Non-Metallic Reinforcement for Concrete

What Structural Engineers Should Know About GFRP Reinforcement

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In steel-reinforced concrete (steel-RC) structures, reinforcing steels corrosion reduces the structure's lifespan and requires expensive repairs. When steel-RC structures are exposed to moisture coupled with chlorides and CO_2, concrete deterioration is caused, leading to significant repairs typically after 25 years of service. As the structure ages, major repairs can be expected every ten years until it needs to be replaced, typically after 50 to 75 years of continuous service. Researchers and engineers have been studying corrosion in concrete structures and exploring ways to prevent it. The use of Fiber Reinforced Polymer (FRP) reinforcing bars was considered in the early 1960s as one potential solution for preventing corrosion in reinforced con-crete. There was a significant development in FRP research, field demonstrations, and commercialization starting in the 1980s and continuing since then.

As with any new construction technology or building material being developed, it is critical to have building codes for these materials to ensure safe and resilient structures. Over the last few decades, there have been industry consensus design guidelines for FRP-reinforced concrete. ACI PRC-440.1R Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars was first published in 2001. ACI PRC-440.1R describes many unique aspects and design considerations for FRP-reinforced concrete that are widely used within the industry; however, it is a non-mandatory guideline. As research and applications of FRP-reinforced concrete have advanced, there has been an increasing need for standards and codes for this technology that can be directly referenced and adopted by other building codes.

In 2017, ASTM D7957, *Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement*, was introduced as a material specification covering Glass Fiber Reinforced Polymer (GFRP) bars. The GFRP bars covered by this specification must meet the minimum requirements for geometry, material, mechanical, and physical properties. In 2008, ACI published a standard construction specification for FRP-reinforced concrete that was recently updated in 2022. ACI SPEC 440.5-22, *Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars*, provides mandatory language construc-tion requirements that project specifications can directly reference. In September 2022, ACI published ACI 440.11-22, *Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars*. With the publication of this code, there are now a complete set of codes and standards that allow engineers to confi-dently and safely specify and design FRP-RC structures. Notably, these codes and standards all center around Glass FRP (GFRP) bars. ASTM material standards for other FRP bars and ACI design standards for the respective bars may be developed in the future.

What are FRP Reinforcing Bars?

In concrete structures, FRPs are an alternative to steel reinforcement. They are composite materials made of fibers embedded in polymeric resins (*Figure 1*). The non-magnetic and non-corrosive nature of FRP materials allows them to be used as reinforcement without encountering problems of electromagnetic interference or steel corrosion. Furthermore, FRP materials exhibit characteristics such as high tensile strength that are suitable for reinforcing structures.

Figure 1. Types of FRP bars predominantly used in building and construction.

As reported in ACI 440.1R-15, the mechanical behavior of FRP reinforcement differs from the behavior of conventional steel reinforcement. Accordingly, a change in the traditional design philosophy of RC structures is needed for FRP reinforcement. Fiber-reinforced polymer materials are anisotropic and are characterized by high tensile strength only in the direction of the reinforcing fibers. This anisotropic behavior affects the shear strength and dowel action of FRP bars and the bond performance. Additionally, FRP materials do not yield; they are elastic until failure. Design procedures should account for the lack of ductility in structural concrete members reinforced with FRP bars. The stress-strain relationship of various reinforcing systems is demonstrated in *Figure 2.*

Benefits and Uses

First, one of the main benefits of FRP reinforcing bars is that they **do not corrode**. This has led to the use of FRP reinforcing bars as an alternative to steel reinforcing bars in applications where corrosion of reinforcing steel is a significant concern. For example, these might include: a) Marine structures that are directly exposed to chloride-laden seawater; b) Coastal buildings and infrastructure that are exposed to airborne chlorides from nearby seawater bodies; c) Bridge decks and pavements exposed to high levels of aggressive deicing salts; d) Parking garages exposed to vehicles carrying deicing salts; e) Highly corrosive industrial applications.

Next, FRP is a high-strength, **lightweight** material with a unit density of ⅓ to ¼ that of mild steel. For example, a #5 GFRP bar weighs approximately 0.30 pounds/lineal foot, whereas a #5 steel reinforcing bar weighs 1.04 pounds/lineal foot. The lighter weight of GFRP reinforcing bars may reduce transportation costs and labor cost and provides easy handling.

In addition, GFRP reinforcing bars are relatively **easy to cut** using a circular saw with a carborundum blade. Reciprocating saws with metal cutting blades can also be used (torches or shearing-type tools such as bolt cutters should never be used to cut FRP bars). These bars are cut quicker and with far less effort than steel bars which can speed up and ease the installation process.

Finally, FRP reinforcing bars are **non-metallic** and non-magnetic and have benefits in certain applications involving exposure to elec-tromagnetic fields. For example, using steel reinforcement around equipment that generates magnetic fields can disrupt the operation of the equipment. Similarly, equipment that generates high current may induce high heat in adjacent steel reinforcement, reducing its structural capacity. In these applications, non-metallic reinforcement becomes a necessary component of the safe and effective operation of the equipment. These applications may include areas around magnetic resonance imaging (MRI) units in hospitals, magnetic levitating (maglev) trains, and reactors in power plants. GFRP bars are **electrically non-conductive and have low thermal conductivity.** Therefore, they have been used in applications where thermal bridging needs to be avoided.

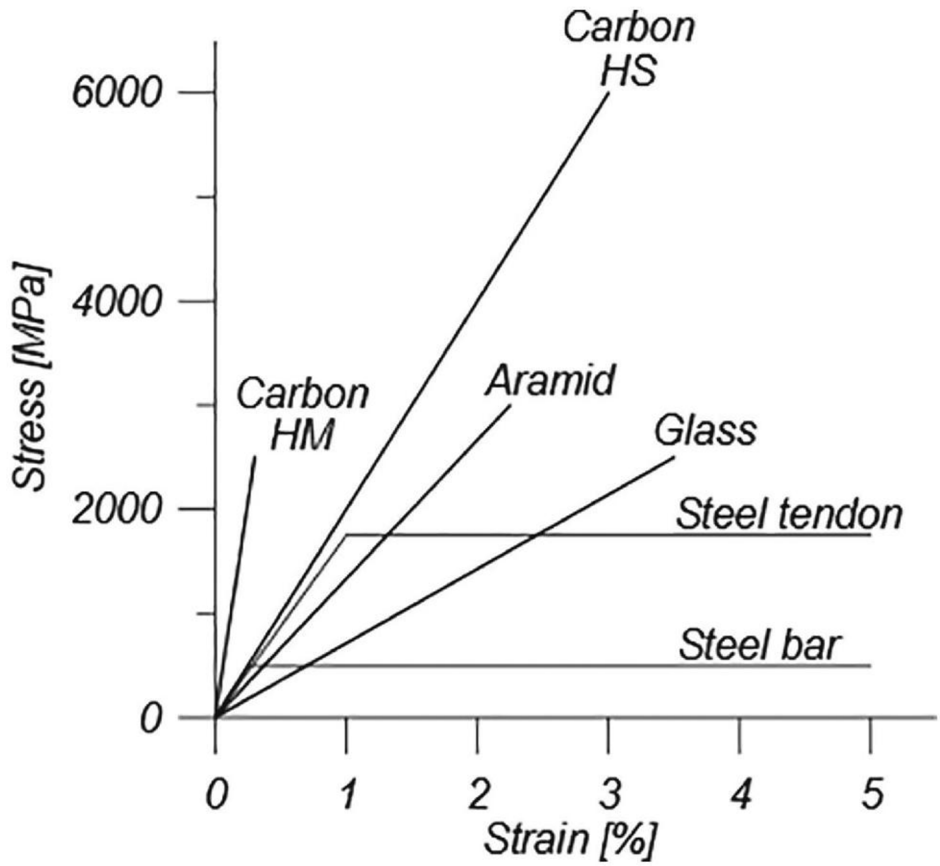

Figure 2. Stress-strain curve for several concrete reinforcing systems.

Material Properties of GFRP Bar

The GFRP reinforcing bars consist of fibers that contribute to mechanical strength, resin that helps transfer or distribute stress from one fiber to another to protect the fiber against environmental and mechanical damage, and fillers that reduce cost and shrinkage. The interface between the fiber and matrix significantly affects the performance of GFRP composites. Moreover, factors such as fiber volume, fiber type, resin type, fiber orientation, dimensional effects, and quality control during manufacturing play a critical role in defining the characteristics of a GFRP bar.

The volume fraction is the ratio of the volume of fibers in a composite to the overall volume of the composite material. The higher volume fractions, typically ranging from 70% to 80%, yield higher tensile properties. Similarly, the orientation of the fiber plays an essential role in governing the mechanical and other properties, such as the coefficient of thermal expansion (CTE), thermal conductivity, and electrical conductivity of GFRP bars. The fiber orientation can be aligned with principal stress directions to optimize performance and accommodate applied loads. Orienting the fibers along the length of the bar results in high strength and stiffness along the length but relatively lower strength and stiffness in the transverse direction. This explains lower shear strength, bond strength, and lower level of dowel action in the reinforcing GFRP bars compared to steel bars.

Mechanical Properties

1) *Tensile Properties* – As shown in *Figure 2*, the tensile behavior of the GFRP bar is characterized as linear elastic up to failure. FRP bars' tensile strength varies with the bar8 size, while the longitudinal modulus does not exhibit notable change. Larger bar diameters generally have lower net tensile strength because the outer fibers of the bar are more highly stressed than the inner fibers of the bar when loaded in tension (and bonded to concrete). ACI 440.11 uses a property referred to as the *guaranteed ultimate tensile strength* as specified in ASTM D7957. ASTM D7957 provides a table of the minimum tensile force for GFRP bars with a range of values depending on the bar size. For example, the minimum tensile force for a ¼-inch-diameter (No. 2) bar is 6.1 kips which translates to 125 ksi, whereas the minimum strength of an 11¼-inch-diameter (No. 10) bar is 98.2-kips which translates to 77-ksi.
2) *Compressive Properties* – Compressive strength and stiffness of GFRP materials can be significant but typically not as high as the material's tensile strength and stiffness. ACI 440.11 design criteria assume that FRP bars have the same compressive modulus as concrete and provide equivalent compressive resistance.
3) *Shear Strength* – The shear strength of GFRP bars is generally lower than comparably sized steel bars due to the anisotropic nature of GFRP bars. ACI 440.11 provides for a lower shear contribution of the concrete (Vc) based on testing of GFRP-reinforced concrete beams and may be in part due to the lower dowel action of the steel bars. ACI 440.11 does not cover using FRP bars or dowels across an interface to transfer shear.
4) *Bond Strength* – FRP bars intended for concrete reinforcement generally have surface treatments that allow for bonding to

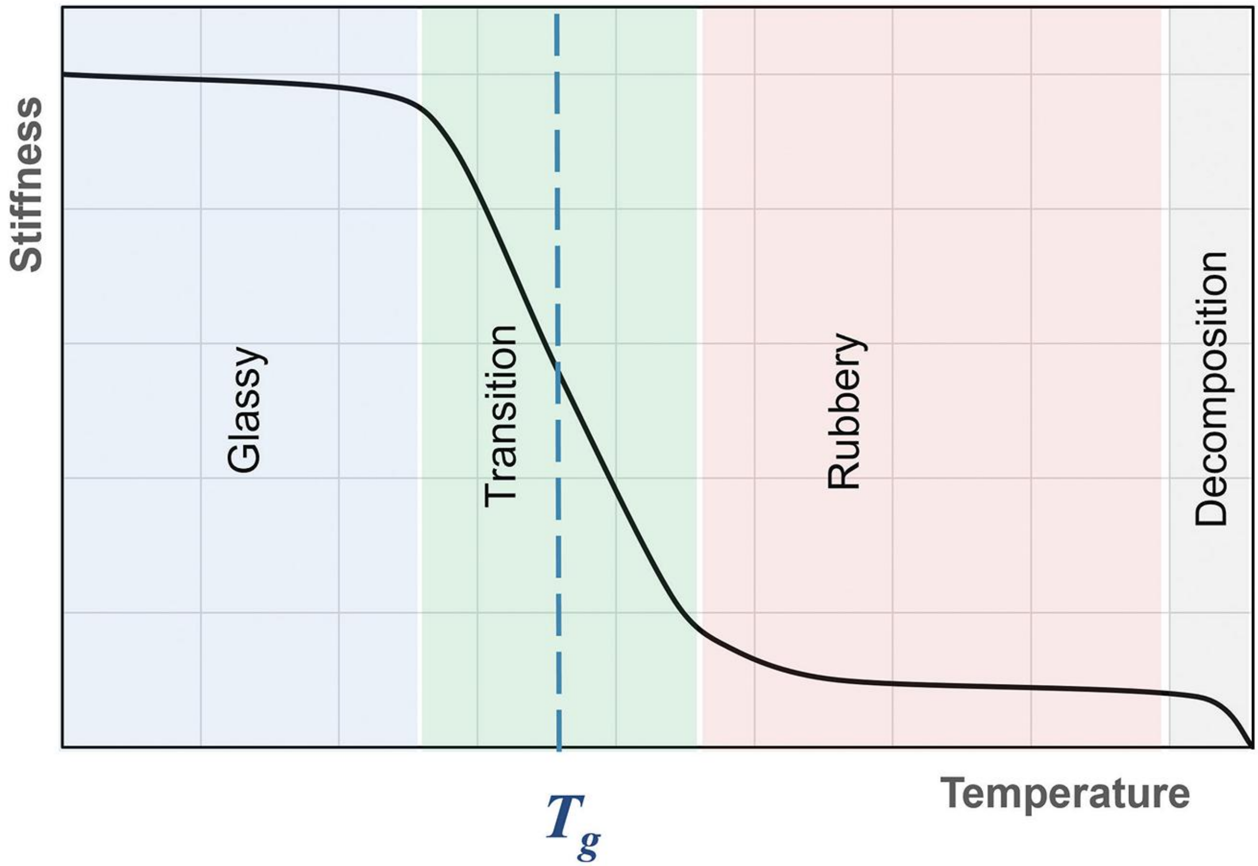

Figure 3. Idealized stiffness versus temperature curve for FRP materials.

con-crete. These can be sand coatings, deformations such as helically wound fibers that indent the bar's surface, or protrusions or lugs machined into the bar's surface. (There are other FRP bars used with concrete that do not use surface treatments, such as GFRP dowel bars and GFRP bars embedded in epoxy used for strengthening existing structures. Those types of reinforcements are outside the scope of ACI 440.11.) GFRP bars conforming to ASTM D7957 must have an appropriate surface treatment and a *guaranteed bond strength* of at least 1,100-psi to concrete when tested per ASTM D7913, Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing. ASTM D7913 is a bond pull-out test similar to what is used to characterize the bond strength of steel bars.

5) *Strength at Bends* – FRP bars cannot be field bent due to their linearly elastic behavior. However, bars are commonly produced with 90° bends by bar manufacturers. Bends larger than 90° are not generally available; since FRP bars do not plastically bend in use, larger bend angles do not improve performance. In addition, the bend radii the fibers must follow to allow such bends result in a lower tensile strength at bend locations. ASTM D7957 requires the tensile strength of the bent portion of a bar to be at least 60% of the strength of the straight bar.

Table of coefficient of thermal expansion of FRP reinforcing bars. (U.S. Conversion)

Bar Type	Longitudinal CTE (10-6/°C)	Transverse CTE (10-6/°C)
AFRP	-6 to -2	60 to 80
CFRP	-1 to 0	22 to 50
GFRP/BFRP	6 to 10	19 to 23

Thermal Properties

1) The coefficient of thermal expansion (CTE) of FRP materials can vary directionally depending on the fiber orientation. Typically, the polymers in FRP materials have a relatively high CTE, and the fibers have a relatively low CTE (aramid and carbon fibers can have negative CTE values). In the direction of the fibers, the lower CTE of the fibers restrains the overall composite CTE. In directions perpendicular to fibers, the CTE remains rather large with no restraint provided by the fibers. The *Table* shows typical ranges of CTE for various FRP reinforcing bars in the longitudinal and transverse directions. The CTE of GFRP and BFRP bars in the longitudinal direction are similar to the CTE of concrete and steel reinforcement. There is the potential for the difference in CTE to cause splitting crack-ing under large temperature changes, especially for larger bar sizes. However, these effects have not been observed in any field installations.
2) *Glass Transition Temperature* – The polymer component of FRP materials softens under moderately high heat. At elevated temperatures, the polymer rapidly transitions from a glassy material to a rubbery material, and the FRP material rapidly loses strength and stiffness. The glass transition temperature, T_g, of FRP materials is the average temperature

over which it transitions from a rigid, glassy material to a rubbery material. The transition occurs rapidly over a small temperature change, as shown in *Figure 3*. It is important to note that the transition to a rubbery material is an irreversible change for thermosetting polymers typically used in FRP reinforcing bars. Most commer-cially available FRP bars constructed using vinyl ester polymers have a glass transition temperature near 250°F. ASTM D7957 requires a minimum glass transition temperature of 212°F tested per ASTM E1356.

Durability Properties

1) *Corrosion* – FRP materials are inherently non-corrosive. In cor-rosive environments, it is not necessary to use specific concrete properties that may be required with steel-reinforced concrete. Notably, ACI 440.11 Table 19.3.1 does not use Exposure Category C (Corrosion Protection of Reinforcement) that exists in ACI 318 Table 19.3.1. It is anticipated that the service life of FRP reinforcing bars is greater than steel in certain corrosive environments.
2) *Accelerated Aging* – Accelerated aging studies of FRP bars have shown reductions in tensile strength (but not modulus) under exposure to certain environments. ASTM D7957 provides requirements on moisture absorption and retention of properties after exposure to elevated temperatures and alkalinity to ensure the durability performance expected with GFRP bars. And ACI 440.11 utilizes an environmental reduction factor, C_E, to account for the loss of strength over time. The C_E value is applied to the guaranteed tensile strength and bends' guaranteed strength to arrive at the design values for these properties. C_E is defined as 0.85 by ACI 440.11 Section 20.2.2.3.
3) *Creep Rupture* – FRP materials, in general, are susceptible to a phenomenon known as creep rupture or static fatigue. When the material is loaded in sustained tension, the creep of the material results in higher induced strain. If the strain levels from creep become large enough, the material can suddenly experi-ence tensile failure/rupture. To avoid this failure mode, ACI 440.11 Section 24.6.2 limits the sustained stress in the GFRP reinforcing bars to 30% of their design ultimate tensile strength. The material's resistance to creep rupture greatly depends on the type of fibers.

What ACI 440.11-22 Includes

ANSI-certified ACI 440.11-22 specifies minimum requirements for building materials, design, and detailing of structural buildings and non-building structures reinforced with GFRP bars that comply with ASTM D7957-22. This Code mirrors ACI 318-19, *Building Code Requirements for Structural Concrete and Commentary.* It includes design and construction for strength, serviceability, and durability; load combinations, load factors, and strength reduction factors; structural analysis methods; deflection limits; development and splicing of reinforcement; construction document information; field inspection and testing; and methods to evaluate the strength of existing structures. In addition, it provides design provisions for beams, one-way and two-way slabs, columns, walls, foundations, and connec-tions between members. Furthermore, the code explains differences in design between GFRP- reinforced concrete and steel-reinforced concrete in the commentary. FRP reinforcement behaves differently than steel reinforcement, so merely replacing steel reinforcement with the same size and spacing is inadequate. For instance, GFRP bars do not yield and exhibit linear elasticity until failure. ACI 440 addresses this difference and approaches design from the perspective of deform-ability, in contrast to steel reinforcement, which emphasizes ductility. Additionally, GFRP bars possess high tensile strength only in the direc-tion of the reinforcing fibers, affecting shear strength, dowel action, and bond performance. As a result, the equations for shear strength and development length in ACI 440.11 are different from those for steel reinforcement, even though the design procedures are similar.

Fire resistance of FRP RC structures is an important consideration. The Commentary to ACI 440.11 provides guidelines for establishing the fire ratings of FRP RC elements. However, this topic needs to be developed further, and the code currently limits the use of FRP reinforcement to structures that do not require a fire rating unless the building official approves an approach that establishes a fire rating.

Several topics are not covered in the current version of the Code but are expected to be covered in future editions. These include seismic provisions, diaphragms, anchorage to concrete, strut-and-tie methods, prestressed construction, lightweight concrete, shotcrete, connections of precast members, deep beams, drilled piers and caissons, brackets and corbels, and shear friction. Additionally, it does not cover the design of hybrid members with mixed steel and FRP reinforcement, but this is also envisioned for future code editions.

NEx Workshops and Other Educational Resources

NEx is an ACI center of excellence for non-metallics in building materials. It is actively educating engineers on the newly developed ACI CODE 440.11-22 and the application of GFRP reinforced concrete by organizing workshops and seminars and developing manuals for the use of this code. For the latest update, please visit **nonmetallic.org** or email us at **info@nonmetallic.org**.▪

Full references are included in the online version of the article at **STRUCTUREmag.org**.

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