

FRP Strengthening of Concrete Bridges

Fiber-reinforced polymer (FRP) composites are now a routine tool for strengthening and repairing concrete bridge members. Thin carbon or glass laminates bonded to a girder soffit, U-wraps on a web, near-surface-mounted bars in grooves, and wraps on columns and piles can add flexural, shear or axial capacity in hours of work, with little added weight and no corrosion of the strengthening material itself. They also fail in ways steel and concrete do not, mostly by debonding at the ends of the laminate or across cracks, and their performance depends almost entirely on the condition of the concrete they are glued to. This course explains FRP materials, the strengthening methods state DOTs have used, the failure modes that govern design, the questions to ask before strengthening, and the installation and inspection controls that decide whether the design capacity is ever achieved. It draws on FHWA's Report on Techniques for Bridge Strengthening (FHWA-HIF-18-041), the front matter, contents and introductory chapter of ACI PRC-440.2-23, the FHWA/NHI Underwater Bridge Repair, Rehabilitation, and Countermeasures reference manual (FHWA-NHI-10-029), and Chapter 7 of the Florida DOT Bridge Maintenance Course Series Reference Manual. The numerical design provisions of ACI 440.2 and the AASHTO guide specifications are not reproduced here; use the current documents for design.

Learning objectives

- Explain FRP materials
- Identify failure modes including debonding
- Apply strengthening limits
- Detail installation QC

Why FRP, and where it fits

FHWA's Report on Techniques for Bridge Strengthening (FHWA-HIF-18-041) set out to update the two earlier national references on the subject: NCHRP Report 293, *Methods of Strengthening Existing Bridges* (1987), and NCHRP Synthesis 249, *Methods for Increasing Live Load Capacity of Existing Highway Bridges* (1997). Those reports list the traditional strengthening techniques: (1) reduced dead load, (2) lightweight decks, (3) development of composite action, (4) improved member strength, (5) increased transverse stiffness, (6) adding or replacing members, (7) strengthening connections, (8) post-tensioning members, and (9) development of bridge continuity.

What changed in the twenty years after 1997 was composites. In the FHWA project's literature search, "nearly 90 percent of the reports and papers found involved applications of advanced composite materials." Of the FHWA Innovative Bridge Research and Construction (IBRC) and Innovative Bridge Research and Deployment (IBRD) repair or strengthening projects, about 85 percent used FRP composites as the innovative technology, and FRP sheet or plate bonding to increase flexural or shear strength was the most common method.

ACI PRC-440.2-23 frames FRP as "an alternative to traditional strengthening techniques such as steel plate bonding, section enlargement, and external post-tensioning," and gives the reasons it is attractive: FRP systems "are lightweight, relatively easy to install, and noncorroding." It adds that thin cured profiles suit places "where aesthetics or access is a concern," that FRP adds little weight, and that it can be used where access is limited.

First, confirm the bridge needs strengthening

The FHWA report makes a point that should precede every FRP design: "the first step in the process is to determine whether or not the candidate bridge actually needs to be strengthened." Retrofit and traffic disruption costs are substantial. Refined analysis and field testing "can often be conducted at a fraction of the cost of a complete retrofit," and can sometimes show the bridge does not need strengthening at all. The report recommends that engineers consider advanced analysis or field testing before designing an extensive retrofit. Among its shear findings is the same lesson from the field: "Load testing of a bridge should be conducted prior to strengthening, because capacity calculations based on strengthening codes can vary from the actual capacity." BR-L01 and BR-L06 cover load rating and load testing.

What an FRP composite is

FHWA-HIF-18-041 defines FRPs as a thermosetting or thermoplastic polymer matrix with embedded reinforcing fibers. "The fiber network is the load-carrying component of the composite and the matrix serves to bond the fibers together, transfer loads to the fibers, maintain fiber orientations, and provide protection to the fibers." Glass, carbon and aramid fibers give GFRP, CFRP and AFRP. ACI PRC-440.2-23 defines an FRP system as "the fibers and resins used to create the composite laminate, all applicable resins used to bond it to the concrete substrate, and all coatings applied to protect the constituent materials"; purely aesthetic coatings are not part of the system.

Fibers

The FHWA report's Table 2 gives representative fiber properties (all values as listed there):

Fiber	Tensile modulus (ksi)	Tensile strength (ksi)	Pros	Cons
E-glass	10,500	500	Low cost, high tensile strength, chemical resistance, insulating	Low modulus, relatively high density, relatively low fatigue resistance
S-glass	12,400	665	As E-glass	As E-glass
Basalt	12,500	580	Low cost, chemical resistance, thermal stability	Brittle, limited applications, lack of codes and guidelines
PAN-based carbon	33,360 to 86,300	280 to 900	High specific modulus and strength, very low thermal expansion, high fatigue strength	High cost, complex manufacture, brittle
Kevlar 49 (aramid)	18,000	525	High damping, impact resistance	Hygroscopic, low compressive strength, prone to UV degradation

For comparison, the report lists mild steel at a modulus of 30,000 ksi. So a carbon fiber can be stiffer than steel, while glass fibers are about a third as stiff. These are fiber properties. A cured laminate contains resin as well, so its properties are lower; the report's Table 1 lists a unidirectional carbon/epoxy composite (62 percent fiber volume) at 19,700 ksi modulus and 278 ksi strength, and a unidirectional glass/epoxy at 4,000 ksi and 114 ksi.

The report also notes that aramid fibers have compressive strength about 45 times lower than their tensile strength, and that boron fibers are very stiff but very costly. ACI PRC-440.2-23 now includes basalt FRP among commercially available systems.

Fiber architecture

Properties depend on how fibers are arranged. In unidirectional (UD) fabrics, over 95 percent of fibers run in one direction; UD composites are strong along the fibers and weak across them, so plies are stacked at chosen angles for multidirectional demand. Woven fabrics conform better to complex surfaces, but fibers are crimped at crossovers, which can reduce tensile strength, and maximum fiber content is lower than in UD composites. For strengthening, this means FRP is strong only in the directions the designer put fibers. A sheet applied in the wrong orientation adds little.

The matrix and glass transition temperature

The matrix controls transverse and shear properties and "particularly the service temperature of the composites." Polymers soften as temperature rises, passing from a glassy to a rubbery state at the glass transition temperature (T_g). The FHWA report's Table 3 lists T_g ranges for thermosets: polyester about 165 to 300 °F, epoxy about 210 to 480 °F, vinyl ester about 190 to 390 °F. Epoxies are described as superior to polyesters for chemical resistance and adhesion to fibers. The NHI underwater repair manual summarizes the practical consequence: composite properties are temperature dependent and "may be reduced at temperatures above approximately 180° F," while some materials become brittle in cold. FDOT notes for FRP decks that FRP "can lose strength when exposed to high heat that could result from vehicle accident and resulting fire," which is one reason FRP decks carry a wearing surface.

How FRP differs from steel

The NHI manual lists differences bridge engineers should keep in mind: FRP is non-isotropic; strength-to-weight is high; the composite modulus can be low, which increases deflection; "failure strength and other properties are time dependent. The allowable sustained load is smaller than the short term"; creep is larger than in steel or concrete; and FRP bars "do not exhibit yielding prior to failure." The last point matters most: FRP is linear elastic to rupture. A strengthened member's ductility comes from the existing steel, not from the FRP.

How FRP is made and supplied

The FHWA report describes the processes used for composite products. Three are relevant to bridge strengthening:

- **Wet layup (hand layup)**, "the simplest and most commonly used processing method," where fabrics are saturated with resin and placed by hand with rollers or brushes, then cured in place. Most field-applied sheet and wrap systems are wet layup. Complete air removal and resin saturation are needed for consistent quality.
- **Pultrusion**, an automated process that pulls fibers through a resin bath and a heated die to make constant-section products with high fiber volume. Pre-cured strips and laminates and many FRP deck sections are pultruded.
- **Resin transfer molding and VARTM**, closed-mold processes where resin is drawn into a fiber preform, in VARTM by vacuum under a bag. FDOT notes that solid-core sandwich FRP decks are made by VARTM, and the FHWA report describes research on using VARTM in the field because it "yields a better, stronger bond due to even and thorough distribution of epoxy."

Because the materials are engineered, the FHWA report notes there is "not [a] set of standard material properties, nor a standard set of material handling and construction guidelines," and each vendor's products have their own properties and guidelines. It recommends that bid specifications "provide a range of properties that have to be satisfied" and installation specifications consistent with the vendor's guidelines, so the project need not be sole-sourced.

ACI PRC-440.2-23 is direct about mixing products: "Untested combinations of fibers and resins could result in an unexpected range of properties as well as potential material incompatibilities and should be avoided." Any system "should have sufficient test data to demonstrate adequate performance of the entire system in similar applications, including its method of installation." ACI 440.8 is cited as the specification for unidirectional carbon and glass wet layup systems. Practically: specify and accept a system, not a fabric and a separately sourced resin.

Strengthening methods used on bridges

The FHWA report describes seven families of newer methods and says the most prevalent on state DOT projects were externally bonded FRP, near-surface-mounted composites, and column retrofitting with composites.

Externally bonded (EB) FRP

EB FRP applies the composite to the member's external face with epoxy, as strips, plates, sheets or wraps. With pre-cured plates the epoxy is an adhesive; with dry sheets applied on site the epoxy becomes the matrix and the adhesive. Curing takes "a matter of hours, so traffic closures are minimal," and some research suggests traffic loading does not affect bond, so the bridge may stay open. FRPs bonded to the tension face increase flexural capacity; bonded to beam sides, shear capacity; wrapped around columns, axial, flexural and shear capacity and impact resistance. EB FRP also restrains crack opening, which can improve stiffness, and protects the concrete surface.

The main drawback: "the ends of the FRP are vulnerable to peeling or delaminating from the structure due to high shear stresses at the end locations." Remedies include beveling pre-cured plate edges and anchoring ends with transverse composite strips or mechanical fasteners. The report states that "a combined system of externally bonded and mechanically fastened FRP material provides the most reliable strengthening effect."

Near-surface-mounted (NSM) FRP

NSM cuts a groove in the concrete surface, fills it partly with epoxy, places an FRP strip or rod, and fills the rest. The idea, quoted in the report, is to add reinforcement "in such a way that it acts compositely with the rest of the section in the same way as if it were cast into the concrete." Three sides of the bar are bonded, which "minimizes the chance for debonding and increases force transfer," and the bar is better protected from the environment. NSM gives "a significant increase in moment capacity with relatively little repair material," and NSM bars can be prestressed. Cover must be enough to cut the groove without hitting existing bars.

Post-tensioned FRP

Tensioning an FRP strip or rod before anchoring it puts the member into compression, lets the FRP carry part of the dead load, and uses more of its strength. The report notes the increase in total capacity is greater if the FRP carries dead load, either by jacking the structure before application or by post-tensioning the FRP, but jacking requires a closure that a passive FRP retrofit would avoid.

Fiber reinforced cementitious matrix (FRCM)

FRCM uses dry fiber fabric in a cement-based mortar. The report lists benefits over epoxy-based FRP: inorganic water-based binder, UV resistance, permeability compatible with concrete, and workability between 40 and 105 °F. ACI 549.4R covers its design.

Spray FRP and column wraps

Spray FRP applies resin and short random fibers with a spray gun; the report cites a field repair of severe spalling that looked unchanged three years later, but calls beam rehabilitation with spray FRP an area of ongoing research. FRP column wraps for seismic ductility are described as "quite mature" (BR-E02 covers seismic retrofit); they are also used outside seismic regions to restore strength of columns damaged by impact or deterioration.

Lightweight FRP decks

The other common IBRC composite application was FRP decks to reduce dead load and so raise live-load capacity. A source quoted by FHWA says they weigh 80 percent less than cast-in-place concrete decks, erect twice as fast, and may last two to three times longer. Lessons learned include needing a sufficiently flexible wearing surface, drilling drain holes at installation, not using foam cores, and that full composite action with the girders has been difficult to achieve.

Failure modes: why debonding governs

A steel-reinforced concrete beam usually fails in flexure by yielding of the steel and then crushing of the concrete. Adding a bonded laminate creates new ways for the member to fail, and most of them involve the bond rather than the FRP itself. ACI PRC-440.2-23 states it plainly: "For both flexural and shear strengthening, there are different modes of debonding failure that can govern the strength of an FRP-strengthened member. While most of the debonding modes have been identified by researchers, more accurate methods of predicting debonding are still needed."

Because debonding is hard to predict, the guide's design procedures impose "significant limitations on the strain permitted in the FRP system (and thus, the permitted stress)" to "conservatively account for debonding failure modes." This is the most important design concept in the course: **in a typical EB design the FRP is not taken to its rupture strength.** The usable strain is capped well below rupture, which means the tensile strength printed on the data sheet is not the strength the design uses. The specific strain limits are in the current ACI 440.2 and AASHTO guide specifications and are not reproduced here.

The failure modes to recognize

- **End peeling (plate-end debonding).** The FHWA report says the ends of EB FRP are "vulnerable to peeling or delaminating from the structure due to high shear stresses at the end locations." Peeling can rip off the concrete cover along with the laminate, so the failure plane is in the concrete, not the adhesive.
- **Intermediate crack-induced debonding.** In regions of high moment, flexural or flexure-shear cracks open and the laminate debonds starting at the crack and moving toward the end. The FHWA report notes for shear strengthening that "dynamic debonding and deformation from the movement of a composite strengthening system on either side of a shear crack can cause the composite to fail at lower strains than the failure strain of tensile coupons."
- **Debonding of U-wraps.** U-wraps add shear capacity, "but the new governing failure mode is debonding of the U-wrap."
- **Debonding at plate joints.** Joints in EB plates "may be vulnerable to delamination under large strains," so they should not be placed at maximum-moment locations.
- **FRP rupture.** With adequate anchorage the laminate can reach rupture. The report notes that U-wraps used as anchorage "allow the FRP to reach rupture without debonding." Rupture is brittle; the FRP does not yield.
- **Concrete crushing or failure of the existing member.** Adding tension reinforcement moves the neutral axis and can shift a tension-controlled section toward compression failure. The member's own steel and concrete limits still apply.

Anchorage

The tools for delaying debonding are anchorage and detailing. ACI PRC-440.2-23 lists anchorage methods researched to date, "such as U-wraps, mechanical fasteners, fiber anchors, and U-anchors," and says the 2023 edition contains design provisions for fiber anchors used with shear U-wraps. "For other anchorage systems and applications, few design guidelines are currently available," and their performance "should be substantiated through representative physical testing that includes the specific anchorage system, installation procedure, surface preparation, and expected environmental conditions." The guide also says that "steps related to the surface preparation and proper termination of the FRP system are vital in achieving the levels of strength predicted."

The FHWA report's field findings point the same way: U-wraps at laminate ends, transverse strips, beveled plate edges, and mechanically fastened FRP. Its conclusion that "a combined system of adhesively-bonded and mechanically fastened plates provides the most reliable strengthening procedure" appears twice, once in the methods review and once in the IBRC lessons.

Ductility

The FHWA report found that EB FRP "can increase the ultimate capacity of concrete girders significantly without sacrificing the member's ductility," but it also found that "steel beam failure is less ductile when the beam is retrofitted with composite materials." Since FRP is elastic to failure, the designer has to confirm that the existing steel still yields before the FRP debonds or ruptures if a ductile failure is wanted.

Strengthening limits and the unstrengthened member

A key concept in ACI 440.2 is the strengthening limit: how much strengthening a member can be given, considering what happens if the FRP is lost to fire, vandalism, impact or debonding. Chapter 9 of ACI PRC-440.2-23 (General Design Considerations) contains Section 9.1, Design philosophy, and Section 9.2, Strengthening limits. The 2023 preface says the load combination in Section 9.2.1 for minimum structural fire resistance of an FRP-strengthened member was revised to be consistent with ACI CODE-562. The specific load combinations are in the current guide and are not reproduced in this course; use them for design.

The reasoning behind a strengthening limit is easy to follow from the material properties already covered:

- FRP and its epoxy lose properties at elevated temperature, as the T_g discussion showed, so a fire can remove the FRP's contribution.
- An EB laminate sits on the outside of the member, exposed to vehicle impact and vandalism.
- Debonding is hard to predict, as ACI notes.

So the existing member has to be able to carry some defined load on its own without the FRP. That puts a ceiling on what FRP can do for a badly under-strength member. A girder that needs a very large increase may be a candidate for replacement, supplemental members or external post-tensioning instead.

Whole-bridge capacity

The FHWA owner survey adds a bridge-specific caution: "strengthening a bridge does not always increase its live load capacity if only a portion of the bridge is being patched or repaired. Analyses should always be run to verify that the strengthening repair will increase the live load capacity of the entire structure before allowing heavier traffic." Strengthening the positive-moment region of an interior girder does not help if the exterior girder's shear, the deck, the bearings or the substructure still controls. The load rating after strengthening is a check on every element.

Service limit state and dead load

Passive FRP bonded to a loaded member carries only loads applied after installation. The owners told FHWA to "consider the service limit state" and recommended jacking before repair "so that the FRP material can arrest cracks due to service loads as well as increase the maximum capacity," while noting that jacking requires a closure a composite retrofit might otherwise avoid. Two other ways to get the FRP into the dead-load path are post-tensioning the FRP and, where a deck replacement is planned, bonding the FRP first: "application of the repair prior to replacing the deck allows the FRP to help carry the new deck dead load."

Sustained load and creep

The NHI manual notes that FRP properties are time dependent and that "the allowable sustained load is smaller than the short term." ACI PRC-440.2-23 says fatigue and creep "are also addressed by stress limitations" in the guide, and the 2023 edition updated fatigue behavior. For bridges, with constant dead load and many live-load cycles, those limits must be checked.

Environmental reduction

ACI PRC-440.2-23 accounts for environmental degradation and long-term durability "by providing reduction factors for various environments," and cautions about applications where the FRP system "is subjected simultaneously to extreme environmental and stress conditions." Exterior bridge exposure generally falls in the harsher categories. The guide states that "based on the available research, the design procedures outlined herein are considered conservative."

Flexural strengthening in practice

Hundreds of structures have been strengthened in flexure with FRP, and the FHWA report says many installations date to the 1980s. Through IBRC alone, concrete T-beams, prestressed bulb-T beams, arch bridges, concrete box beams and steel plate girders were strengthened in flexure. Most of that work used EB FRP.

Key findings for concrete members

- Repair the substrate first: "The concrete substrate should be repaired, and spalling and chloride ions removed, prior to strengthening to prevent further deterioration from these problems after strengthening."
- U-wraps at the laminate add anchorage, stiffness and cracking moment and can allow the FRP to reach rupture without debonding.
- One-way slabs can be strengthened with soffit strips and two-way slabs with a grid pattern.
- EB FRP combined with prestressed steel rods gave higher ultimate capacity while keeping ductility and improving serviceability.
- CFRP laminates can be prestressed directly.
- Bi-directional fabric can increase both flexural and shear capacity.

IBRC lessons

- "As few as two people can install pre-cured FRP plates," making the technique suitable for agencies with limited staff, such as counties.
- Traffic can stay open during bonding, "but closing traffic may lead to a stronger bond." The epoxy reaches full strength in hours.
- Early projects had installation problems, "leading to longer than anticipated installation times and less than ideal final products (with air bubbles or peeling)." Training materials were developed in response.

- FRPs are susceptible to UV deterioration, so a protective coating is recommended.
- "The most significant factor in the success of external FRP bonding is proper surface preparation." If the surface is not properly prepared, the FRP may delaminate, causing a loss in strength.
- Don't place joints between adjacent plates at maximum-moment locations.

Steel girders

FRP has been bonded to steel girders as well. The FHWA report gives three specific cautions: prevent galvanic corrosion between a steel girder and carbon fibers; do not encase the bottom flange in wraps or sheets, "because it will trap water and salts"; and prefer extra layers on the bottom flange to layers on the web. Prestressing improves the effect of CFRP plates on steel girders. BR-F01 covers steel fatigue, which matters if FRP is used near fatigue-sensitive details.

Timber

For timber beams, glass FRP has increased flexural capacity; it should be applied only to the tension face, and mechanically fastened FRP worked best with closer fastener spacing. Diagonal layup of EB sheets beat vertical layup for timber shear strengthening.

Shear strengthening in practice

Shear strengthening uses FRP sheets or strips on the web, U-shaped stirrups, L-shaped plates, NSM laminates or rods, and shear spikes. Concrete T-beams, channel beams, prestressed girders and timber beams have been strengthened in shear in the field, sometimes together with flexure.

Wrapping schemes

ACI PRC-440.2-23 Chapter 11 includes a section on wrapping schemes (11.2). The FHWA findings below mention full wraps, U-wraps and side-bonded vertical strips. On a girder with a deck on top, a full wrap cannot pass around the section without going through the slab, so U-wraps and side strips are the practical choices, and their anchorage becomes critical.

FHWA findings

- U-wraps increase shear and deformation capacity, but debonding of the U-wrap becomes the governing failure mode.
- "The application of vertical strips with a horizontal anchoring strip was found to be the most effective shear strengthening system orientation for RC girders."
- Where a full wrap is used, leave it unbonded on the sides of the beam, which gave a greater increase in shear strength than full bonding.
- Partial or full embedment of L-shaped CFRP stirrups is more effective than EB FRP.
- The embedded through-section (ETS) method drills through the web and bonds bars in the core, giving a better bond than EB or NSM. A UK compilation quoted in the report says "FRP bars glued into drilled holes in the web of a beam adds substantial shear strength."
- For bridges built without internal shear reinforcement, EB FRP stirrups can work, but implanted shear bars are more effective.
- CFRP grids installed vertically in deck slabs can change the failure mode from shear to flexure, and FRP double-headed shear bars are easy to install in shallow members.
- Load test before strengthening, because code-based capacity calculations "can vary from the actual capacity."

The quoted UK finding adds that "shear strengthening is affected by the size of the beam being treated and debonding and strain checks need to be made." Many lab tests used small beams; full-size bridge girders may not show the same gains.

The substrate and corrosion

An EB laminate is only as strong as the concrete it is bonded to. The owners told FHWA: "The effectiveness of the repair is directly related to the soundness of the substrate it is bonded to. In the case of concrete applications, the strengthening only works to its full extent if the concrete surface is in good condition (not spalling)." Since the failure plane in a debond is often in the concrete just beneath the adhesive, weak, contaminated or delaminated cover concrete means a weak strengthening system.

Corrosion

Many bridge members that need strengthening are deteriorated, and the usual reason is corrosion of the reinforcement. The NHI underwater repair manual warns: "When FRP is used to strengthen piles with active corrosion, consideration should be given to the potential for future corrosion within the strengthened area. ACI 440.2 guidelines caution that installation of FRP systems does not stop ongoing corrosion." The FHWA flexural findings say the same thing from the design side: repair the substrate and remove spalling and chloride ions before strengthening, "to prevent further deterioration from these problems after strengthening."

The risk is that a laminate or wrap covers the concrete and hides continuing corrosion. Expansion of corrosion products can then push the cover, and the FRP with it, off the member, while the inspector sees only an intact composite surface. TxDOT studied this directly in research cited by FHWA, including *Effects of Wrapping Chloride Contaminated Concrete with Fiber Reinforced Plastics* (FHWA/TX-03/1774-2) and later reports on FRP-wrapped columns and beams in a corrosive environment.

So a sound FRP project starts with a condition assessment of the member: delamination survey, chloride and cover data where corrosion is suspected, and repair of section loss and spalls (BR-C01 covers concrete deterioration mechanisms, BR-C02 concrete repair methods, and BR-P02 damage to prestressed members). Corrosion mitigation, such as galvanic anodes or removal of contaminated concrete, may be needed before the FRP goes on.

Vendor bid items for concrete repair

The vendor bid templates summarized by FHWA list the work that comes before the FRP: "repair of defective reinforcement, restoration of concrete cross section, and cleaning and preparation all concrete surfaces prior to installing the FRP system," followed by surface preparation, "surface grinding, chamfering corners, grooves for near-surface mounted FRP system, surface profiling, and surface cleaning." Chamfering corners matters for U-wraps and column wraps, since fibers wrapped around a sharp corner are stressed there.

Installation and quality control

Every part of an FRP strengthening design assumes a correct installation. The FHWA report and ACI PRC-440.2-23 agree on where things go wrong: surface preparation and termination details.

Who installs it

ACI PRC-440.2-23 Chapter 6, Installation, begins with Section 6.1, Contractor competency. The FHWA owner survey adds that "it is essential to have a manufacturer representative on site to ensure successful installation of the material," and that a knowledgeable workforce is needed for design, installation, maintenance and inspection. The early IBRC projects showed what happens otherwise: longer installation times and finished products with air bubbles or peeling.

The sequence

The chapters of ACI PRC-440.2-23 give a useful checklist of the topics an installation specification needs to cover:

- Shipping, storage and handling (Chapter 5).
- Temperature, humidity and moisture considerations (6.2). Resins have minimum application temperatures and are sensitive to moisture on the substrate.
- Equipment (6.3).
- Substrate repair and surface preparation (6.4).
- Mixing of resins (6.5). Two-part epoxies must be proportioned and mixed correctly and used within their pot life.
- Application of FRP systems (6.6).
- Alignment of FRP systems (6.7). Fiber direction is the strength direction.
- Multiple plies and lap splices (6.8).
- Curing of resins (6.9).
- Temporary protection (6.10).

The vendor templates FHWA summarized cover much the same ground: shoring of repaired members, environmental conditions before and after installation, application by system type (wet layup with primer, putty, saturant, plies, overlaps and anchors; pre-cured with adhesive; NSM with embedding paste; column wraps), curing (method, time for full cure, minimum application temperature), protective coating "especially [against] UV radiation," temporary protection, inspection and quality assurance, and repair of defective work.

Inspection and acceptance

ACI PRC-440.2-23 Chapter 7 (Field inspection, testing, and evaluation) was revised in 2023 "to be consistent with industry standards and specifications such as the IBC, ACI SPEC-440.12, and ACI CODE-562." It covers field inspection (7.2), material testing (7.3), evaluation and acceptance criteria (7.4) and evaluation of coatings (7.5). The vendor templates list inspection items as "inspection for debonding, inspection for adhesion, inspection for cured thickness, and auxiliary tests," and repair of defective work as "repair of protective coating, epoxy injection of small defects, patching of minor defects."

In plain terms, the inspector is checking that the substrate was prepared as specified; that the right system, in the right number of plies, was placed in the right direction; that resin was mixed and cured within the manufacturer's limits; that there are no voids or delaminations beyond acceptance limits; and that the cured system bonds to the concrete. The acceptance limits and test methods are in the current ACI documents and the project specification.

Records

Because FRP is proprietary and its properties vary by product, the as-built record should identify the specific system, the material data the design relied on, batch information, and the inspection results. A future inspector or load rater needs to know exactly what is on the member.

Specifications and state DOT practice

The FHWA report summarizes the national documents for composite strengthening that existed when it was written:

- AASHTO, *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*, 1st edition, 2012.
- ACI 440.2R (now ACI PRC-440.2-23), ACI 440.8 (specification for wet-layup carbon and glass systems), ACI 440.3R-12 (guide test methods for FRP), and ACI 549.4R (FRCM).
- NCHRP Reports 503, 514, 564, 609, 655 and 678 on FRP design, construction specifications, field inspection and related topics. The NHI manual cites NCHRP Report 514 alongside ACI 440.2 for design.

Chapter 5 of the FHWA report describes states active in FRP:

- **Florida:** Structures Manual Volume 4, Fiber Reinforced Polymer Guidelines (FRPG), plus durability research.
- **California:** LRFD guidelines for FRP strengthening of reinforced concrete (2006).
- **Maine:** design and construction guidelines for FRP piles, structural FRP tubes and FRP strengthening, including flexural retrofit of concrete slab bridges.
- **Texas:** long-term performance research on wrapped members in corrosive environments, plus CFRP anchor design recommendations and quality control procedures (FHWA/TX-16/0-6783-1).
- **Kentucky:** FRP projects since 1996, including over 20 externally bonded FRP projects on in-service bridges.
- **Virginia:** FRP girders, FRP decks and GFRP bars.
- The report also reviews New York State DOT, Oregon DOT, Washington State DOT and Michigan DOT documents.

The report notes that early state projects were treated largely as "demonstration" projects, often with research partners. Before designing FRP strengthening, check whether your own agency has an FRP design guide, special provision or qualified-product list. Where it does, it controls.

Design examples

Chapter 8 of the FHWA report points designers to three existing worked examples from NCHRP Report 655 (flexural strengthening of a reinforced concrete T-beam with EB FRP, shear strengthening with an EB U-jacket, and flexural strengthening with NSM FRP), plus four new traditional-materials examples published separately as FHWA-HIF-18-042 through -045. ACI PRC-440.2-23 Chapter 16 has further examples, including flexure of RC and prestressed beams, NSM bars, shear of a T-beam, column confinement and seismic applications.

Inspecting and maintaining FRP-strengthened members

FRP strengthening changes what an inspector can see. The laminate covers the concrete surface where cracks, rust staining, efflorescence and spalls would normally show up. The FHWA owner survey reported that "inspection of FRP repairs was reported as extremely difficult," and the report concluded that while design and construction guidance is fairly available, "inspection and maintenance guidelines are not. This is an obvious target for future research and development." The 2023 ACI guide has a Chapter 8 on maintenance and repair, with sections on inspection and assessment (8.2), repair of the strengthening system (8.3) and repair of surface coating (8.4).

What to look for

FDOT's maintenance manual gives a list for FRP decks of when to call the structural engineer and the same conditions apply to bonded strengthening:

- Delaminations between fiber layers.
- Blistering on the surface or debonding of the material.
- Cracking or fiber exposure.
- Voids, wrinkling or discoloration.

Add to that the conditions the earlier sections point to: peeling at laminate ends and at plate joints; rust staining, efflorescence or bulging at edges that could mean corrosion underneath; damaged or chalking UV coating; impact or fire damage; and moisture trapped behind wraps. Sounding the laminate with a hammer or coin can locate debonded areas, much as it locates delaminated concrete. BR-I06 covers concrete inspection generally.

Repair

The vendor templates list the repairs for defects found at installation: coating repair, epoxy injection of small defects and patching of minor defects. FDOT advises that FRP deck repair "is not advised for bridge maintenance crews unless they have had special training in the repair of FRP and are capable of wet lay-up repairs," because of the variety of fibers and resins; wet layup repairs have restored load capacity, but their durability "is not well documented." For localized deterioration of an FRP deck, FDOT suggests steel plating as an emergency repair until the engineer can assess the situation.

Recording it

For inventory and rating purposes, an FRP-strengthened member should be clearly flagged in the inspection file so future inspectors know what is under the laminate, and the load rating should document whether the FRP was counted. If the FRP is damaged, the rating may need to revert to the unstrengthened capacity.

FRP decks, bars and piles

This course is mainly about strengthening existing concrete members, but FRP shows up on bridges in three other ways that an owner or inspector should recognize.

FRP decks

FDOT describes FRP decks as "very light," "very strong" and noncorroding, and "particularly well suited for moveable bridges and for decks and slabs subject to highly corrosive environments." Modern decks are usually pultruded sections (honeycomb, trapezoidal, or double-web I-beams), solid-core sandwich panels made by VARTM, or hollow-core panels. They are almost always covered with a wearing surface for friction and fire protection, and concrete or polymer wearing surfaces also protect against chemical attack from deicing. When repairing the wearing surface, "care should be taken... to avoid saw cutting or chipping into the FRP deck surface."

The FHWA review gathered lessons from FRP deck projects, including that a flexible wearing surface and bonded joints are crucial (especially on moving bridges), foam cores are not recommended, drain holes should be drilled at installation, and full composite action with steel or concrete girders has been difficult to achieve. West Virginia reported difficulty with FRP decks while finding FRP wraps worked "fairly well."

FRP reinforcing bars

FDOT lists FRP bars as a corrosion-free deck reinforcement option, with drawbacks of "initial costs and field workability," and rates them "Excellent" for corrosion resistance but "Fair" for field workability in its reinforcing bar comparison table. The NHI manual notes that FRP bars do not yield, that tensile strength may vary with bar size, and that they "cannot be field bent." AASHTO published LRFD guide specifications for GFRP-reinforced concrete in 2019, according to the FHWA report's list of national documents.

Piles and substructures

The NHI underwater manual describes FRP strengthening of piles "both above and underwater," noting it is "well suited to providing increased strength and concrete confinement for seismic requirements," and that design should follow ACI 440.2 and NCHRP Report 514, sometimes with design by the FRP system supplier. Glass and carbon fiber with epoxy resins are commonly used. Its corrosion caution, that FRP does not stop ongoing corrosion, applies with special force in splash zones. BR-I09 covers underwater inspection.

An illustrative decision walk-through

All numbers and circumstances in this example are illustrative and do not come from the cited sources.

A county owns a 1960s reinforced concrete T-beam bridge, four girders, simple span of 40 ft (illustrative). A new load rating shows the interior girders' flexural rating factor for a legal load just below 1.0, and the county is considering posting. A consultant proposes CFRP sheets on the girder soffits.

Step 1: Does it need strengthening? Following FHWA-HIF-18-041, the engineer first considers refined analysis or a diagnostic load test. T-beam bridges often carry load more favorably than simplified distribution assumes. If testing shows adequate capacity, no strengthening is needed (BR-L06).

Step 2: What controls the whole bridge? Assume testing confirms a modest shortfall. Before designing FRP, the engineer checks shear in all girders, the deck, the bearings and the substructure. If the exterior girder's shear rating is lower than the interior girder's flexural rating, flexural FRP alone would not raise the bridge's rating.

Step 3: Is the substrate sound? The inspection report notes delamination and rust staining on two girder stems near the drains. Those areas get chloride testing, removal of contaminated concrete and patching before any FRP, with time for the patches to cure as required by the FRP system.

Step 4: Is FRP within limits? The engineer checks the strengthening limit in the current ACI 440.2 and the AASHTO guide specification: can the girder carry the required load without the FRP? Here the shortfall is small, so the answer is yes.

Step 5: Design. The engineer designs to the strain limit for debonding, not the FRP rupture strength; locates terminations away from maximum moment and provides U-wrap anchorage at the ends; checks the service limit state, recognizing that passive FRP carries only live load; and selects a tested system with a UV-resistant coating.

Step 6: Construction and records. The specification requires a qualified installer, the manufacturer's representative on site, environmental limits for application and curing, inspection for debonding and cured thickness, adhesion testing, and repair procedures for defects. The as-built drawings identify the system and plies, and the inspection file flags the strengthened girders. The load rating documents the FRP's contribution.

The steps are general practice drawn from the sources; the bridge and its numbers are invented to show the sequence.

Sustainability and the life-cycle case

ACI PRC-440.2-23 added a sustainability section (1.1.2) that is useful when making the case for FRP to an owner. It recommends a life-cycle approach covering construction, service life (maintenance and preservation) and end of life.

- Carbon and glass fibers have high embodied energy, on the order of 86,000 Btu/lb and 8,600 Btu/lb respectively, against 5,600 Btu/lb for steel, 430 Btu/lb for concrete and 3,870 Btu/lb for reinforcing steel. But the weight of FRP used is "orders of magnitude lower" than steel.
- Lower weight reduces transportation impacts and allows smaller installation equipment.
- FRP is characterized as having a longer service life and needing less maintenance.
- End of life is harder: "less than 1% of FRP composites are currently recycled," and recycled material is generally lower grade.
- Using FRP to extend the life of a structure that would otherwise be replaced "is inherently sustainable," often at "only a fraction" of the monetary and environmental cost of replacement.

The FHWA owner survey makes the economic version of the argument: FRP installations "can be very expensive, but they also offer a much longer service life than traditional materials," and long-term maintenance savings should offset the higher initial cost. Several states reported FRP materials cost more than concrete or steel, and the report expected costs to drop as the materials become mainstream and non-proprietary specifications are published.

Key takeaways

- Confirm the bridge actually needs strengthening with refined analysis or load testing before designing FRP (FHWA-HIF-18-041).
- An FRP system is the fibers, resins, adhesives and protective coatings as a tested whole; untested fiber/resin combinations should be avoided (ACI PRC-440.2-23).
- FRP is linear elastic to rupture and its properties fall at elevated temperature; ductility comes from the existing steel.
- Debonding, at laminate ends, across cracks, at plate joints and in U-wraps, usually governs, so design strains are limited well below rupture.
- Anchorage (U-wraps, transverse strips, mechanical fasteners, fiber anchors) and proper termination are essential; combined bonded and mechanically fastened systems were the most reliable in FHWA's review.
- Strengthening limits mean the existing member must carry a defined load without the FRP; take the load combinations from the current ACI 440.2 and AASHTO documents.
- Strengthening one element does not raise the bridge's rating if another element controls; rerun the whole-bridge analysis.
- The substrate controls bond: repair concrete and remove chlorides first, because FRP does not stop ongoing corrosion.
- Surface preparation is the single most significant factor in success; require a qualified installer and the manufacturer's representative on site.
- FRP repairs are hard to inspect; record the system on the as-built drawings and inspection file and look for debonding, blistering, edge peeling and staining.

References

1. ACI 440.2R-17, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
2. FHWA, Report on Techniques for Bridge Strengthening, FHWA-HIF-18-041 (University of Delaware for FHWA)
3. ACI Committee 440, ACI PRC-440.2-23, Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide, November 2023 (front matter, contents and Chapter 1 reviewed)
4. FHWA, Underwater Bridge Repair, Rehabilitation, and Countermeasures, NHI Course 130091A Reference Manual, FHWA-NHI-10-029
5. Florida DOT, Bridge Maintenance Course Series Reference Manual, Chapter 7 (Section 7.5, Fiber Composite Decks)

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.