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A SunCam online continuing education course

Fiberglass Rebar Fundamentals

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Introduction

Reinforced concrete is a, if not *the*, backbone of modern civil infrastructure. It's one of the most common engineering materials and is extraordinarily useful. While concrete dates back millenniums, the practice of embedding rebar in concrete to add additional structural capacity is relatively new, only about two hundred years old. The combination of steel and concrete revolutionized construction and modern infrastructure by substantially increasing the load carrying capacity of concrete. Concrete, of course, has extraordinary compression strength, and rebar resists stress in tension; the combination creates a very versatile, robust, infinitely shapeable material. The concrete provides protection and cover for the steel, and the steel carries the tensile loads that would have otherwise compromised the concrete.

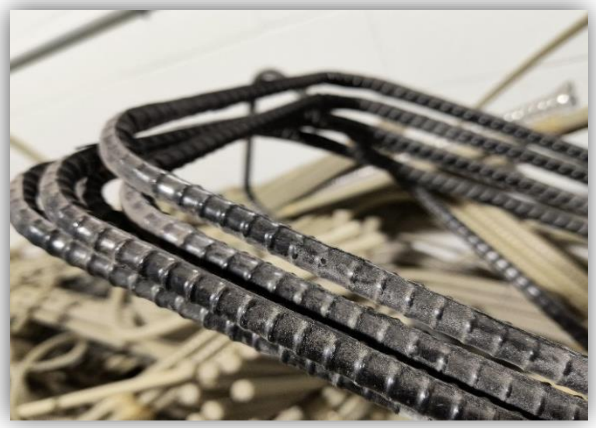
Up until the mid-20th-century, steel rebar was practically the only concrete reinforcement option. However, even this fantastic marriage of materials has drawbacks: namely corrosion, weight, and in some specific cases, electromagnetic interference. Composite materials, specifically fiberglass rebar, can achieve both short- and long-term performance that exceeds traditional methods. Fiber-reinforced polymer (FRP) composite materials have been used in aerospace, sporting equipment, automotive, boating, and other industries for many years. FRP rebar is relatively new to the infrastructure and construction industry. Although other steel reinforcement products are available at present (stainless steel, epoxy-coated, galvanized, etc.), FRP rebar has eliminated many of the drawbacks associated with alternative materials, namely cost. It also brings its own set of required techniques, as we'll soon see.

This course will address the fundamentals of composite rebar; strength calculations and structural substantiation are not included for the sake of brevity. We'll review the fundamentals of FRP rebar, the common issues that exist from using steel rebar, the materials that make up fiberglass rebar, and why FRP is better (or not) than traditional materials. We'll also discuss bending FRP rebar, and the FRP industry itself.

What is FRP Rebar?

FRP is a generic term for a composite material comprising of a fiber/matrix combination of unique materials. The fibers or matrix alone aren't sufficient to be structurally substantial; when mechanically combined in the proper ratio, however, they perform beautifully. FRP composite fibers are strong and stiff. Examples include carbon-fiber, fiberglass, aramid, and even basalt (which you'll recall, is a type of rock). The matrix is a polymeric thermoset resin that bonds to and encapsulates the fibers, thereby protecting them, and translates the stresses between fibers. Examples of an FRP matrix are epoxies, vinyl-esters, and polyester resins. There are several types of FRP rebar, categorized by various external deformations below: sand coated & wrapped (A&F), helical wrap (B), ribbed (C), sand coated (D), and helically grooved (E).

Benefits of FRP composites are numerous: its light weight, superior tensile strength, corrosion resistance, electromagnetically transparency, and the ability to engineer or customize the material. In fact, FRP composites in various forms are common in many industries today, such as aviation, sporting goods, construction, defense, automotive, and so on. In this course, we'll proceed directly to FRP rebar and overlook the plethora of applications outside of this scope.



Although steel rebar has been used in concrete since mid-19th century, FRP rebar began early development in the United States in the 1960's and became commercially available in the 1980's when the need for electromagnetically transparent reinforcement appeared for the benefit of MRI rooms in hospitals. Many bridges, foundations, seawalls, and other infrastructure have been constructed with modern vinyl-ester reinforced FRP rebar since the 1990's. Substantial research and testing, and many successful applications have promoted FRP rebar to a greater level of acceptance. Growth of the FRP rebar industry is apparent. At least 25 states have used fiberglass rebar in DOT bridges.

Problems with Steel Rebar

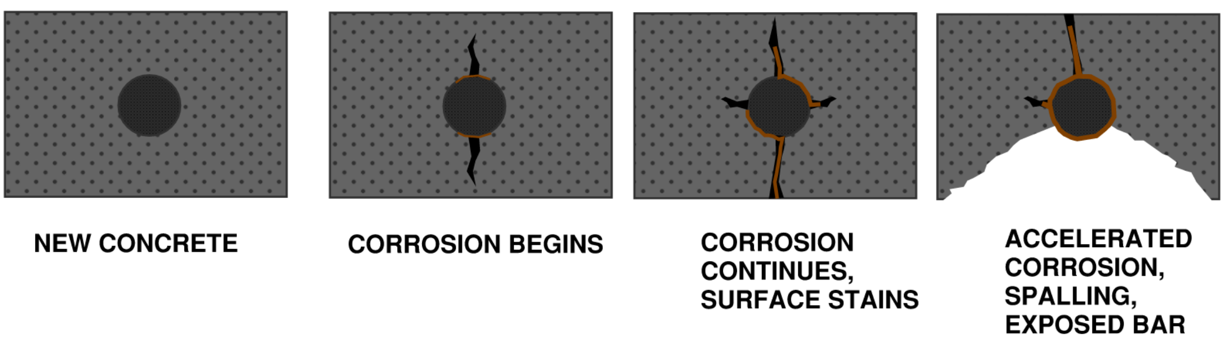
Although steel rebar and concrete have traditionally been the literal foundation of modern infrastructure, it does come with its problems.

Namely, steel corrodes. When moisture or salt, specifically chlorides, come in contact with steel, it begins the corrosion/oxidation process. Corrosion, of course, is the electromechanical reaction between a metal and its environment. This is the chemical reaction that causes iron to corrode, creating iron oxide, which we commonly know as rust:

$$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$$

In harsh marine environments, or in regions where deicing salts are used, corrosion in rebar is a very real threat. Steel expands when it corrodes and turns to iron oxide. This causes the adjacent concrete to spall and begins to compromise the integrity of the structure.

Corrosion is the single largest cause of concrete repair, annually estimated to cost more than several trillion dollars globally, and hundreds of billions in the USA alone.

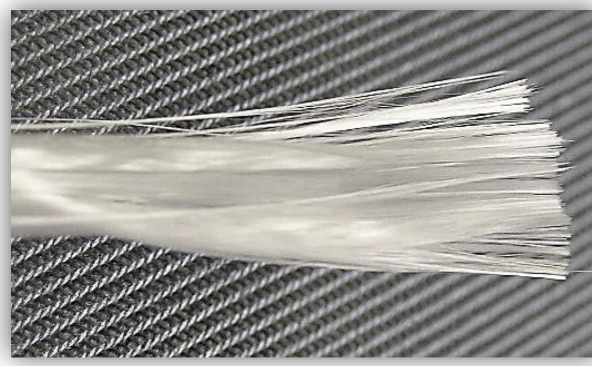


The traditional ways to combat corrosion with steel rebar include:

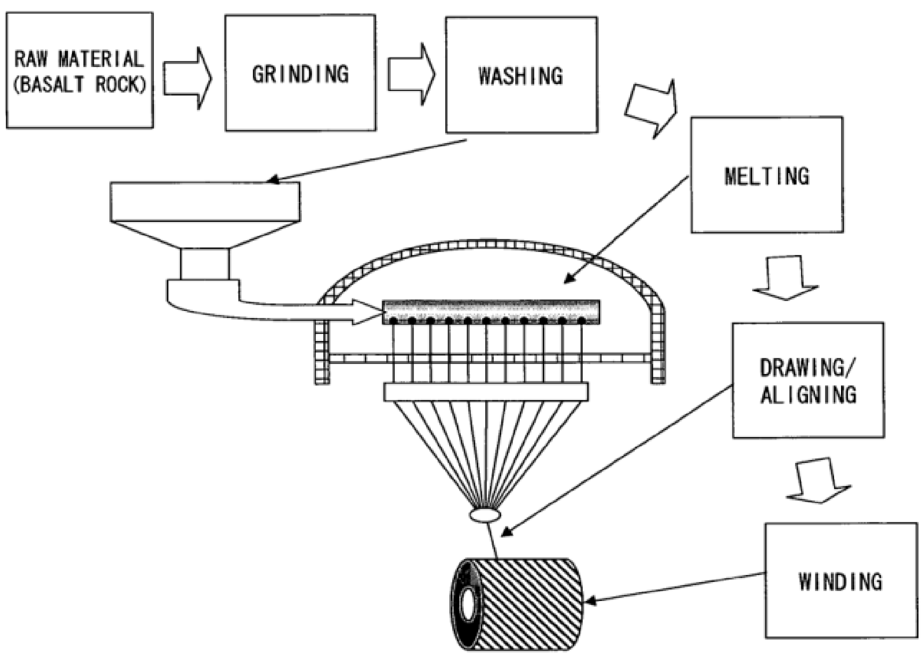
- Regular maintenance
- Preventative repairs
- Increased concrete cover
- Admixtures
- Modified concrete mix
- Overlays or membranes
- Epoxy-coated steel rebar
- Galvanized steel rebar

Material Composition

FRP rebar is made from two non-metallic components: fiber and matrix. The fiber is the structural element, consisting of thousands of strands of E-CR (Electrical, Corrosion Resistant) silica-based glass fibers, which has good chemical resistance, excellent thermal resistance, and high mechanical and dielectric strength. The other types of fiberglass include A (Alkali), C (Chemical), D (Dielectric), M (Modulus), R (Reinforcement), S (Strength), and T (Thermal). Alternatively, basalt (BFRP) and carbon (CFRP) fibers may also be used in composite rebar manufacturing.

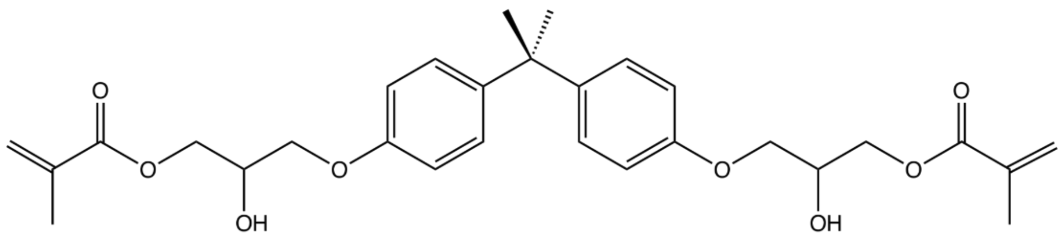


This image demonstrates the process of manufacturing basalt fibers, which is not unlike glass fiber manufacturing:

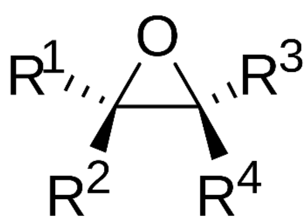


The matrix is a binder that holds the fibers together and transfers applied loads, allowing the fibers to act as a single member. It also protects the fibers from damage by embedding them into the product. The matrix for FRP rebar is usually a vinyl ester (most common), epoxy, or polyester resin (lower grade), all of which are thermoset materials. With carbon fibers, an epoxy matrix is typically utilized.

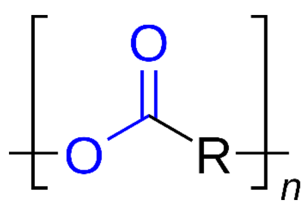
Vinyl ester has the benefits of epoxy resin with improved handling and accelerated curing properties of polyester resin. It's essentially a combination of polyester resin combined with epoxy molecules in the molecular chain, causing it to be resistant to water penetration and shrinking.



Vinyl Ester



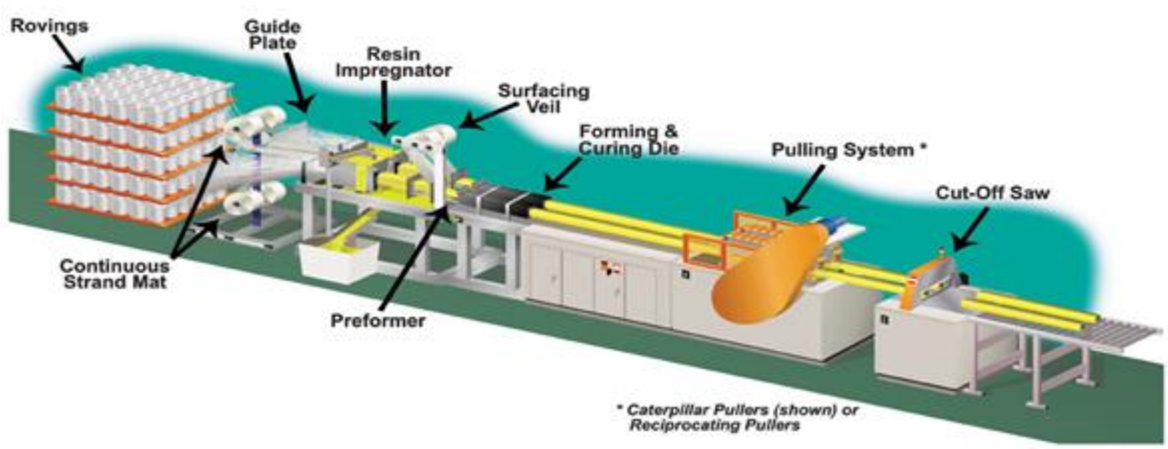
Epoxide group



Ester group

How It's Made

There are several ways to make FRP rebar: pultrusion (the most common method), braiding, weaving, or combinations of each process. The cross section of FRP bars can vary from solid, deformed, round, and/or hollow. Wound fibers, sand coatings, and mechanical deformations can all be used to increase development strength. Pultrusion, a combination of "pull" and "extrusion", is the continuous process of pulling the fibers through a resin bath and a die. Fibers remain parallel during and after the pultrusion process (see below), which provides the highest strength by uni-directionally orienting the fibers. Continuous glass fibers, or rovings, are pulled off creels, through a resin bath. Fibers are wetted out and formed into the final shape with heated forming dies; the resin cures by passing through a heated die, and the finished product is complete.



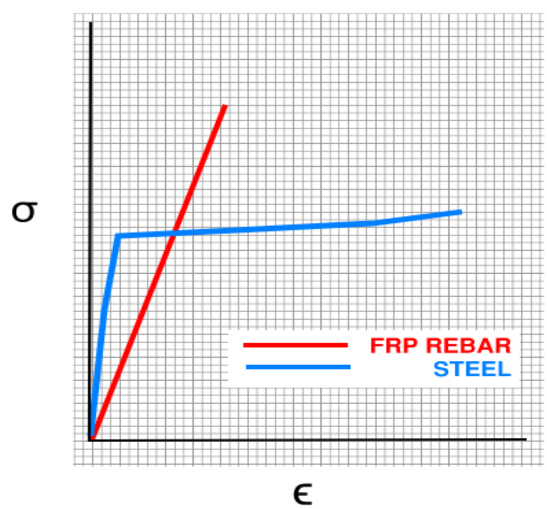
Braiding and weaving are mechanical processes that form a longitudinal rope or mat of fibers, and may be used to create external deformations. Once the rebar is formed, it remains uncured until heated at the proper time and temperature to activate the resin, typically in a heated die. Since the common FRP resins are thermosets, once cured, they can't be uncured. Thus, after curing, FRP rebar is not formable (i.e. it can't be bent after manufacturing). This is perhaps the largest physical difference from steel rebar.

Material Properties

Material properties of FRP rebar are anisotropic. Strength and stiffness values are greatest in the longitudinal direction, and depend largely on the type of fibers, and the fiber-to-resin ratio. Other properties are affected by the matrix composition, cure temperatures and time, fiber orientation, manufacturing process, and quality inspections. Below is a fundamental comparison of FRP rebar properties versus steel. Note that FRP products may vary, but these are generally the specifications you'll see in the market today:

	FRP		STEEL	
TENSILE STRENGTH	110-147	KSI	45-70	KSI
MODULUS OF ELASTICITY	5900-8700	KSI	29000	KSI
TRANSVERSE SHEAR	19-26	KSI	36	KSI
WEIGHT (#5 BAR)	0.3	LB/FT	1.0	LB/FT
COEFF. THERMAL EXPANSION (Long.)	3.5-5.6	E-6/°F	6.5	E-6/°F
COEFF. THERMAL EXPANSION (Transverse)	12	E-6/°F	6.5	E-6/°F

When it comes to material failure, FRP rebar is linear elastic (2% elastic deformation), and has no yield point. The stress-strain curve does not plateau; it can add stress in a linear fashion until it fails. The failure modes of FRP are concrete crushing and/or bar rupture. Warning signs are present, as visible indicators include major deflection and cracks, before sudden and often catastrophic failure. Some "smart" FRP rebar can be made to include tensile load monitoring. FRP rebar is longitudinally strong and laterally weak (in shear), although shear strength changes with bar size. Dead loads are recommended to limit at 25% of ultimate tensile strength.



Embedment strength varies somewhat between manufacturers since the surfaces differ. Some FRP rebar has sand coating, others have deformations that match traditional rebar. Others still are wrapped and have a woven texture. Bond dependent coefficient (k_b) is about 0.9. Fatigue resistance with FRP rebar is far superior to steel rebar; on the order of 20X more cycles to ultimate failure.

Quality control test specifications for FRP rebar properties are as follows:

Tensile Strength	ASTM D7205
Ultimate Elongation	ASTM D7205
Tensile Modulus	ASTM D7205
Interlaminar Shear	ASTM D4475
Fiber Content	ASTM D2584
Cure Ratio	ASTM E2160
Glass Transition Temperature	ASTM E1356
Measured Cross-Sectional Area	ASTM D7205
24-Hour Moisture Absorption	ASTM D570
Shear Strength	ASTM D7617
Bond Strength	ACI 440.3R-B.3
Resistance to Alkaline Environment	ACI 440.3R-B.6
Void Content	ASTM D5117
Bend Strength	ACI 440.3R-B.5

Benefits & Superiority

- FRP rebar is non-metallic and non-ferrous; it does not corrode. This feature alone sets FRP rebar in its own category as a phenomenal structural element in infrastructure that is susceptible to corrosion (bridge decks, piers, foundations, roads, etc.). In the presence of salts or chlorides, low pH concrete additives, and situations with minimum cover, FRP rebar reliably performs without disappointment. In fact, marine applications create a unique opportunity for FRP rebar; studies have shown sea water can even be used in the concrete mix if fresh water is unavailable, if the proper fiber/resin combination is used. No corrosion means concrete will not spall and degrade during service life of the structure. It also means less cover is required (approximately 2 bar diameters).

- FRP rebar has very high tensile strength compared to traditional steel rebar; generally it's about 2X steel. However, since it's anisotropic, it can be used with advantage for tunnel construction, where a boring machine can consume the rebar without issue.

- It also is light weight; FRP rebar is less than one-quarter the weight of steel. This helps to significantly increase labor savings (> 50%) and ease of installation. Workers can carry significantly more bars per trip. For a mental image, picture a 20' stick of #8 bar (1" diameter), which weighs less than 15 lbs.

- FRP is compatible with steel rebar. There is no issue with galvanic corrosion or any other dissimilar metal problems.

- FRP rebar holds up to chlorides, low pH, and general chemical exposure extremely well.

- As discussed already, the lack of electromagnetic interference creates a transparent grid when needed. Additionally, FRP is electrically and thermally non-conductive, rendering it very stable and safe, especially in construction zones with high voltage contact risk. FRP also does not conduct heat, which enables extra heat resisting benefits for cold or hot environments.

- The thermal coefficient of expansion in concrete (approximately $7x10^{-6}$ in/in°F) is like FRP rebar (5-$6x10^{-6}$ in/in°F)

- FRP rebar can extend the working life of a structure by many years. Common 20- or 50-year service life terms can be lengthened to 75-100+ years with FRP.

- In tunneling or demolition scenarios, FRP rebar can be "consumed". Although tensile strength is significantly higher than steel, FRP rebar can easily be cut or sheared by boring equipment.

- Regarding cost, the price of FRP rebar tends to be much more stable than steel rebar, since fiberglass and resin and not global commodities that wildly fluctuate due to economic and political changes.

- Cutting FRP rebar does not create hot ends. Also, FRP rebar doesn't get hot when lying in the sun.

- Less energy is required to manufacture, transport, and handle FRP rebar than conventional steel rebar

- Electrical grounding and cathodic protection aren't required

Drawbacks

- FRP rebar is susceptible to creep in places where there is a large, sustained load; current design codes typically limit sustained loads to approximately 25% of ultimate load. Reinforcement design is typically governed by serviceability issues such as deflections, creep rupture, and crack widths. Research suggests that if sustained stresses are limited to less than 60% of short-term strength, creep rupture does not occur in GFRP rebar. Therefore, prestressing with GFRP is not viable.

- FRP rebar does not yield before failure.

- Lower transverse (shear) strength, strain capacity, and modulus of elasticity.

- FRP rebar can discolor and fade when exposed to direct sunlight for long periods of time. This is only a cosmetic effect; performance is not affected.

- When tying FRP rebar, chairs should be placed more frequently than steel grids for stability. Non-metallic ties are typically used, although steel ties work with FRP.

- FRP rebar can only be cut with a diamond blade or a fine-toothed saw. It can't be sheared, bent, or cut with a torch or plasma cutter.

- Field-forming bars into bends or stirrups isn't currently possible. Bent pieces must be pre-ordered from the manufacturer.

- FRP is sold by the linear foot, rather than by weight (this could be a benefit or a drawback).

- High coefficient of thermal expansion in transverse direction

- Excess vibration can cause FRP rebar to float in concrete due to low density.

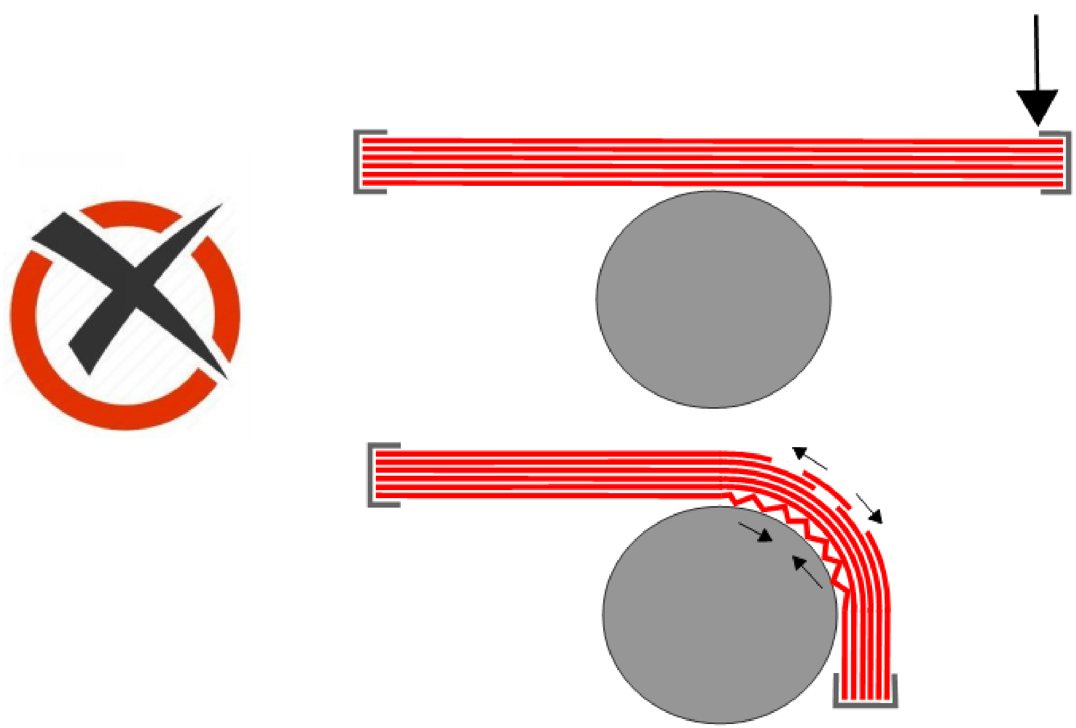
Bending FRP Rebar

As mentioned already, FRP rebar can't be bent in the field; once the resin cures, it's done. Therefore, bending must be done in the factory, meaning contractors and engineers have to pre-order bent stirrups and bars. This is one aspect that differs between FRP and steel rebar.

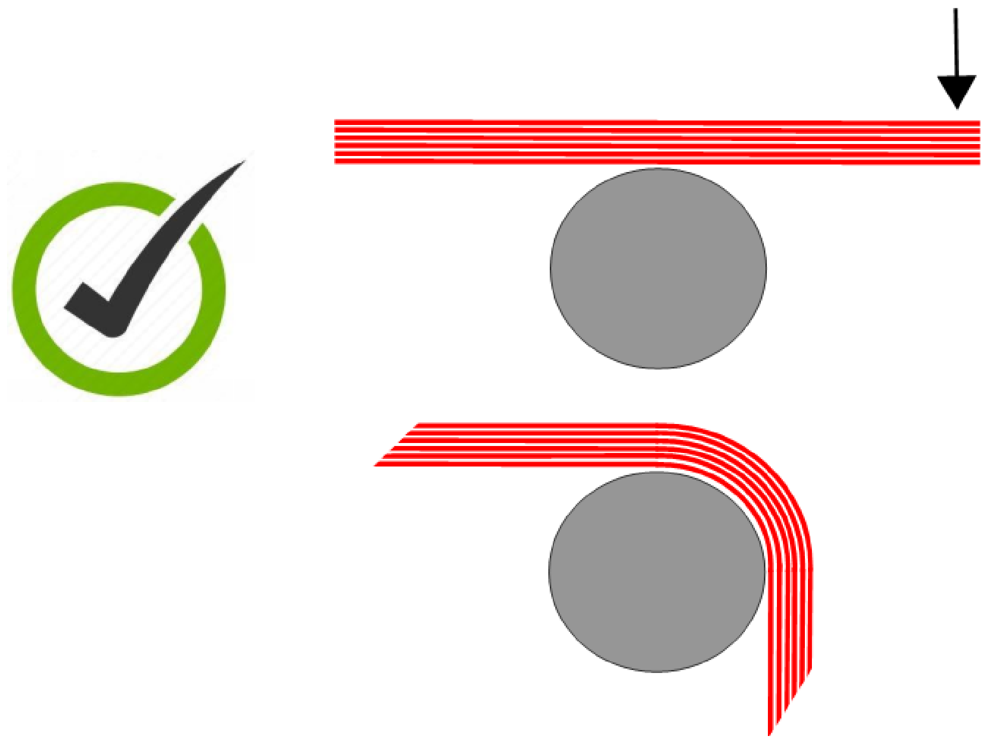
The other significant aspect is the strength of the bent FRP bars. Due to current manufacturing and material properties, bent FRP bars are not as strong (tensile strength) as straight bars. This seriously changes design criteria for engineers. The bent segment of FRP varies by manufacturer, but generally ranges from 50%-60%, and can be as low as 25%; the current ACI codes account for this. Some of the highest strength bends on the market are from Marshall Composites (C-BAR), which are around 90%, due to their patented modified pultrusion method. A study by Thanongsak, et. al (2020), describes strength degradation in curved FRP bars.

The reason FRP rebar changes strength when bent is explained here:

When uncured bars are formed with crimped or constrained ends, the internal fibers are not able to freely slide, causing them to fail and buckle, thereby reducing the bend strength by causing fewer fibers to carry the applied loads.



When the fibers are allowed to freely slide past each other as part of the bending process, they remain intact and the bend strength increases.



ACI 440.3R-12/B.5 *Guide Test Methods for Fiber-Reinforced Polymer (FRP) Composites for Reinforcing or Strengthening Concrete and Masonry Structures* specifies the test method for FRP bent bars and stirrups in bend locations.

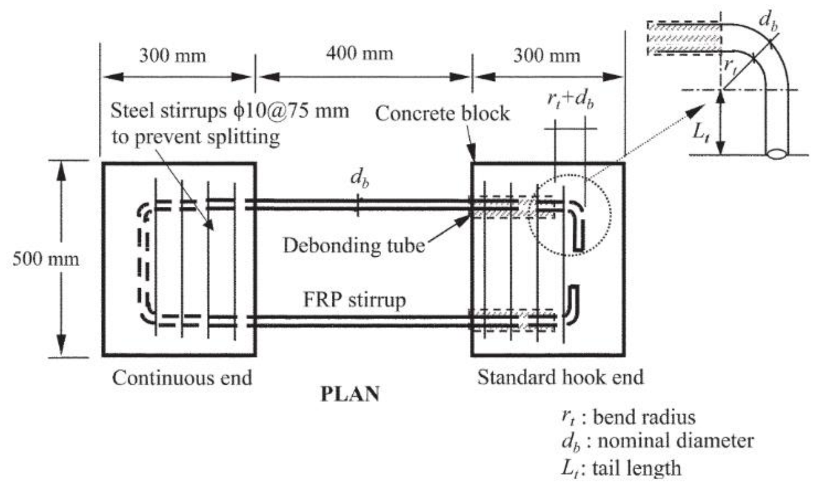


Fig. B.5.5.1—Configuration of specimen.

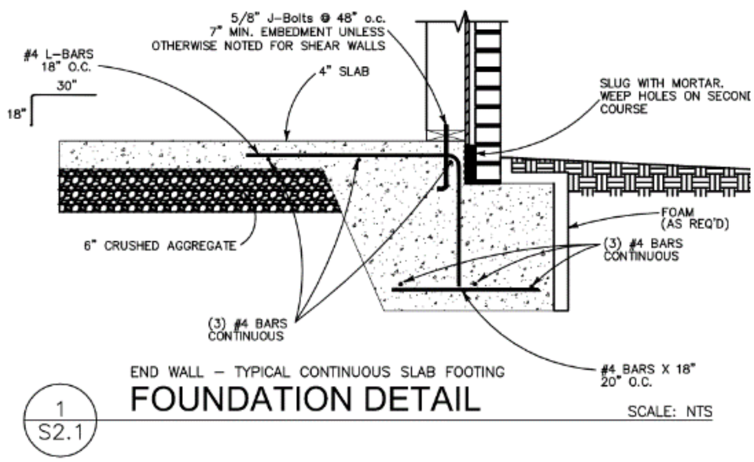
Applications

FRP rebar applications vary little from traditional reinforced concrete and steel rebar usages. The common elements where FRP rebar and concrete is used are as follows:

Parking Lots
Driveways
Roads
Columns
Precast Stairs
Precast Blocks
Precast Barriers
Retaining Walls
Curbs
Utility Boxes
Canals
Culverts
Foundations
Retaining Walls
Wall Panels
Sea Walls
Tunnel Segments
Piles
Bridge Girders
Bridge Decks
Sidewalks
Piers
Building Structures
Light Rail Transit
Water Treatment Facilities
Parking Garages
Balconies
MRI Rooms
Railroads
Dams
Floors
Drainage Structures
Pier Caps
CIP Slabs
Traffic Railings

However, FRP rebar shouldn't be considered as a direct substitute for steel because design considerations need to be addressed. Even with the benefits of synthetic rebar, steel and FRP are different materials, and they perform differently. Traditional steel reinforced concrete design dictates a maximum amount of steel (so the steel is the weak point of the structure). Steel yielding creates warning signs of potential failure of a concrete member.

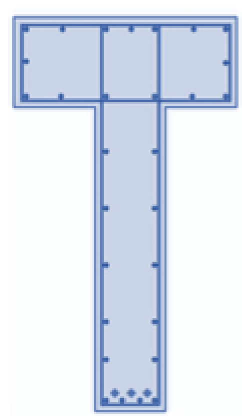
FRP reinforced concrete design, per ACI 440, specifies a minimum amount of FRP rebar, making the concrete the weak point. Concrete failure is the warning sign of potential failure, while retaining FRP tensile strength.



Long term durability must be reviewed when evaluating FRP rebar. Field performance of existing structures that contain FRP rebar demonstrate that service life of concrete structures can be extended to more than 100 years.

Codes & Design Guides

ASTM D7957	*Fiberglass Rebar Material Specifications*
ACI CODE-440.11-22	*Building Code Requirements for Structural Concrete Reinforced with GFRP Bars*
ACI 440.1R-15	*Guide for Design & Construction of Structural Concrete Reinforced with FRP Bars*
ACI 440.5-22	*Construction with Fiber-Reinforced Polymer Reinforcing Bars*
AASHTO BDS	*Bridge Design Guide Specifications for GFRP-Reinforced Concrete*
ACI 440.6-08	*Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement*
ACI 440.3R-12	*Guide Test Methods for FRP Composites for Reinforcing or Strengthening Concrete Masonry Structures*
ACI 440.2R-08	*Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*
ACI 440.7R-10	*Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures*
CSA 807-19	*Specification for Fibre Reinforced Polymers*
CSA 806-12	*Design & Construction of Building Components with FRP*
CSA S6019	*Highway Bridge Design Code*
CAN/CSA-S6-06	*Fibre Reinforced Structures, Canadian Highway Bridge Design Code*



Industry & Association

The FRP rebar industry is growing and has global influence. Initiatives from the NSF and FHA prompted early promotion of FRP technology in the United States. ACI created Committee 440 in 1991, which paved the way for design guidelines and construction recommendations. AASHTO specifications follow mandated LRFD methods. Recent events and legislation, including Congress passing the Infrastructure Investment and Jobs Act in 2021, have only bolstered FRP rebar use in Federal, State, and Local construction projects. Outlook for FRP rebar remains strong and has substantial potential for growth.

Here is a non-comprehensive list of various manufacturers, suppliers, and academic institutions in North America:

Manufacturers

- B&B FRP Manufacturing Inc.
- Marshall Composite Technologies, LLC
- Owens Corning Infrastructure Solutions, LLC
- Pultrall, Inc.
- Pultron Composites
- TUF-BAR Inc.
- Forest Products Supply Co.
- C1 Pultrusions
- Composite Rebar Tech.
- MST Bar
- Raw Energy Materials Corp.
- BP Composites
- American Fiberglass Rebar

Suppliers / Distributors

- AOC
- Aramco Services Company
- Arkema, Inc.
- Composites One, LLC
- INEOS Composites
- Interplastic Corporation
- Mafic Inc.
- Olin Epoxy
- Owens Corning
- Teijin Holdings USA, Inc.
- SuperForm
- Kodiak Fiberglass Rebar
- ConServ Epoxy
- Tillco
- Dow Chemical

Affiliates

- Clemson Composites Center
- Miller & Long Co., Inc.
- North Carolina State University - Civil Engineering
- Ryerson University
- University Of Massachusetts Lowell
- University Of Miami; Civil, Architectural, & Environmental Engineering
- University Of Sherbrooke
- West Virginia University

The major associations and administrations in the FRP industry include:

ACMA — American Composites Manufacturers Association

FRP-RMC — FRP Rebar Manufacturers Council

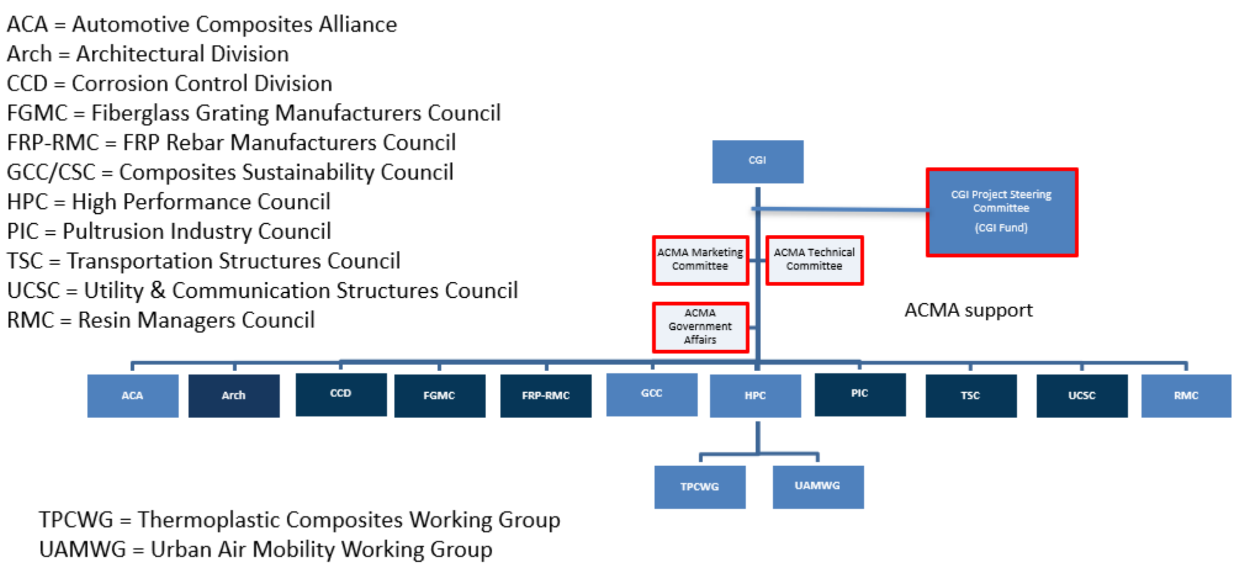
aci

U.S. Department of Transportation Federal Highway Administration

ICC International Code Council®

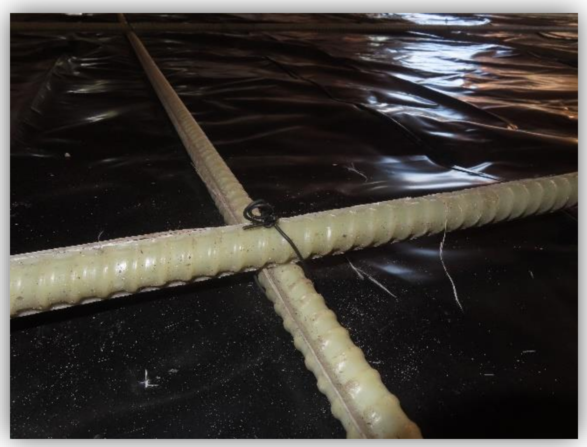
AASHTO

In parallel to manufacturers, vendors, and regulators, there are many partnerships in place to aid in promotion and endorsement of construction technology. A map of several councils and alliances for FRP-related groups is shown here:

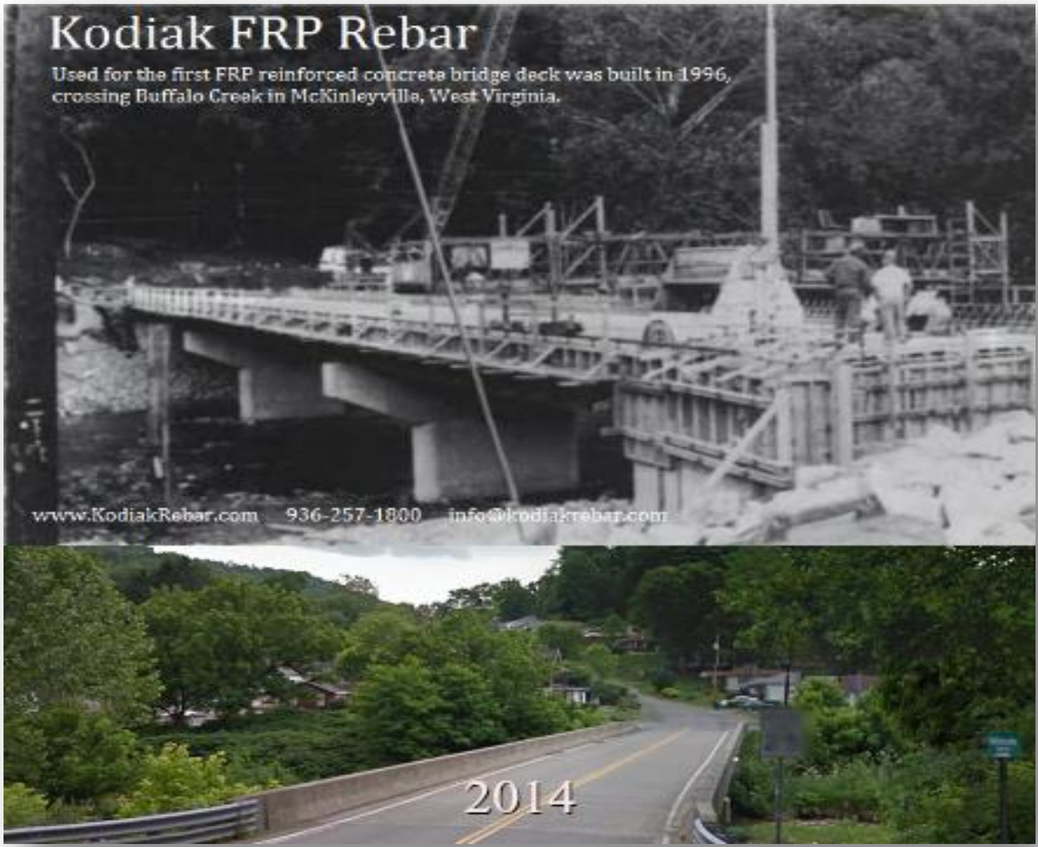


Conclusion

In summary, FRP rebar remains an emerging technology that has great potential for use in the United States and abroad. In fact, the global FRP rebar market is presently valued at more than $600 million and is projected to reach $1.8 billion by 2032. As a resilient, corrosion-resistant alternative, FRP rebar continues to be a corrosion resistant innovative construction material. Civil infrastructure life can be extended, maintenance costs can be reduced, and structural integrity can be upheld with proper engineering and construction techniques. If the superior properties of FRP rebar are fully considered, and remaining obstacles can be overcome, it's hard to disagree that a better material can be found to replace traditional steel bar reinforcement.



FRP Rebar Project Examples



Kodiak Fiberglass Rebar, used for the First FRP Reinforced Bridge in U.S. History
(Mckinleyville Bridge over Buffalo Creek, West Virginia 1996)

References

1. *Reinforced Concrete with FRP Bars*, *Antonio Nanni et. al, 2014*
2. *Field Applications of FRP Reinforcement: Case Studies, ACI International, 2003*
3. *Fiber Reinforced Polymer Composites Rebar, J. Busel, ACMA, 2016*
4. *Glass Fibre Reinforced Polymer Bars in Concrete Compression Members, Joel Brown*
5. *Why GFRP is Becoming Material of Choice in 2023, Borna Hajimiragha*
6. *Fiber-Reinforced Polymer Reinforcement for Concrete Members, Ekenel et. al, 2021*
7. *Strength Degradation in Curved FRP Bars Used in Concrete Reinforcement, Imjai et. al, 2020*
8. *Maximum Strength Deformed GFRP Reinforcement Bar, SureBuilt, 2024*
9. *Bend Strength of FRP Bars: Experimental Investigation and Bond Modeling, ASCE, Imjai et. al, 2017*
10. *Analysis of Properties of the FRP Rebar to Concrete Structures, K. Brozda et. al, 2017*
11. *FRP Rebar-A State of the Industry Report, ASCE, D. Gremel, 2012*
12. *Allied Market Research: FRP Market Forecast*, 2024
13. *Composites World, FRP Rebar,* 2024
14. *ACI 440.11-22 Designing with GFRP Rebar*, ACMA, C. Shield, 2023

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