A REVIEW OF FIBER REINFORCED POLYMER PROPERTIES AND ITS UTILISATION IN REPAIRING WORKS FOR THE CIVIL STRUCTURES

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ABSTRACT*: The application of fibre reinforced polymer (FRP) in concrete structures has increased quickly in the last decades due to their excellent corrosion resistance, high tensile strength, ease of installation and good non-magnetization properties especially for structures exposed to aggressive environment. However their low module of elasticity cause excessive deflection and more cracks in the structural elements but the replacement of conventional steel reinforcement with FRP bars has been investigated to overcome the corrosion problem. The study discusses about FRP properties (engineering properties) in detail in order to document an accessible and technically paper for students and engineers to comprehend the behavior of FRP and its suitable applications in civil engineering structures.*

Key words: FRP rebar, steel reinforcement, corrosion, durability, tensile strength

1. INTRODUCTION

The population of the modern developed world depends on a complex and extensive system of infrastructure for maintaining economic prosperity and quality of life. The existing public infrastructure of Canada, the United States, Europe, and other countries has suffered from decades of neglect and overuse, leading to the accelerated deterioration of bridges, buildings, and municipal and transportation systems, and resulting in a situation that, if left unchecked, may lead to a global infrastructure crisis. Many of our infrastructures are unsatisfactory in some respect, and public funds are not generally available for the required replacement of existing structures or construction of new ones.

One of the primary factors which has led to the current unsatisfactory state of our infrastructure is corrosion of reinforcing steel inside concrete (Fig. 1.1), which causes the reinforcement to expand, and results in delamination or spalling of concrete, loss of tensile reinforcement, or in some cases failure. Because infrastructure owners can no longer afford to upgrade and replace existing structures using the same materials and methodologies as have been used in the past, they are looking to newer technologies, such as non-corroding FRP reinforcement, that will increase the service lives of concrete structures and reduce maintenance costs.

Fig. 1.1 Severely corroded reinforcing steel in this bridge column has resulted in spalling of the concrete cover and exposure of the steel reinforcement. (Ranger and Willams, 2011)[1]

FRPs have, in the last ten to fifteen years, emerged as a promising alternative material for reinforcement of concrete structures. FRP materials are non-corroding and non-magnetic, and can thus be used to eliminate the corrosion problem often encountered with conventional reinforcing steel. In addition, FRPs are extremely light, versatile, and demonstrate extremely high tensile strength, making them ideal materials for reinforcement of concrete.

2. FRP PROPERTIES

Unidirectional FRP materials used in concrete reinforcing applications are linear elastic up to failure, and they do not exhibit the yielding behaviour that is typically displayed by conventional reinforcing steel. This is shown in Fig. 2.1, which demonstrates the significant differences in the tensile behaviour of FRPs as compared with steel. FRP materials generally have much higher strengths than the yield strength of steel, although they do not exhibit yield, and have strains at failure that are much less. The differences in behaviour between FRPs and steel have important consequences for the design of FRP-reinforced concrete members [1].

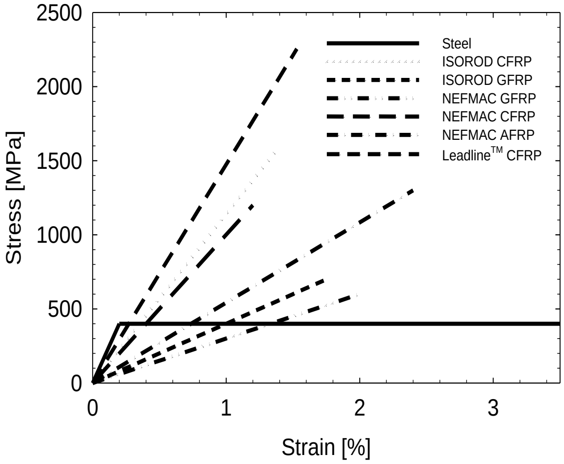

Fig. 2.1 Comparison of stress-strain relationships for various reinforcing materials

The specific properties of FRP materials vary a great deal from product to product, and depend on the fibre and matrix type, the fibre volume content, and the orientation of the fibres within the matrix, among other factors. It is important in the design of FRP-reinforced concrete members to specify which FRP material is to be used and what minimum mechanical properties are required.

2.1. Corrosion resistance

The resistance of thermosetting polymers to chemical attack depends upon its chemical composition and the bonding in its monomer. These polymers can degrade by several mechanisms, but degradation may be divided into two main categories, (i) physical and (ii) chemical.

Physical corrosion is the interaction of thermosetting polymer with its environment causing an alteration in its properties but no chemical reaction occurs. [2]

Chemical corrosion is when. the bonds in the polymer are broken by a chemical reaction with the environment in which the polymer is situated. During this process the polymer may become embrittled, softened, charred, delaminated, discoloured or blistered; these are usually non-reversible reactions.

A correct curing procedure of the polymer is important to reduce these degrading effects. Thermosetting polymers have a poor resistance to concentrate sulphuric and nitric acids. Furthermore, the attack of aqueous solutions occurs through hydrolysis in which moisture degrades the bonds of the polymer molecules. Polymers with high crystalline/density or a high degree of cross-linking will generally have low permeability, thus gasses and other small particles will not readily permeate through it.

Hackman and Hollaway [3] have shown that the ingress of moisture will permeate through polymers over time particularly if the polymer (and therefore the composite) is permanently immersed in water or salt solution or is exposed to de-icing salt solutions.

There are two-ways of measuring durability of polymers:

1) Long-term testing in the natural environment.

2) Accelerated test procedures.

Detailed discussion about the above method can be found in literature[1-2].

FRP materials, originally developed for use in the automotive and aerospace sectors, have been considered for use as reinforcement of concrete structures since the 1950s. However, it is really only in the last 15 years or so that FRPs have begun to see widespread use in large civil engineering projects, likely due to drastic reductions in FRP material and manufacturing costs, which have made FRPs competitive on an economic basis [4]

2.2. Coefficient of Thermal Expansion

The thermal properties of FRP reinforcing products are substantially different than those of conventional reinforcing steel and concrete, and can also vary a great deal in the longitudinal and transverse directions (Table 2.1), Hollaway, 2010) [2]. The characteristics are highly variable among different FRP products, and it is difficult to make generalizations regarding thermal expansion or other properties. The thermal properties of any FRP reinforcing material should be thoroughly investigated before it is used as reinforcement for concrete, since differential thermal expansion of FRPs inside concrete has the potential to cause cracking and spalling of the concrete cover [5].

2.3. Fire resistance

The polymer component of the composite used in the civil engineering industry is an organic material and is composed of carbon, hydrogen and nitrogen atoms; these materials are flammable to varying degrees. Consequently, a major concern for the construction engineer using polymers is the problem associated with fire. Most building structures must satisfy the requirements of building codes relating to the behaviour of structures in a fire. A measure of fire ratings for buildings refers to the time available in a fire before the structure collapses [6]. However, the major health hazard derived from polymer and composites in a fire accident is generated from the toxic combustion products produced during burning of materials. The degree of toxicity generated depends on the phase of burning of the fire including: oxidative pre-ignition, flaming combustion or fully developed combustion and ventilation controlled fires. Smoke toxicity plays an important role during fire accidents in buildings, where the majority of people die from smoke inhalation [2].

The basic approaches to reduce the fire hazards of polymers are:

(a) To extinguish the fire, to control the fire, or to provide exposure protection for structures on site, by sprinkler system and foam system.

Table 2.1 Typical Coefficients of Thermal Expansion for FRP Reinforcing Bars [×10-6/°C] (Hollaway, 2010)[2]

Direction	Material			
	Steel	GFRP	CFRP	AFRP
Longitudinal	11.7	6 to 10	-1 to 0	-6 to –2
Transverse	11.7	21 to 23	22 to 23	60 to 80

(b) To introduce additives into resin formulations, by incorporating halogens into resins formulations (e.g. fluorine, chlorine, bromine and iodine family of chemicals), combining synergists in the resin (e.g. het acid resin), and adding epoxy-layered silicate nano-composites at the time of formulating the resin. The process is complicated and at present is expensive for the civil engineering industry [3] .

(c) To apply a passive fire protection system to treat the surface of the manufactured composite by using intumescent coating technology. These coatings incorporate an organic material which will char and evolve gases at a designed temperature so as to foam the developing char [6].

2.4. Ultraviolet light (UV)

The ultraviolet light from the radiation of the sun is strong enough to cleave the covalent bonds in organic polymers, causing yellowing and embrittlement. All polymers are susceptible by varying degrees to the degradation by UV light. For a high degree of UV resistance, UV stabilisers are incorporated into the polymer during manufacture. Designers should seek advice from the manufacturer of the specific materials regarding their UV resistance to ascertain whether the UV stability is an important performance parameter [2].

2.5. High-strengths

Stiffness drives the design of FRP decks, they have high safety factors; decks also have high ductility. Lower life-cycle costs savings have been shown to more than offset the relatively high initial cost of the FRP materials compared to conventional materials; the service life of the FRP deck can be about three times greater than concrete decks [5]. However, few public agencies select materials based on projected life-cycle costs, most materials are chosen on the experience and judgement of the engineer, agency preferences and industry standard practice, generally with a strong bias towards minimising initial construction costs. The high-strength to low-weight ratio enables the bridge deck to carry the currently designed traffic loads with little or no upgrading of the superstructure. The dead load of the bridge deck is about 20% of the weight of an equivalent size of a RC deck and can be erected within 2 days. FRP composite bridge decks have been used in the United States since the mid-1990; the span of these bridges is generally about 10–12 m. The bridge market represents a major and largely untapped potential market for light-weight, corrosion resistant FRP composite materials. Light weight FRP bridge decks weigh about 10–20% of the structurally equivalent of a reinforced concrete deck. Consequently, using FRP deck to replace a concrete deck reduces the dead load significantly a lighter dead load can translate into savings throughout the structure and the foundations are reduced for new structures.[4]

2.6. Durability

Karbhari et al. (2003) noted that although the term ‘durability’ is widely used, its meaning and implications are often ambiguous [7]. Durability of a material or structure as its ability to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects or foreign objects damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions [8]. The durability of a polymer is a function of the aggressive environments into which the polymer is placed. Potential durability versus traditional steel reinforcement is one of the chief benefits of FRP Rebars. However, being a relatively new material for use as a concrete reinforcement, decades of performance data are not available. Fortunately, research from the institutes in all around the world, involved extracting FRP bars from several bridges and structures that have been in service from between 5 to 8 years reveals no degradation of the GFRP bars. This performance matches that of GFRP dowel bars that had been extracted from service in Ohio after 20 years.There are many different polymers that are available to the civil engineer and some of these have been modified by chemists over the years to improve a particular physical and in-service property. In addition, additives are on occasions incorporated into polymers at the time of manufacture to enhance particular properties. Each time these polymers are changed/modified the durability will be affected.

All glass fibres are very susceptible to alkaline environments, which is primarily due to the presence of silica in the glass fibres. These conclusions have been made when glass fibres (and therefore GFRP composites) are immersed into concentrated alkaline solutions. however, attack is minimal under civil engineering normal environments [8]. There are, nevertheless, glass fibres on the market that are more resistant to this environment and are used to increase the durability of composites. Advantex, and ARcoteXTM are glass fibres which increase the durability of GFRP composites; the former is manufactured by Ownes Corning, and the latter by Saint- Gobain Vetrotex. Carbon fibres do not absorb liquids and are subsequently resistant to all forms of alkali or solvents ingress, Aramid fibres have been reported to suffer some reduction in tensile strength when exposed to an alkaline environment [9-10].

2.7. Bond Properties

The properties of the bond between FRP reinforcing bars and concrete depend on many factors, including the surface treatment applied to the FRP reinforcing bar during manufacturing, the mechanical properties of the FRP, and the environmental conditions to which the bar is subjected during its lifetime. Again, generalizations are difficult to make, although the bond between currently available FRP reinforcing materials and concrete appears equivalent (or superior in some cases) to that between steel reinforcement and concrete. The bond of FRP bars to concrete does not depend on the concrete strength, as it does for steel reinforcement. This occurs because FRP-concrete bond failure is initiated by shearing off at the surface of the FRP bar whereas steel-concrete bond failure is a result of crushing of the concrete around the bar deformations Refer to the ISIS Design Manual No. 3 and (ACI 440.1-06, 2002) for further details and references on this topic.[8,11]

2.8. Creep

The creep characteristics of glass, aramid and carbon fibres are very small and are not generally considered in the design of polymer composite components for civil engineering [4]. When subjected to a constant load, all structural materials, including steel, may fail suddenly after a period of time, a phenomenon known as creep rupture [12]. Creep tests conducted in ermany by Bundelmann & Rostasy in 1993,[13] indicate that if sustained stresses are limited to less than 60% of short term strength, creep rupture does not occur in GFRP rods. For this reason, GFRP rebars are not suitable for use as prestressing tendons. In addition, other environmental factors such as moisture can affect creep rupture performance. Based on proposed ACI 440 design guidelines, it is recommended that the sustained tensile stress not exceed 20% of minimum ultimate tensile stress [11].

2.9. Cracking

In steel-reinforced concrete members, it is necessary to control crack widths both for aesthetic reasons and to limit corrosion of reinforcing steel. As well, strict crack control is required for structures that are designed to be watertight [7]. For FRP-reinforced members, the effect of cracking on corrosion is not a concern (FRP bars have excellent corrosion resistance), and so cracking must be limited at service load levels primarily for aesthetic reasons or to provide watertight conditions.Crack widths in reinforced concrete are a function of several factors, including the level of tensile stress in the flexural reinforcement. Thus, crack widths may be reduced by limiting the stress in the reinforcement. This has the parallel benefit of controlling service load stresses in the reinforcement to prevent creep-rupture. Control of cracking in FRP-reinforced concrete members can be approached in several different ways. A conservative approach described in the ISIS Design Manual No. 3. Is to limit the maximum strain in tensile FRP reinforcement at service to 0.2%, thus $\varepsilon_{frps} \leq 0.002$. The strain in the FRP at service load levels can be determined using the concept of transformed sections in either cracked or uncracked conditions.

Crack control may also be provided by calculating crack width at service load levels for an FRP-reinforced concrete member, and ensuring that the estimated crack width is less than permissible limits. For example, the limiting crack width for FRP-reinforced members is recommended by the Canadian Highway Bridge Design Code (CSA S6-06) to be 0.7 mm, except for members subjected to aggressive environments where 0.5 mm is recommended [1,14].

2.10. Deflection

Since the modulus of elasticity of FRP reinforcement may be substantially lower than that of steel reinforcement, FRP-reinforced members typically display significantly larger deflection than equivalent steel-reinforced members (same member shape/size and loading). This means that the minimum thickness (overall member depth) requirements used in CSA A23.3-04 or CSA S6-06 for steel-reinforced concrete are unconservative, and are thus not directly applicable to members reinforced with FRPs.[14]

2.11. Effective Moment of Inertia

If a member remains uncracked under service loads, then deflection requirements can be checked using the concept of transformed gross sections. However, if the member is cracked under service load, the effective moment of inertia should be calculated (for a rectangular section) using the following equation, which was empirically derived from test data on FRP-reinforced concrete members:[7]

$$I_e = \frac{I_t I_{cr}}{I_{cr} + \left(1 - 0.5\left(\frac{M_{cr}}{M_a}\right)^2\right)\left(I_t - I_{cr}\right)}$$

Where: I_{cr} is the moment of inertia of the cracked section transformed to concrete with concrete in tension ignored, calculated using the Eq. below {mm^4}

I_t is the moment of inertia of a non-cracked section transformed to concrete {mm^4}

M_{cr} is the cracking moment {N·mm}

M_a is the maximum moment in a member at the load stage at which deflection is being calculated {N·mm}

$$I_{cr} = \frac{b(kd)^3}{3} + n_{frp} A_{frp} d(1-k)^2$$

Where: b is the width of the compression zone {mm}

d is the effective depth of the section {mm}

n_{frp} is the modular ratio E_{frp}/E_c

2.12. Permeability

Within a FRP composite, the polymer matrix offers the fibre some protection from moisture attack. However, it is relatively inefficient especially at normal fibre volume fractions of 60–65% where the average distance between the fibres is of the order of 2 lm or less. Methods to improve the permeability of FRP composites are:

1) To apply a thin (few mm) polymer coating (gel-coat) to the outer surface of GFRP structures as a moisture barrier. However, this layer does not offer sufficient protection against moisture intrusion.

2) The successful use of GFRP composites in wet environments has been largely due to the development of coupling agents that are applied directly onto the fibre at the time of manufacture. As with the protection of polymers against moisture ingress, silanes (organofunctional trialkoxysilanes) or organotitanates are two agents which have been used.

Moisture will diffuse into all organic polymers leading to changes in their mechanical, chemical and thermophysical characteristics. A successful method to decrease the diffusion for civil engineering polymers is to apply an additive to the matrix polymer at the time of manufacture. Silanes (organofunctional trialkoxysilanes) or organotitanates are two agents which have been used as a barrier against moisture ingress [15].

Furthermore, epoxy-layered silicate nanocomposites introduced into the polymer at the time of manufacture has the potential to lower its permeability, thus improving its barrier properties and its mechanical strengths [3].

2.13. Handling and Placement

When necessary, cutting of GFRP rebars should be done with masonry or diamond blade, grinder or fine blade saw. A dust mask is suggested when cutting the bars. It is recommended that work gloves be worn when handling and placing GFRP rebars Sealing of cut ends is not necessary since any possible wicking will not ingress more than a small amount into the end of a rod. GFRP rebar has a very low specific gravity and will tend to "float" in concrete during vibration. [4]

2.14. Constructability

The following are additional considerations which must be accounted for when designing with FRP reinforcement:

- All FRP materials should be protected against UV radiation.

- Storage and handling requirements for FRPs may vary significantly depending on the specific product being used.
- Carbon FRPs should not come into contact with reinforcing steel in a structure due to the possible risk of galvanic corrosion. Glass FRP bars may be placed in contact with steel bars,
- FRP reinforcement is light and must be tied, with plastic ties, to formwork to prevent it from floating during concrete placing and vibrating operations.
- Care must be taken when vibrating concrete to ensure that the FRP reinforcement is not damaged (plastic protected vibrators should be used).

3. DESIGN CONSIDERATIONS

A direct substitution between FRP and steel rebar is not possible due to various differences in the mechanical properties of the two materials. In traditional steel reinforced concrete design, a maximum amount of steel reinforcing has been specified so that the steel is the weak link in a structure. When weakened, the steel rebars stretch or yield and a give a warning of pending failure of the concrete member. When using FRP Rebars, ACI committee 440's design guidelines [11] recommend a minimum amount of FRP rebar rather than a maximum. If a member fails, the concrete will be the weak link and will crush in compression. The crushing concrete will serve as the warning of failure and there will still be ample reserve tensile capacity in the FRP reinforcing. Another major difference is that serviceability will be more of a design limitation in GFRP reinforced members than in steel reinforced members. Due to its lower modulus of elasticity, deflection and crack width will affect the design. Deflection and crack width serviceability requirements will provide additional warning of failure prior to compression failure of concrete. In many instances, deflection and crack width will control design.

4. FIELD APPLICATIONS

4.1. Taylor Bridge

A significant research milestone was achieved on October 8, 1998 when Manitoba's Department of Highways and Transportation opened the Taylor Bridge in Headingley, Manitoba (Fig. 4.1). The two-lane, 165.1-metre-long structure has four out of 40 precast concrete girders reinforced with carbon FRP stirrups. These girders are also prestressed with carbon FRP cables and bars. Glass FRP reinforcement has been used in portions of the barrier walls. As a demonstration project, it was vital that the materials be tested under the same conditions as conventional steel reinforcement. Thus only a portion of the bridge was designed using FRPs. [16]

Two types of carbon FRP reinforcements were used in the Taylor Bridge. Carbon fibre composite cables produced by Tokyo Rope, Japan, were used to pretension two girders, while the other two girders were pretensioned using Leadline bars produced by Mitsubishi Chemical Corporation, Japan.

Two of the four FRP-reinforced girders were reinforced for shear using carbon FRP stirrups and leadline bars in a rectangular cross section. The other two beams were reinforced for shear using epoxy coated steel reinforcement. The deck slab was reinforced by Leadline bars similar to those used for prestressing. Fig. 4.1 shows the deck reinforcement during concrete placement. Glass FRP reinforcement produced by Marshall Industries Composites Inc. was used to reinforce a portion of the barrier wall. Double-headed stainless steel tension bars were used for the connection between the barrier wall and the deck slab.

The bridge incorporates a complex embedded fibre optic structural sensing system that will allow engineers to compare the long-term behaviour of the various materials. This remote monitoring is an important factor in acquiring long-term data on FRPs that is required for widespread acceptance of these materials through national and international codes of practice [17].

Fig. 4.1 The Taylor Bridge during construction.

4.2. Joffre Bridge

Early in August of 1997, the province of Québec decided to construct a bridge using carbon FRP reinforcement. The Joffre Bridge, spanning the Saint-François River, was another contribution to the increasing number of FRP-reinforced bridges in Canada. The bridge is shown under construction in Fig. 4.2. A portion of the Joffre Bridge concrete deck slab is reinforced with carbon FRP, as are portions of the traffic barrier wall and the sidewalk.

The bridge is outfitted extensively with various kinds of monitoring instruments including fibre optic sensors embedded within the FRP reinforcement (these are referred to as smart reinforcement). The deck reinforcement is shown in Fig. 4.2, where the sensor wiring is also visible. Over 180 monitoring instruments are installed at critical locations in the concrete deck slab and on the steel girders, to monitor the behaviour of the FRP reinforcement under service conditions. The instrumentation is also providing valuable information on long-term performance of the concrete deck slab reinforced with FRP materials. [17]

Fig. 4.2. the Joffre Bridge

5. CONCLUSION

FRP materials for use in concrete reinforcing applications have a number of key advantages over conventional reinforcing steel. Some of the most important advantages include:

- FRP materials do not corrode electrochemically, and have demonstrated excellent durability in a number of harsh environmental conditions;
- FRP materials have extremely high strength-to-weight ratios. FRP materials typically weigh less than one fifth the weight of steel, with tensile strengths that can be as much as 8 to 10 times as high; and
- FRP materials are electromagnetically inert. This means that they can be used in specialized structures such as buildings to house magnetic resonance imaging (MRI) or sensitive communications equipment, etc.

There are, however, some disadvantages to using FRPs, as opposed to conventional reinforcing steel, as reinforcement for concrete. The main disadvantage is the comparatively high initial cost of FRP materials. Although prices have dropped drastically in recent years, most FRP materials remain more expensive than conventional reinforcing steel on an initial material cost basis. However, because of the high strength of these materials, they are often competitive on a cost-per-force basis. Furthermore, the excellent durability of FRP reinforcing materials in concrete, which has the potential to increase the service life of structures while reducing inspection and maintenance costs, makes them cost-effective when the entire life-cycle cost of a structure is considered, rather than the initial construction cost alone.

Another often cited potential disadvantage of FRP materials is their relatively low elastic modulus as compared with steel. This means that FRP-reinforced concrete members are often controlled by serviceability (deflection) considerations, rather than strength requirements.

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