FRP Strengthening

What designers need to know

BY SCOTT F. ARNOLD AND HEATH CARR

When designers started using fiber-reinforced polymers (FRP) for structural retrofits over 20 years ago, they had only full-scale structural testing to justify their designs. As codes and guidelines have become more widely available, however, we've observed that designers have become more reliant on the use of empirical equations and less reliant on basic mechanics and structural proof testing. Because empirical equations may not be appropriate for a specific application, however, designs based on these equations may not achieve the desired performance targets.

We've also noted that designers may not be aware of some of the critical issues necessary for proper installation of FRP systems. These systems can't be installed successfully without careful attention to existing conditions, service requirements, material properties, and application details.

WHAT IS STRENGTH?

To properly apply FRP systems, the designer must understand the actual material properties of composite systems. Unfortunately, there has been a trend to market these materials with a focus on their ultimate tensile strength. Descriptions such as "three to ten times the strength of steel" can cause considerable confusion. Strength is important, but all failure modes must be considered.

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Figure 1 contrasts the stress-strain behavior of Grade 60 (420) steel to the behaviors of various precured laminates of FRP materials. As the data indicate, a precured, carbon fiber-reinforced polymer (CFRP) laminate has an elastic modulus of about 20,000 ksi (138,000 MPa). It's important to note, however, that most CFRP wet layup materials have a modulus of about 10,000 ksi (69,000 MPa), much less than the modulus values for precured laminates or carbon fibers alone (a typical modulus for dry carbon fiber is about 33,000 ksi [228,000 MPa]). The tensile strength and modulus values must be determined using the actual thickness and area of the cured laminate.

The flexural capacity of a member strengthened using FRPs may be governed by rupture of the FRP system, detachment of the FRP system from the concrete, or

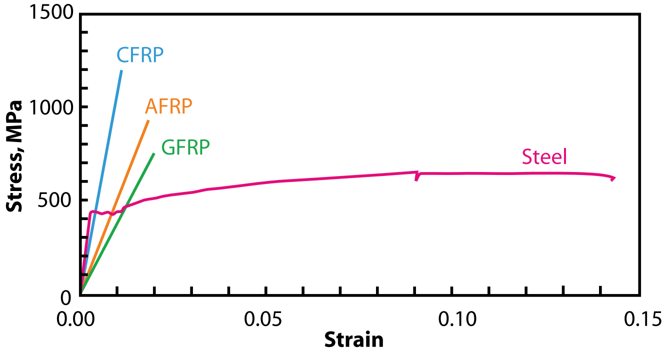

Fig. 1: Carbon fiber-, aramid fiber-, and glass fiber-reinforced polymers (CFRP, AFRP, and GFRP) exhibit markedly different responses than Grade 60 (420) steel to tensile loads (1 MPa = 145 psi)

concrete compressive failure (crushing).[1] At concrete crushing, an FRP laminate on a strengthened beam could be well below its rupture strain, even if the conventional steel reinforcing within the beam has yielded. This can be illustrated with a simple example: A steel reinforcing bar will reach a stress of about 60 ksi (410 MPa) at a tensile strain of about 0.002 in./in. A nearby CFRP laminate could have about the same tensile strain. Yet, because the CFRP laminate has an elastic modulus of only about 10,000 ksi (69,000 MPa), it will reach a stress of only 20 ksi (138 MPa). So, in this example, the stress in the steel is actually three times the stress in the CFRP.

It's also important to keep in mind that FRP materials are linear-elastic to failure. There is no yield strength—there is only an ultimate tensile strength. The ultimate tensile strength, however, should not govern when designing a repair or retrofit. Design engineers must carefully select the material, and they must know the design modulus that can be used when assuming a 50- to 100-year service life. Based on the geometry and loading requirements for their project, they must determine an operating strain (using, for example, strain compatibility for flexural reinforcement). They must also verify the design modulus using prepared samples of the cured composite. Appropriate test methods are described in ACI 440.3R,[2] ASTM D3039,[3] ASTM D7290,[4] and ICC-ES AC178.[5]

SELECTION OF MATERIALS

The stress-strain behavior of the constituent materials in an advanced composite material is illustrated in Fig. 2. While the fibers are the main load-carrying component,[6] that doesn't mean the matrix is unimportant. The matrix material plays a major role in the system's overall durability, bonding the fibers to adjacent fibers and bonding the laminate to the substrate. When choosing a particular product, designers focus on the type of fiber (generally, carbon or glass) and the fabric architecture (generally, unidirectional or bidirectional), but they must also be sure to specify the polymer as part of a tested FRP system.

The mechanical properties of some FRP systems can degrade over time when exposed to such conditions as alkalinity, salt water, chemicals, or UV light. Further information and references are available in ACI

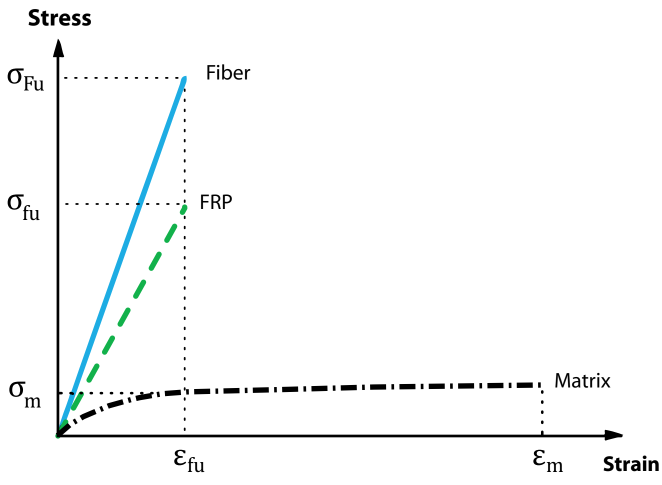

Fig: 2: An FRP and its constituents exhibit these typical responses to tensile loads. The respective tensile strength values for the fiber, the matrix, and the composite are σ_{Fu}, σ_{fu}, σ_m

Fig. 3: This GFRP system was poorly installed around the barrier cables; it was subsequently removed and replaced

440.2R.[6] The designer should select a system that has demonstrated durability in testing consistent with the environment where it is to be used.

In the U.S., requirements for FRP materials used in buildings are detailed in ICC-ES AC125.[7] This standard designates the method for establishing tensile strength and modulus values, defines a series of durability tests required for a system, and provides minimum acceptable design criteria. Per AC125,[7] strength and modulus values are established using ASTM D3039,[3] and ASTM D7290[4] provides a statistical method for finding conservative values for material properties. For materials to be used in civil infrastructure, additional environmental durability tests should be run. Further details on environmental exposure testing and references can be found in ACI 440.2R.[6]

INSTALLER QUALIFICATIONS

The performance of an FRP system is highly dependent on the quality of the installation. Figures 3 and 4 provide only a few examples of the work of inexperienced installers. Project specifications must clearly define tested and accepted FRP systems, but they must also define the requirements for the specialty contractors who perform the work. The personnel installing FRP systems must be experienced, and they should be certified by the system manufacturer to ensure that they have been properly trained. Specifications must call for documented experience, references, and trained crew members. ACI 440.2R[6] indicates that competence can be demonstrated by "providing evidence of training and documentation of related work" completed previously and/or by sample work on portions of the structure. We suggest that designers enforce strict specifications relative to the specialty contractors who will perform the work.

CRITICAL APPLICATION ISSUES

Surface preparation and finish requirements are critical issues for FRP applications. If not properly considered, both can potentially disrupt the schedule and budget for a project. Careful consideration must be given to the proper surface preparation, the existing conditions properly documented, and a detailed specification must be prepared.

For bond-critical applications such as walls, slabs, and beams, existing nonstructural coatings must be removed. When a coating is found to be a hazardous material (for example, a lead-based paint), additional costs will be incurred. Even for contact-critical applications such as columns, surface preparation is important. Sharp corners can have a large cost impact because they must be removed by grinding. Cracks or spalls will also add to the project cost, as they must be repaired before FRP repairs can be applied.

The polymers used to wet out the fabric generally consist of a resin and a hardener. The resin-to-hardener

Fig. 4: Signs of poor installation techniques: (a) bubbles and sagging fibers; and (b) large voids

ratio is critical and should be checked prior to mixing. When wetting out the relatively thick fabrics used for retrofits, simple "painting" or roller application of the resin to the fabric may starve the system of polymer, so we recommend the use of a saturation machine to prewet the fiber before installation. When completed, the installed material should be inspected for any delaminations or discontinuities. ICC AC178[5] and ACI 440.2R[6] provide additional information on inspection and testing.

If a fire-resistant finish is required, the design engineer must account for the added cost and logistics related to installing and protecting the fire protection system. Fire ratings are the primary issue, but designers must account for aggressive exposure conditions and special aesthetic requirements.

There is no doubt that demand for FRP materials will continue to grow. Even as more designers have become more comfortable with using FRP materials, designers and contractors must be aware that this is still a relatively new technology—without the proper attention to detail, there can be major issues. Given a detailed specification, clear procedural notes, a tested and proven FRP system, and properly trained and certified applicators, however, FRP strengthening can provide a great value to owners.

References

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Selected for reader interest by the editors.

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