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DURABILITY OF COMPOSITES IN REINFORCED CONCRETE

L.J. Malvar
Naval Facilities Engineering Service Center
Port Hueneme, CA 93043-4370

ABSTRACT

Many fiber reinforced plastics (FRP's) have excellent corrosion resistance properties and can be engineered to have mechanical properties comparable to steel. These characteristics have promoted their use in many structural applications all over the world. Although the short-term mechanical properties of these materials are usually well documented, long-term durability issues still remain. Some of these issues are hereby summarized, mostly for the case of reinforced concrete applications.

Experimental observations indicate that all fiber reinforced plastics have long-term strengths that are only a fraction of the short-term strength. For glass, aramid and carbon FRP's, the fraction is about 30%, 50% and 80%, respectively. In addition glass and aramid FRP's will degrade if in direct contact with concrete, in the presence of moisture, and when subjected to UV radiation. These poor durability characteristics place significant restrictions on the working stress allowables for design.

INTRODUCTION

Excellent mechanical and corrosion resistant characteristics have promoted the use of fiber reinforced plastics (FRP's) in many structural applications all over the world (Malvar, 1996; Nanni, 1993). Although the short-term mechanical properties of these materials are usually well documented, long-term durability issues still remain. Some of these issues are hereby summarized, mostly for the case of reinforced concrete applications.

BACKGROUND

Recent structural applications of FRP materials include:

(a) reinforcing bars for concrete structures, typically with E-glass fibers embedded in a vinylester or epoxy matrix. For these bars, strengths are around 80 to 100 ksi (552 to 690 MPa), but the modulus of elasticity is only around 6 Msi or 41 GPa (versus 29 Msi or 200 GPa for steel bars) (Malvar, 1995). Aramid, carbon, vinylon, as well as hybrid rebars can also be obtained

(b) prestressing strands (Iyer, 1993, 1994; Sen et al, 1993a, 1993b, 1996c; Malvar, 1996)

(c) fiberglass sheets to retrofit columns (Fyfe, 1995; Priestley et al., 1992)

(d) carbon sheets to retrofit columns, beams and slabs (Sultan, 1995; Inaba, 1996)

(e) gratings and railings (Warren et al., 1995), structural shapes

(f) cables (Burgoyne, 1993)

Current FRP composites for structural applications use mainly three types of continuous fibers: carbon, aramid and glass. These are often designed as CFRP, AFRP and GFRP composites, respectively. E-glass fibers are the cheapest (around $0.80 per lb.) and most commonly used. They have a tensile modulus of 10.5 Msi (72 MPa) and a tensile strength around 500 ksi (3.45 GPa) at a strain of 4.8%, although in composite applications ultimate strains rarely reach 3.4% (2.5% is more common), with the corresponding strength reduction. S-glass fibers have more desirable properties, e.g. about a 20% higher strength and modulus of elasticity, but may cost up to 8 times more. Aramid fibers have slightly higher tensile moduli E (between 83 and 186 GPa, i.e. between 12 and 27 Msi, with 1 Msi = 10^3 ksi = 10^6 psi) and similar tensile elongations (between 2 and 4%). Carbon fibers, however, offer a wide variety of moduli, from 25 to 120 Msi (172 to 827 GPa). The most common (such as AS4 and T300) have a modulus around 33 Msi (227 GPa) and a strength around 550 ksi (3.8 GPa) (Malvar, 1996). Other fibers have been used, such as Vinylon (or polyvinyl alcohol, PVA) and Polyester, but in limited applications. With respect to fiber content, total contents from 45% to 68% by volume (i.e. 60% to 80% by weight) have been reported for pultruded composites.

Epoxies and polyesters are often used as the composite matrix for their fiber protection properties. Polyester resins are not very resistant to alkalis and are typically avoided for uses in concrete. Vinylester resins are resistant to a wide range of acids (sulfuric, hydrochloric, hydrofluoric, phosphoric, nitric) as well as to chloride salts and chlorine making them ideal for marine environments. For use in concrete, BPA fumarates have shown the best resistance to strong basic solutions (ASM, 1987). Epoxies can be even more resistant but are somewhat more expensive.

LONG-TERM STRENGTH

Most composites exhibit a long-term static strength that is significantly lower than the short-term strength. This long-term static strength is observed by exposing the material to sustained stress for a long period of time and without any specific adverse environmental exposure (tests typically run in air, indoors, and at ambient temperature). This failure due to the degradation of the material properties with time is also referred to as creep rupture. This loss of strength can be accelerated in adverse environments, such as in the presence of water, or strong acidic or alkaline solutions.

For Polystal E-glass tendons, the long-term static strength at 10,000 hours (about 1 year) has been reported to be 70% of the short-term static strength (Wolff and Miesseler, 1989; Taerwe, 1993). Sultan et al. (1995) report remaining strengths after 10 to 15 years of 40% for hand laid-up fiberglass, and 55% for filament wound composites. Slattery (1994) reports that long-term tests on Glass/Epoxy composites showed failure of about half of the samples tested at a sustained stress of only 50% of ultimate, after about 7 years. Some of the samples ruptured at levels as low as 33% of ultimate. Active E-glass composite wraps applied as confinement for some of CALTRANS circular highway columns and pressurized via grout slurry failed after 3 years under sustained stresses around 32% of the manufacturer's reported strength (Hawkins et al., 1996). If the most conservative estimates from these tests are used, it appears that the long-term static strength of glass composites can be as low as about 32% of the short-term strength.

For Kevlar fibers, the 100-year sustained strength is around 60% of short-term strength (Taerwe, 1993; Horn et al., 1977). PARAFIL ropes using the high modulus Aramid fibers limit the long-term (100 year) tensile strength to 50% of the short-term strength (Burgoyne, 1993). This matches tests on Kevlar/Epoxy composites which show a sustained strength of 60% after about 7 years (Slattery, 1994). If the most conservative estimate from these tests is used, it appears that the long-term static strength of aramid composites can be as low as 50% of the short-term strength.

Test data on carbon fibers shows very few failures after several years and a sustained stress of 80% of the short-term ultimate (Slattery, 1994).

DESIGN ALLOWABLES VERSUS LONG-TERM STRENGTH

Working stress design is often recommended for concrete members reinforced with commercially available FRP rebars. Most of these use E-glass fibers in a vinylester matrix. The recommended allowable working stress is often 30% to 40% of the ultimate tensile strength, that is around 30 ksi or 200 MPa (since most E-glass rebar manufacturers claim short-term ultimate strengths from around 80 to 100 ksi, or 550 to 690 MPa) (Malvar, 1995, 1996). Assuming that no alkali degradation will occur during the structure's life, the recommended working stress is approximately equal to the long-term strength for E-glass composites, as indicated previously. Hence the long-term design factor of safety is 1. In contrast, if working stress design is used for a grade 60 bar, the allowable stress is limited to 24 ksi or 165 MPa. The long-term ultimate strength for a typical grade 60 bar (also assuming no corrosion) is about 109 ksi or 750 MPa (Malvar, 1998). Hence for a steel bar the long-term factor of safety is 4.5 for working stress design. To get a similar safety factor for an E-glass bar, its allowable stress should rather be around 6% to 10% of the measured short-term strength, i.e., not more than 10 ksi (69 MPa) for a typical 100 ksi (690 MPa) nominal strength pultruded E-glass bar. At least one manufacturer recommends limiting sustained stresses to 25% of the tensile strength, and another recommends limiting the allowable working stress to 25%. In the design of fiberglass pipes, the recommended axial tensile design stress is often 25% of ultimate (Composites Institute, 1992). It should, however, be noted that some conservatism could be built into the measurement of the short-term strength of the rebar if standard tensile tests (e.g. ASTM D3916) are used (Malvar and Bish, 1995).

To adopt a design allowable stress level, it appears that perhaps a distinction should be made between sustained and transient loads. In reinforced concrete structures, however, the dead load is often a large portion of the total load applied to the structure. Hence a simple limit on the allowable working stress, both for reinforced and poststressed applications may be sufficient.

In summary, it appears that, in the absence of adverse environmental factors, and until further research is conducted, the allowable working stress for glass FRP rebar should be limited to 25% of the ultimate tensile strength or 25 ksi (172 MPa), whichever is lower. This would provide some safety with respect to the observed long-term strengths of about 32% of the short-term ultimate. For glass rebars in concrete, this would apply *only* if either (1) direct contact with the concrete is prevented, or (2) a pH-neutral concrete is used, or (3) a glass fiber that is really resistant to alkali attack is developed (otherwise the allowable working stress should be lowered).

ALKALI RESISTANCE OF CARBON FIBERS

With regard to environmental interaction, carbon fibers are not affected by moisture, atmosphere, solvents, bases and weak acids (ASM, 1987). In terms of their specific resistance to alkalis, Judd (1971) showed that carbon was resistant to alkaline solutions at all concentrations and all temperatures up to boiling. Carbon tows immersed for 257 days in a very basic 50% w/v sodium hydroxide solution showed variations in strength and elastic modulus only around 15%. Carbon strands soaked for 9 months in a pH 13 solution (at 60°C) showed no variation in strength nor modulus (Santoh et al., 1993a, 1993b). Beams prestressed with carbon strands and subjected to wet/dry cycles in an alkaline solution showed no degradation of flexural strength after 9 months (Arockiasamy, 1995). In summary, carbon fibers have the potential to withstand direct interaction with concrete for long periods of time.

ALKALI RESISTANCE OF ARAMID FIBERS

Para-aramid fibers (such as Kevlar) are fairly resistant to many solvents and chemicals, but are affected by strong acids and bases (ASM, 1987). Kevlar 29 exposed to a 10% sodium hydroxide solution for 1000 hours loses 74% of its strength. Higher modulus Kevlar 49 is much more resistant but still shows some strength loss in an alkaline environment (3% loss in a 40% sodium hydroxide solution after 100 hours (DuPont, 1992). Due to the protection provided by the resins, aramid composite bars show smaller losses (from 2% to 10%) due to exposure to sodium hydroxide solutions (Noritake et al., 1993; Tamura, 1993). The estimated 100-year sustained strength of an aramid rod (Arapree) decreased from 60% in air to 50% of the short-term strength in an alkaline environment (Horn et al., 1977; Gerritse et al., 1992, 1995). Separate tests on the same aramid bar showed sustained to short-term strength ratios of 75%, 70%, 60% and 50% for exposures to 20°C air and 20°C, 40°C and 60°C alkaline environments, respectively (at 10,000 hours) (Scheibe and Rostasy, 1995).

In summary, aramids will show strength decay when in contact with concrete. Higher modulus aramids exhibit better alkali resistance and should be the ones used in such applications.

ALKALI RESISTANCE OF GLASS FIBERS

Glass fibers are chemically vulnerable to many acids and bases and will deteriorate if in direct contact with concrete. In composites, it is generally expected that the matrix will provide the needed chemical protection for the fibers. However this may not always be the case.

Concrete environment

As mentioned earlier, the phenomenon of creep rupture, or static fracture, is the gradual reduction of the tensile strength of glass under stress. This problem is accelerated significantly in the presence of water, acids and alkalis, and may result in sudden cracking of the fibers. This was emphasized in a paper summarizing the findings from a symposium on durability of glass fiber reinforced concrete: glass fiber composites can exhibit “spontaneous loss over time of much of the flexural and tensile strengths of the composite to little more than that of the matrix” in case of exposure to wet conditions in an alkaline environment (Diamond, 1985).

The resins used in the composite must provide a two-fold protection in a concrete environment: the matrix toughness must be high enough to prevent the development of matrix microcracks, and diffusion through the matrix must be minimal.

Fujii et al. (1993) tested E-glass composites with a relatively brittle polyester matrix. These composites showed significant matrix microcracking when loaded to only 40% of their short-term ultimate strength. The matrix microcracks effectively would allow for direct contact between fibers and concrete. This microcracking resulted in a significant loss of tensile strength (more than 50% in 720 hours) when the composite was immersed in an acidic solution. The same tests under the same conditions but with a tough vinylester resin resulted in no matrix cracking and no strength loss. Although currently used resins exhibit elongations at failure of up to 4%, tougher resins with elongations of 10% or more can be obtained.

Sen et al. (1993a, 1993b) tested 12 beams pretensioned with two 3/8-inch, seven rod fiberglass strands. The strands were made of S-2 glass fibers in a Shell Epon 910 epoxy resin, and were stressed at about 50% of short-term ultimate. Five beams were precracked, and a total of nine were exposed to simulated tidal cycles in a 15% sodium chloride solution. Three of the five precracked beams failed at a load lower than the cracking load, indicating a total loss of the fiberglass strands after less than 9 months of exposure. One of the uncracked beams failed without the application of any external load (exposure time 18 months). Scanning electron microscope examination of the strands showed the fiber deterioration for the exposed specimens. This total loss of the strands is a concern, particularly since S-2 glass fibers are more resistant than E-glass fibers to alkalis and the matrix used is also one of the most resistant to basic environments. Scanning electron microscope examination of the strands showed that no matrix cracking was apparent. Damage was attributed to diffusion of the hydroxil ions through the matrix, indicating that, in some cases, even an uncracked matrix of the best type available may not be sufficient to protect the fibers.

Tests by Dolan et al. (1997) also show long-term strengths (at 5500 hours and for GFRP tendons embedded in concrete) of about 55% of short-term ultimate.

Alkaline solutions

Alkaline solutions are often used to evaluate the fiber protection provided by the matrix. This evaluation may be somewhat conservative, as shown in the first case below, but it emphasizes the importance of this problem with GFRP.

The Federal Highway Administration sponsored an evaluation of GFRP gratings for use in concrete bridge decks (Anderson et al., 1994). Tests were conducted in an alkaline environment on two sets of gratings using E-glass fibers, one set with a polyester matrix, another with a vinylester matrix. Polyester resins are less resistant to alkali attack and showed very rapid deterioration when compared to the vinylesters. Three-point bending tests on the grating samples after 160 days showed strength reductions of up to about 80% for polyester, and up to 25% for vinylester. Tests of the gratings embedded in small concrete beam specimens showed significant degradation for both polyester and vinylester gratings, with 30% to 40% loss of ultimate strength after 168-day exposures.

Tests by Katsuki et al. (1995) for GFRP rods in a NaOH solution (1 mol/liter at 40°C) showed strength losses of 70% after 120 days. Hou and Martine (1996) tested GFRP bars in a basic solution with pH of about 13. They reported losses in flexural strengths of 7% to about 30% for the vinylester bars (depending on the sizing) after 90 days. They also tested polyester bars that showed significantly higher degradation.

Tests at Iowa State University used accelerated aging techniques to determine the long-term strength of GFRP composites (Porter et al., 1996a, 1996b). The accelerated aging procedure involved exposing specimens to an alkaline solution at high temperature (up to 140°F) for 2 to 3 months, simulating about 50 years of exposure to real weather. Tensile tests on 3 rebar types indicated remaining strengths of 34%, 52%, and 71% of the measured short-term strengths.

Tests by Sen et al. (1996a) for the Navy and U.S. Army showed that rebars in concrete exposed to a 13.5 pH solution would lose 70% of their strength after 9 months under long-term stresses equal to 10% of the static strength. They state that "it would be unwise to use [current E-glass rebar] as reinforcement for structural concrete members."

OTHER ENVIRONMENTAL EFFECTS

Effect of water

Carbon fibers are not affected by water. However, the matrix is usually affected, and consequently so are the composite properties. For unidirectional carbon composites this usually translates into a reduction of the compressive and shear strengths, but a small effect on the tensile strength (Ciriscioli, 1988; Sen et al., 1996c). Graphite composites used as bonded external reinforcement in beams and subjected to 100 freeze-thaw and wet-dry cycles showed little effect on the composite itself, but some loss of the composite-to-concrete adhesion (Chajes et al., 1994; Karbhari and Engineer, 1996).

Para-aramid fibers (such as Kevlar) absorb and are affected by water, mostly at higher temperatures (Dolan, 1993; Horn et al., 1977). Saturated aramid composites have been reported to lose 35% of their flexural strength at room temperature (Allred, 1984), and up to 55% if stressed and under wet/dry and thermal cycles (Sen et al., 1996b).

Glass fibers are also affected by moisture. Typically, losses in tensile and flexural strengths of 10% or more may be expected after a few months of exposure (Springer et al., 1981; Novinson et al., 1998; Faza et al. 1994; Pantuso et al., 1998), although some studies indicate that the losses may be negligible (Rahman et al., 1996).

UV effects

Aramids are most vulnerable to ultraviolet (UV) attack. A thin Kevlar 29 fabric exposed to Florida sun for 5 weeks lost 49% of its strength [48]. However, a thick (1/2 inch) rope lost 31% of its strength after 24 months due to the protection of the inner fibers by the outer ones (DuPont, 1992). Resins, in general, will be affected by UV unless adequate protection is provided by additives or coatings. In turn, the composite properties would also be affected, mostly in compression, shear, and transverse tension.

DRAFT CODES IN CANADA, JAPAN AND THE U.S.

Canada, Japan, and the U.S. have issued draft codes for the design of reinforced and prestressed concrete structures (Canadian, 1996; CHBDC, 1996; Japanese, 1995a, 1995b; Sonobe et al., 1997; Gilstrap et al., 1997; ACI 440, 1996; ACI 440, 1997).

The Canadian Standards Association (1996) is in the process of amending the Canadian Highway Bridge Design Code to include Chapter 16: "Structures with Fibre Reinforcement". In this chapter, composite applications are limited by fiber type. These limitations are necessary due to the potentials problems described earlier.

In the Canadian Code, the use of GFRP was proposed to be restricted as follows:

- GFRP rod can be the sole primary tensile reinforcement only for barrier walls and for the interior panels of deck slabs of slab-on-girder bridges
- If GFRP is used as primary tensile (or shear) reinforcement, then CFRP, AFRP or steel must be used to withstand the unfactored dead loads
- GFRP tendons shall be used only when not in direct contact with concrete
- GFRC (glass fiber reinforced concrete) shall not be used
- Stresses in GFRP tendons at transfer are limited to 48% of short-term ultimate

The use of AFRP and CFRP was restricted as follows:

- Stresses in AFRP tendons at transfer are limited to 35% of short-term ultimate
- Stresses in CFRP tendons at transfer are limited to 60% of short-term ultimate

In addition, all FRP should be protected against UV rays.

PROPOSED ALLOWABLES FOR DESIGN WITH FRP BARS

To arrive to an allowable design stress the Canadian draft code proposes limiting the factored loads to ϕF times the ultimate strength for FRP rebars. Using the most conservative data presented here, F should be 0.32, 0.5 and 0.8 for GFRP, AFRP and CFRP, respectively (Table 1, Proposed F). For ratios of dead load to live load greater than 2, the Canadian draft code suggests values of F of 0.7, 0.5 and 0.9 (for mostly dead load, these values were shown as 0.6, 0.45, and 0.75 in a draft). It is estimated that the value for GFRP may be too liberal, given the failure studies previously mentioned. For tendons, the Japanese code suggests a factor β_3 of 0.7 for all three FRP types.

The Canadian draft code also proposes a resistance factor ϕ of 0.9. This resistance factor is a function of the variability of the rebar strength. This seems also liberal since (1) tests on some of these rebars have shown coefficients of variation in strength in excess of 20% (Malvar, 1995), and (2) the product ϕF provides a very low safety factor when compared to working stress design with steel rebars. The Japanese draft code recommends ϕ factors of 0.77 for glass, 0.87 otherwise. Hence it is proposed that ϕ could be taken around 0.8 (Table 1).

The Eurocode draft (Gilstrap et al., 1996) uses safety factors of 3.3, 2.0, and 1.67 for GFRP, AFRP and GFRP, respectively. An equivalent ϕ*F* factor could be taken as the inverse of these safety factors.

Hence, it is proposed that the ϕ*F* ratio of allowable stress to ultimate strength may be chosen as 0.25, 0.40 and 0.64 for GFRP, AFRP and CFRP, respectively (Table 1). Note that (a) these values are close to the most conservative of all code values, and (b) these values should be further reduced for direct exposure to concrete, water, and U.V.

For tendons, the stresses at transfer, which would be long-term sustained stresses, could be limited to similar values. Further limits at jacking and ultimate should be determined, which is beyond the scope of this work.

Table 1. Proposed Allowable to Ultimate Stress Ratio ϕ*F* for FRP Rebar Design.

FACTOR	SOURCE	GFRP*	AFRP*	CFRP
F	Canadian draft, R ≥ 2	0.7	0.5	0.9
	Canadian draft, R → ∞	0.6	0.45	0.75
	Japanese draft, tendons, β_3	0.7	0.7	0.7
	Proposed	0.32	0.5	0.8
ϕ	Canadian draft	0.9	0.9	0.9
	Japanese draft	0.77	0.87	0.87
	Proposed	0.80	0.80	0.80
ϕ*F*	Canadian draft, R ≥ 2	0.63	0.45	0.81
	Canadian draft, R → ∞	0.54	0.40	0.68
	Japanese draft	0.54	0.61	0.61
	Eurocode 1/(safety factor)	0.30	0.50	0.60
	Proposed	0.25*	0.40*	0.64

* These values should be further reduced for direct exposure to concrete, water, and U.V.

CONCLUSIONS

Durability issues of some currently available FRP products limit their use for some structural applications. Long-term strength in the absence of detrimental environmental factors have been measured which are well below the short-term strengths. The presence of water, acids, alkalis, and UV, can further reduce the long-term strengths significantly. The following recommendations are only suggested interim guidelines until formal design criteria is developed. Further limitations may be necessary for allowable stresses and usage.

The use of GFRP composites should be very restricted when in direct contact with concrete, at least until further durability guarantees are provided. It is further recommended that:

- GFRP tendons should not be used in direct contact with concrete;
- GFRP allowable working stresses for bars (and permissible stresses at transfer for tendons) should be limited to 25% of the measured ultimate tensile strength;
- GFRP bars and tendons should not be used as the sole primary reinforcement, except in applications where the reinforcement is not subjected to sustained load;
- GFRP reinforcements should be permitted for secondary reinforcement, such as column transverse reinforcement and passive column wraps;

The use of aramid composites should be allowed with restrictions, such as:

- AFRP allowable working stresses for bars (and permissible stresses at transfer for tendons) should be limited to 35 % of the measured ultimate tensile strength;
- AFRP are not recommended for waterfront applications;
- High modulus AFRP reinforcements are better suited for exposure to concrete.

The use of carbon composites should be allowed with some restrictions, such as:

- CFRP allowable working stresses for bars (and permissible stresses at transfer for tendons) should be limited to 60 % of the measured ultimate tensile strength.

In addition, all FRP reinforcements should be protected against moisture and UV, and the use of pH-neutral concretes is strongly recommended to prevent alkali attack.

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