

DURABILITY ASPECTS OF FIBER REINFORCED COMPOSITES

Durability aspects of fibre reinforced composites

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Abstract

FRP have been used in many civil engineering applications, such as short and long span bridges, buildings, off-shore structures, retaining walls etc. FRP will certainly play a major roll in the construction, rehabilitation and repair of civil engineering structures in the 21st century. The high strength-to-weight ratio and non-corrosive characteristics of these materials could be utilised to build innovative structures that can not be built, using the current conventional materials. FRP could be used to build light, yet more durable and economical structures. Designers should be encouraged to utilise these materials based on its own unique characteristics rather than a replacement for current conventional materials. Eventhough fibre reinforced plastics (FRP) composites are being explored for many applications, including transport systems, offshore structures, marine structures, the durability issue of FRP composites has remained an open question with a composite structural designers.

Keywords: reinforced composites, fibres, resin, durability, failure, laminates

1 Introduction

The problems of building and housing are particularly acute in the developing world and the struggle to provide shelter to the teeming millions at affordable costs, has surfaced as the issue of highest importance the world over. The search for new and alternative building materials will have to be intensified, because, conventional materials are fast depleting. The tremendous variability in the geo-climatic conditions, the life style of the people, the affordability levels and the nature and quantum of available building materials, underline the urgent need for the identification of right materials, with their durability. Appropriate

technology packages, with respect to material characteristics, based on climate of the region and felt needs of the users, are also equally important.

There has been a rapid growth in the use of fibre reinforced plastics (FRP) materials in the civil engineering applications, during last few years. However, the full potential use of FRP technology has not been fully realised for civil and structural engineering applications. FRP is currently produced in the form of laminates, doors, windows, partition panels, structural sections, reinforcing bars, grids, and pre-stressing tendons. FRP materials should not be treated as a direct substitution for conventional materials. However, it should be utilised according to its own fundamental characteristics. The advantages of FRP should provide the designers, the opportunity to design structural systems, that could not be built, using conventional materials.

One of the major problems, that readily reduces the life of concrete structures, is the corrosion of steel reinforcement. This problem is more serious in the cold climate countries, where de-icing salts accelerate the deterioration. Since, FRP are non metallic materials, they have major advantages over steel. Use of these materials could significantly increase the life time of structures, minimising the maintenance requirements and consequently off-set the current high costs of FRP products. The wide spread deterioration of infra-structure due to age, environmental factors and steadily increasing high way traffic patterns, (load and frequency) has created a critical need for cost effective and durable materials and technologies, for use in rehabilitation and retrofit. Fibre-reinforced polymer composites present an attractive alternative, for use in the retrofit and new construction. The high specific strength and stiffness, light weight, corrosion resistance, and enhanced fatigue resistance, combined with capability, to easily mould complex shapes, makes the composite attractive, when compared to steel and concrete.

Along with other properties like workability, durability is a very important property, especially, in building materials and various components. It is the property of FRP in particular, by virtue of which, it is capable of resisting its disintegration and decay, which may be caused due to:

- i) use of unsound resin
- ii) use of less durable aggregate
- iii) entry of harmful gases through the pores and voids, present in FRP components and structures.
- iv) freezing and thawing of water, sucked through the cracks or crevices by capillary action.
- v) expansions and contractions resulting from temperature changes and alternative
- vi) drying and wetting.

Fibre reinforced polymer composites are being explored for many applications, including transportation systems, off shore structures, marine structures, and infrastructure. However, durability issue of fibre reinforced polymer composites, has remained an open question to the composite structural designers. When a specific application is contemplated, it is essential for the design experts to know, not only the answer to the questions regarding strength

and stiffness; but also the question of the life of the material under the conditions anticipated. Many factors play roles in reducing the life of the component. In most cases, it is difficult to define or estimate the life of the component. Characteristics of most of the materials, change by interaction with their surroundings, over a period of time. Oxidation of steel, leads to corrosion and it is a well known fact that, water accelerates the process. Concrete degrades in harsh environment. Therefore it is advisable, that before using FRP composites, we must know the possible changes to happen to FRP composites, under the given service conditions. A knowledge of these changes before hand, can allow us to accommodate them in the design, and to accommodate these changes in the design, the data on rate of change and effect of these changes on the behaviour, must be very well obtained and evaluated. Unfortunately, reliable data on systematic basis on durability, is not easily accessible.

In consideration of life cycle (durability), it is important to define, the limit of life. Some materials may not fail or isolate under certain service condition; but can continue to deform or deflect beyond an acceptable limit. Thus effective life ceases, when pre-determined de-formation or deflection limit is exceeded.

2 Mechanism of degradation

2.1 General

The mechanism of degradation is an important factor, to be considered in the discussion of durability. The mechanism which controls the durability of composites, is well known. This includes:

- i) chemical or physical changes or micro cracks of polymer matrix.
- ii) loss of adhesion or debonding at the fibre/matrix interface.
- iii) reduction of fibre strength and modulus.

All above mentioned processes contribute to the growth of flaws or cracks when failure occurs. For unidirectional composites, the compressive failure mechanisms include:

- i) micro buckling of fibres
- ii) kink banding
- iii) matrix yielding and
- iv) shear through fibre and matrix .

The tensile failure modes are:

- i) brittle failure of the matrix
- ii) matrix brittle failure with fibre pull out
- iii) interface matrix shear failure and constituent debonding.

In case of multi directionally reinforced composites, the initial failure takes the form of cracking of constituent plies, i.e. cracks appear parallel to fibre, long

before the final failure of the laminates. The initial failure is very often referred as first ply failure.

2.2 Environment

Environment plays a very crucial role in changing the properties of polymer matrix composites. The environment, both ambient and loading, can affect the durability of the composites. In ambient environment, both matrix and fibres may be affected by moisture, temperature, ultraviolet radiation, ozone and the presence of degrading chemicals like salts or alkalies. Repeated exposure to very low and high temperatures (freeze thaw cycling), too, may undergo some changes. There are various factors, which affect the durability of FRP composites which include:

- i) Aging of polymer matrix.
- ii) influence of moisture.
- iii) low temperature effects.
- iv) freeze thaw effects.
- v) influence of ultra violet rays.
- vi) creep behaviour.
- vii) fatigue behaviour.
- viii) fire hazards.

2.2.1 Aging of polymer matrix

Durability of composites, must be considered in the context of the role of polymer matrix, as it is most susceptible to changes, in response to environment. The role of matrix in the composites, is to transfer stresses between fibre, to provide a barrier against an adverse environment and to protect the surface of the fibres from mechanical abrasion. Matrix has a major influence on the inter-laminar and in-plane shear load transfer. Therefore, if the matrix itself changes it's characteristics with time, the consequences need to be carefully studied. The environment, temperature and the humidity control, this change. This process is known as aging. The aging occurs, when polymer is cooled below it's glass transition temperature (T_g), the material does not achieve instantaneous thermodynamic equilibrium. As a result of physical aging, some polymers can become stiffer and brittle, influencing the matrix dominating properties, namely, the shear and transverse response. The effects on the fibre dominated properties, will be minimum. Thus in designing with composites, it is necessary to consider the fibre orientations relative to major loading axes.

2.2.2 Influence of moisture

Many polymer composites, when exposed to humid air or water environments, absorb moisture by diffusion and instantaneous surface absorption. In desert conditions, the converse would apply, as relative humidity is very low, moisture being given off. The rate of water uptake (release) and its equilibrium concentration, as well as it's influence on properties, could therefore, be of great concern.

2.2.3 Influence on matrix

Absorption of water by resin, may change the resin properties and glass transition temperature, through hydrogen bonding, of water molecules. The stiffness of the composite may drastically degrade, if the glass transition temperature is lower than the moisture absorption temperature. Moisture absorption is beneficial to composites. Absorption of water, causes swelling of the resin. The swelling of the resin matrix in composites, around the fibre, reduces the residual compressive strength at fibre/matrix interface, caused by the curing shrinkage. This results, in release of mechanical inter-locking stresses between, the fibre and the matrix. Voids present at the fibre/matrix interfaces or in the layer of the composites, can cause plastification of the resin. Water, entrapped in the voids, may cause blisters.

A systematic study has been carried out on kinetics of absorption as a consequence of prolonged immersion in water (Pritchard. and Speake 1987). The data for the pure resin and laminates are shown in Figure 1 and 2.

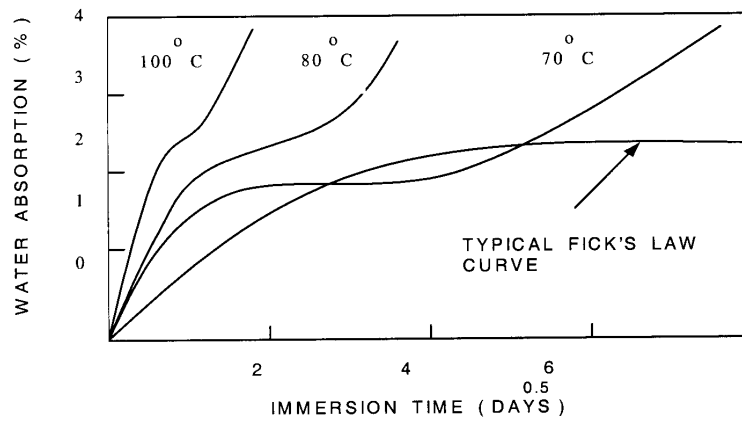


Fig. 1: Water absorption kinetics of pure iso-polyster resin

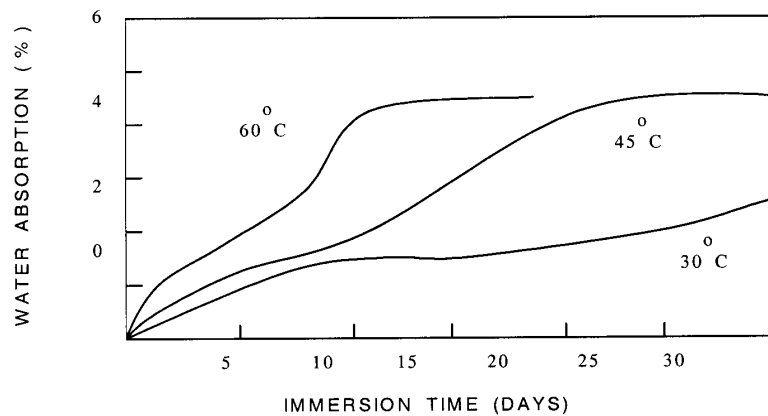


Fig. 2: Water absorption kinetics of glass reinforced iso-polyster resin

The water absorption uptake, of both pure resin and laminate, depends upon temperature. The higher the temperature, quicker is the plateau value. The results have been analysed in terms of Fick's Law and the activation energies for the water uptake and desorption of various materials, in the following table.

Table.1: Water uptake and water desorption of resins

Resin	Water uptake KJ/mole	Water desorption KJ/mole
Iso-polyester resin	55.4	187.6
UD glass/polyester	73.4	175.8
Polyester laminates	45 to 51	--
Epoxy resin	55.6	--
Glass/epoxy laminate	44 to 48	--

2.2.4 Influence of fibres

It is believed that, glass fibres can be damaged by prolonged exposure to water. The glass is silica, in which oxides of alkaline metals are dispersed. Alkaline metallic oxides, are hygroscopic and hydrolyzable. E & S glass contain only small amounts of alkaline metal oxides and hence are resistant to damage, by water. Presence of water, at the glass fibre interface, lowers its surface energy, which promotes the crack growth.

Moisture does not have any known degrading effects on carbon fibres. Aramid fibres can absorb considerable quantities of water, resulting in swelling.

Most of the fibres undergo sizing that ensures good bonding with matrix and protect them water absorption.

2.2.5 General behaviour

Water saturated composites, usually display increased ductility, due to softening of the matrix. This is advantageous in polymer composites and should not be ignored. These degradation changes are mostly reversible

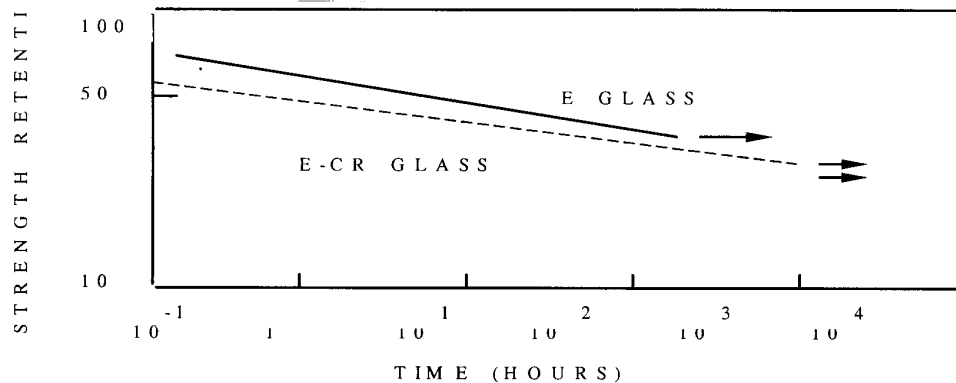
2.2.6 Hygro thermal effects

Temperature plays a crucial role in the water absorption mechanism of composites. Temperature influences the distribution of water, the quantity and rate at which, it is absorbed. Damages, induced by the immersion in boiling water for few hours, produce debonding and cracking of same degree of damage as at 50°C over a period of 200 days.

2.2.7 Alkaline environment

It is essential to use, in this environment, alkali resistant glass, as alkaline solution reacts with glass fibres to form expansive silica-gels. This precaution is specially important for application of glass fibre reinforced composite material, as reinforcing bars in concrete. GRP bars are being increasingly considered to replace steel reinforcing bars, which are corroded by environment or de-icing road salt. During hydration period of concrete, highly alkaline (pH > 12) pore water solution is created. This highly alkaline solution can affect the glass fibre and reduce the durability of the bars. High alkali resistant glass (C-glass) can improve the durability of such cementitious application. Generally glass / polyester has

resistance to most chemicals, except strong bases and strong oxidants (Mayer1985).



2.3 Low temperature effect

Extreme changes in temperature of composite materials result in several important effects. The coefficient of thermal expansion (CTE) of the matrix is usually greater in order of magnitude, than that of fibres. Decrease in temperature, will cause matrix to shrink. Contraction of the matrix is resisted by relatively stiff fibres, through fibre/matrix interface bonding. Energy absorption, before failure at low temperature, is higher, than energy absorption at room temperature.

2.4 Freeze-thaw effects

Unless a composite contains, a significant percentage of inter connected voids, which are filled with water, the freeze thaw effect on strength within a temperature range (+30°C to -20°C) is insignificant. Commercially available GRP composites, contain about 0.4% voids, which do not allow any frozen moisture to cause any serious damage. Under extreme low temperature conditions, the stresses can result in the formation of a micro cracks in the resin fibre inter-face. Chances of micro crack growth, under normal range of service temperature (+30°C to -20°C) are marginal.

2.5 Influence of ultra violet rays

The effect of ultraviolet rays on polymer composites is wellknown. Long time exposure to sunlight hardens the matrix and is discoloured. The problem is generally overcome by incorporation of u-v resistant additives in the matrix. In thicker composites, the effect is minimum and structural properties are not much affected, as it is only a superficial phenomenon.

2.6 Creep behaviour

Creep is the increase in strain with time, at constant stress level. Creep occur, because of combination of elastic deformation and a viscous flow. In composites, the creep strain depends on the stress level and temperature. It is a function of both distribution of stress between the fibre and matrix. Highly cross linked thermosetting matrix, show lower creep rates than thermoplastic polymer composites.

Glass and aramid fibres over a long period of time exhibit failure by stress rupture. Carbon fibres are less prone to stress rupture.

2.7 Fatigue behaviour

Fatigue properties of structural materials, are their response to cyclic loading. The composites are generally well known for their excellent fatigue behaviour. There are many aspects to consider, which include type of loading, load duration, load introduction, loading rate, temperature and finally, environment.

The fatigue is also influenced by the fibre alignment. Combination of fabrics, which contain a mixture of fibre alignment, are often chosen to ensure, that, there are fibres in all directions with more fibres in a direction with higher loading.

The fatigue performance of E & S glass fibre reinforced composite, is poorer than that of carbon-aramid fibre composite.

2.8 Fire hazards

FRP composites used for any structural construction must comply with local construction code requirements, including fire resistive and other life safety specifications. At present, codes for structural composites in building are not extensive. Designers have to deal with fire hazard characteristics of the material. The materials are tested by the following test methods.

Uniform Building code (U.B.C.) standard 52-3 (ASTM - D 1929) for self ignition. Smoke density - (ASTM - E 84)

Specimen will be approved in accordance with UBC standard 524 (ASTM-E 84).

Finally the designer needs to decide, the necessary level of fire resistance and methods to attain and measure of fire safety. Fire tests, like non-combustibility, ignitability, flame spread, rate of heat release, smoke and toxic gas emission, flash over etc. are of prime importance to consider the durability factor.

3 Durability of materials under random exposure conditions

All materials deteriorate, when exposed to aggressive environments. This affects, significantly the strength and durability of structural materials and components. The damage to materials due to an aggressive environment can be in the form of cracking, accumulated permanent strain, or even decolouring. Any damage influences the life and functionality. It is of significant practical interest to assess analytically to cumulative damage to a material, when it is exposed to random environmental conditions. While considering durability issue, it is better to know the damage phenomenon. It is dependent on a number of factors. Experimental studies indicate, that the damage rate can be approximated by an equation.

$$\frac{dD}{dt} = AC^mD^n \text{ where,}$$

t = time of damage,

C= Environmental factor that affects damage

A, m and n are constants.

The environmental factors that affect damage are temperature humidity and concentrations of a chemical in the environment. In real life situations, the variation of C with time is not a definite quantity. But it is a random process.

Durability of Glass Composites, under alkaline environment is really harsh. FRP bars with urethane modified bisphenol vinylester if used, show lowest vulnerability. Bars with isocyanurate vinyl-ester resins (IVE) exhibit, superior strength and stiffness in unconditioned salt and freeze thaw environment.

4 Repair of structures

A number column, slabs and girders have been repaired and strengthened with CFRP products, due to earthquake damage and structural needs to increase their capacity. Many products are currently available for this type of retrofitting. The products are often unidirectional and produced in the form of fibre tapes, fibre winding strands and fabrics. The materials are effective for both flexural and shear strengthening of structures.

A retrofit process of a structure, such as a chimney, begins with preparation of concrete surface, trowelling the surface with epoxy, followed by placement of the auto-adhesive tapes in the longitudinal direction and confining of the outer surface in the circumferential direction, by winding small diameter carbon cables, for which automatic winding machine is available.

4.1 Repair of bridges

Many highway bridges deteriorated due to continuous increase of the truck capacity, legally permitted on highways. The repair of prestressed concrete bridge can also be carried out by CFRP.

5 Conclusion

Confidence of construction industry for long term use of FRP composites has not developed as yet. It is very important that a pre-design study for the long time durability of FRP structures, should be carried out. In order to assess, the durability of FRP structures, it is necessary to have a fair idea of the various chemical constituents present in the environment, their pH, etc. Considering the importance of the structure and the likelihood of salinity, alkalinity, and acidity in the air, some precautionary measures need to be well studied and implemented.

From available literature, general ideas about these materials, their behaviour over a long period of time, it is felt that acceptance of FRP material in

primary load bearing structure may not be immediately accepted by the construction engineers.

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