether reinforced or not. Most FRPs can be buried safely underground for decades without rotting.

Fabrication of products

There are obvious links between fabrication procedures, inspection methods and subsequent product durability. Some methods of manufacturing FRPs produce better quality products than others. They introduce fewer defects, allow better control over fibre placement and orientation, enable a higher volume fraction of fibre reinforcement to be used, or lend themselves to better quality control.

Quality control is an important element in the optimisation of material durability. Achieving consistent output involves sound operator training, regular routine screening of raw materials, competent maintenance of processing machinery and good mould tool design. It also requires vigilant oversight of the actual processing operation, including atmospheric conditions such as humidity, temperature and dust content. Furthermore, it requires the use of up-to-date inspection methods on the final products.

Maintenance

Incorrect maintenance of an FRP structure can deleteriously affect the durability. The use of inappropriate cleaning agents based on strong alkali, solvents or abrasives can damage the surface. Conversely, a beneficial effect can be obtained by the occasional use of a mild cleaning agent and the application of a wax specially formulated for the upkeep of FRP products. Maintenance procedures are given in NGCC Technical sheet 04/02.

Property Retention as a Guide to Durability

After several decades in service the initial properties of a component will have changed, even in the absence of obvious mechanical damage. It is customary to cite the change in properties with time as a measure of the extent of deterioration, and '% retention' has become by implication a measure of durability. Not all properties change equally rapidly and the selection of significant properties requires careful consideration.

Where there are no visible signs of deterioration, any internal changes may be detected using advanced diagnostic equipment, such as thermography, acoustic emission equipment, ultrasonic instrumentation, an electron microscope or spectrometers for chemical analysis.

Effects of Weathering

Resins on their own vary a great deal in their ability to withstand outdoor use for long periods. Poor performance can sometimes be completely transformed by trace additives, so the solution becomes one of using the right grade of resin and appropriate additives.

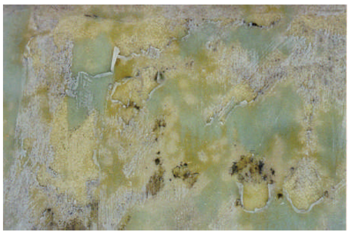
The effects of outdoor use on structural FRPs such as glass/polyester or carbon/epoxy laminates are confined to the surface and do not often involve a serious threat to their structural integrity. The effects are mainly cosmetic including:

- Fading and darkening
- Yellowing
- Blooming
- Loss of gloss and chalking

Figure 2 shows the deterioration that may be observed in extreme cases. These can be prevented by correct choice of resin and additives.

Figure 2: Changes induced by weathering

Crazing of surface



Deterioration of gel-coat

Un-even discolouration

Colour fading or darkening without loss of gloss can be due to the use of unstable pigments or pigment combinations which change colour after exposure. This can be overcome by the appropriate choice of pigment.

Yellowing is due usually to the darkening of the base gelcoat resin, especially in whites. This can be overcome by using a more UV-resistant resin and better UV additives, and by ensuring good cure of the resin.

Blooming is caused by migration of an incompatible pigment or additive to the surface of a gelcoat to give a mat, faded appearance. Certain organic pigments can be the cause of this. Bloom can be removed by polishing, but this is only a short term solution. Judicious choice of the pigment should overcome this problem.

Loss of gloss is normally brought about by erosion of the surface layer of the gelcoat due to chemical and/or physical damage. The colour of the gelcoat then appears to whiten, due to the diffused reflection of light from the matt surface. This is most serious in mouldings with strong bright colours where the phenomenon is most easily observed. On paler colours the effect is less noticeable. Indeed the whiteness of a white structure can even improve by this means because surface dirt is shed, leaving a fresh exposure of white pigment. This phenomenon is termed 'chalking'.

The erosion of gelcoat after many years service with no treatment or repair can bring about the eventual mechanical failure of a laminate by exposing the reinforcement underneath. It should be noted that the onset of loss of gloss or chalking does not presage the immediate disappearance of the gelcoat which normally lasts for many years longer.

Climate effects
The severity of the weathering effects depends on the climate to which a material is exposed. Climates can be classified into a number of types such as temperate, sub-tropical, desert, arctic and Mediterranean, as well as industrial, rural or marine. In addition, variations occur from season to season and from year to year. It is thus complicated to compare the weathering performance of one material with that of another and to predict accurately the performance in service of a new component.

Despite this, FRPs can be designed to meet specific climatic conditions, however severe. For example, they are finding widespread application in the Middle East.

Figure 3: Application in extreme climates

Sharjah Airport Dome, 1974

Arabian Towers Hotel Cladding, 1990

Prediction of durability
Predicting the weathering performance of building materials (including FRPs) can be carried out based on artificially accelerated laboratory weathering experiments and field trials. The latter take several years and relatively few organisations have been able to generate large data banks. However, there are now sufficient case histories of FRP products to give us performance data extending over three decades or more. Accelerated methods can be undertaken indoors or outdoors. Accelerated prediction techniques for FRPs are discussed in detail in NGCC technical sheet 04/03.

Controlling weathering performance with additives
UV Absorbers
UV absorbers are commonly used in the gelcoats on FRP components to absorb UV light and dissipate the absorbed energy. In the first few years of life in temperate climates, the use of a UV agent makes little difference to the weathering properties of a good quality pigmented gelcoat. However, experience shows that patchy yellowing of white gelcoats, which sometimes occurs in these climates, can be overcome by such means. It is thought that this type of discolouration is caused by areas of the gelcoat having a lower pigment content. UV absorbers help to overcome such yellowing of resin.

In the longer term or under conditions of high levels of radiation (such as subtropical climates) UV agents can be shown to improve gloss retention and colour stability. Traditional UV absorbers that have been used for many years are benzotriazole and hydroxybenzophenone derivatives. Other UV agents known as hindered amine light stabilisers (HALS) do not absorb UV radiation, but act by absorbing any free radicals that have been formed.

Fire Retardant Additives
The use of fire retardant additives in gelcoats has a detrimental effect on weathering properties. Thus it is good practice to achieve fire retardancy by using a highly fire retardant resin behind a non-fire retardant gelcoat.

Durability in Liquid Environments

All resins and organic reinforcing fibres (but not glass or carbon) absorb water to varying extents, usually at a very low level, and are water permeable. Water absorption into glass or carbon FRPs is slow and the interfacial adhesion is protected by silane treatments included in surface "sizings" applied during their production . Where absorption occurs, moisture migrates through the resin and eventually reaches the fibre-resin interfaces. It is often said that moisture migrates by 'wicking' along the interface by capillary action, starting from exposed fibre ends. However, hard evidence is usually absent, and a well bonded fibre is not so easily separated from the resin that it would allow migration at the interface of a long, continuous section of its length.

The effects of moisture, once absorbed, are complex. Changes in the appearance and properties of the FRP product may be slight or severe, chemical or physical, permanent or reversible. The more moisture absorbed, the more deterioration in properties is likely to be found and the less reversible are the changes on drying. Reductions in strength and modulus are observed. An initial increase in strength is possible, because of the relief in internal stresses, which is followed by a decline after further absorption.

The more susceptible resins (polyester, polyester urethanes, some epoxies) are attacked by boiling water fairly quickly, but will resist cold water for very long periods. Other resins, with different chemical structures, are unaffected at temperatures within their normal range of use. Thus it is important to specify the correct resin formulation for the particular application.

Thick laminates are much less affected than thin ones in a given period and this explains the durability of many early FRP structures. It has been calculated that an epoxy-based FRP with a typical diffusivity towards moisture of $10^{-13}m^2s^{-1}$ would require 13 months to reach saturation if left in a tropical climate at 35°C and 95% relative humidity (RH) if the thickness was 2mm, but a 90mm thick section would need 1342 years. During the approach to saturation, there is a through-the-thickness variation in moisture content and therefore in properties.

Despite these reported effects of moisture, careful selection of material and component design can overcome any potential problems. FRP components, being tailor-made parts, are designed to prevent moisture absorption. Cutting or drilling on site exposes fibre and resin which could affect the absorption properties of the component and is strongly discouraged. FRPs have been used in the marine industry for many decades with very few reports of moisture ingress problems.

Chemicals

A surprising number of FRP applications involve occasional or prolonged contact with chemicals other than water. Many FRP articles are routinely placed in contact with detergents, cleaning solvents, acids, alkalis, strong oxidising agents, bleach, cleaning and degreasing agents, fuels, hydraulic and brake fluids, de-icers, paint strippers (methylene chloride ones are known to be damaging), lubricants, etching chemicals, flue gases, or food and drink.

It must be stressed that the resistance of FRP to highly reactive chemicals is generally very good. This explains their widespread use in the chemical process equipment industry, where it is often difficult to find any other affordable, processable materials capable of withstanding the very harsh conditions. It is rare for FRP articles to be attacked as rapidly as some common metals when placed in contact with acids. A few chemicals that are handled in chemical factories, such as powerful oxidising agents, strong caustic alkalis, bromine and wet chlorine still pose severe problems for general purpose resins. Otherwise, the well-informed selection of materials, in consultation with the suppliers and after reference to the relevant data banks, means that problems with chemical attack can be avoided.

Effect of Temperature on Performance

Maximum temperatures for use of FRPs are governed by two main factors: the resin's glass transition temperature (Tg) and the temperature at which chemical decomposition starts to become significant. Decomposition temperatures are seldom actually reached in service life. FRPs are pre-eminently load-bearing materials, and it is their temperature-dependent mechanical properties, such as Tg, or the closely related heat distortion temperature, that usually determine the maximum use temperature. Strength, yield stress and modulus all decline with increasing temperature, reflecting the increasing mobility of the molecular structure. Unacceptable levels of loss of physical property will often occur well before the onset of thermal or thermo-oxidative degradation.

Most resins have only a limited ability to withstand high temperatures. High temperature resins are available with superior heat resistance.

The fibres themselves are generally thermally stable materials that give no anxiety to users of FRPs and can withstand a higher temperature than any of the current generation of commercial resins.

When considering FRPs for use in extreme temperatures it is necessary to consider the following factors:

- whether the heating is continuous or intermittent
- the maximum and minimum temperatures in a working cycle
- the heating and cooling rates
- other factors such as mechanical stress, or fluids
- its required lifetime, which may be a matter of decades.

Engineers and designers must be careful to ensure that the thermal properties of a particular material are completely understood before recommending its use for a specific application. Again, correct material selection will ensure the FRP performs as required.

Mechanical stress

Correct material selection and design will ensure the any FRP component or structure has the mechanical properties to meet performance requirements.

Fibre, matrix and interface roles

FRPs containing continuous fibres rely on the load being carried almost entirely by the fibres. The direct contributions of the matrix to the tensile or flexural strength and modulus of the material are trivial in comparison. Most reinforcing fibres have excellent durability towards stress in a wide range of conditions. Mechanical durability is maintained through choice of appropriate resin - this must continue to facilitate load transfer between fibres and must protect individual fibres from mechanical abrasion, as well as penetrating fluids. Surface weathering of the matrix could expose fibres to mechanical damage and a soft matrix is easily eroded or scratched.

Creep rate can be controlled through the use of 0° plies and utilisation of long fibre composites. For other fibre types, choice of resin is critical to control this property.

Minor impact damage

A common hazard for FRPs is minor impact damage resulting from scratching or collision with small objects. The resulting damage is often difficult to see with the naked eye, but it can include delamination, matrix cracking, fibre debonding and in severe cases, fibre fracture. Most impacts occur in practice at an oblique angle which tends to reduce the severity of normal incidence, no matter whether damage is measured by the damage area, indentation depth or residual strength. The fact that there is scope for on-site repair of impact damage in FRPs, even in remote areas, is an important favourable consideration in their durability.

Fatigue

Fatigue 'life' is usually measured as the number of cycles to failure for a given applied load. The degradation and failure of bridges, highways and service piping is nearly always associated with cyclic and dynamic loading. The loading may be mechanical (due to vehicle traffic for example), thermal (due to changes in temperature), or chemical (from seasonal road treatments, oxidation, water etc).

In FRP components with aligned or randomly distributed short fibres, cracks can initiate at flaws, such as pores or in resin-rich areas with local strain in-homogeneities caused by improper fibre alignment or at fibre ends. The local load transfer from the fibre into the matrix can lead to an overstressing of the matrix or a fibre/matrix debonding and then a crack propagation may occur.

In continuous-fibre FRPs the fatigue process is characterised by the initiation and multiplication, rather than propagation, of cracks. Crack initiation occurs early in fatigue life, and coincides with the first ply failure in the laminates, that is the first cracking of the weakest ply. While in metals, crack growth accelerates during fatigue, crack multiplication in FRPs decelerates, resulting in uncontrolled final rupture of the FRP.

Reasonable data have been produced for the fatigue of glass/vinylester, polyester and epoxy FRPs produced from low cost fabrication methods, allowing the longevity of these systems to be predicted with some degree of confidence. Research continues on a global basis to understand the fatigue behaviour of FRPs in order to enable prediction of life of structures that are designed for extended service conditions.

Joints

Joints are necessary in large FRP structures because of production and design considerations. These components are too large to be fabricated in one piece, so several parts have to be joined and stiffeners are necessary.

Joints are potential failure sites. This applies whether they are adhesively bonded or mechanically fastened, and whether they join two FRP sections, or one FRP component and one constructed from another material.

In the construction industry, joint failure in FRPs is likely to mean leakage of water into the building, rather than structural collapse. It is thus recommended that joints should be located well away from supplies of water. On roofs, they should be on ridges and not in gutters. Adequate seal pressure is necessary. Joints should be readily accessible for inspection and replacement.

Adhesively bonded joints

Adhesive joints in FRP structures are capable of achieving higher strength than mechanical ones and may be preferred for that reason. Their durability depends more on the flexibility and toughness of the resin used in the adhesive than on its strength.

Prediction of joint strength can be carried out by performing a stress-strain analysis and applying an appropriate failure criterion. Stresses in the adhesive bonds can be predicted using finite element analysis and closed form or continuum mechanics.

Mechanically fastened joints
Mechanically fastened joints have the advantage that they can be disconnected if desired. Bolts offer the greatest mechanical strength obtainable without adhesives, especially when the bolt is a good fit to the hole. Metal bolts must be protected against corrosion and the use of special materials such as stainless steel can be cost effective. The edges of drilled holes need to be coated if the joint is exposed to liquids that attack the fibres.

Conclusions

FRPs offer the ability to tailor-make components with the properties needed to meet performance requirements of a particular situation. Correct material selection and design means that FRPs can perform in the most demanding of service environments.

FRPs offer good durability, their performance enhanced by incorporation of additives and correct maintenance procedures.

FRP components have demonstrated service lives of over 35 years to date in construction applications in a variety of different environmental conditions. Advances in resin and additive technology mean that design lives of 60 – 100 years are possible.

Further reading

NGCC Technical Sheet 06/02: Maintenance and Repair of FRP Structures

NGCC Technical Sheet 06/03: Prediction of performance for FRP Structures

BRE Report 416: Long-term performance in service of FRP in construction

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