Externally Applied Fiber-Reinforced-Polymer Composites

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The use of fiber-reinforced-polymer (FRP) composites as construction materials is increasing steadily. The application of externally applied FRP composites for the strengthening and rehabilitation of existing structures is an advanced technology that has gained considerable attention over the past three decades. Among design professionals, FRP composites are a preferred solution over traditional materials for applications such as rehabilitation and repair of existing structures because the composites provide significant advantages such as their light weight and ease of application. FRP composites also contribute to more durable, and hence more sustainable, construction than many traditional materials. Using FRP composites for external reinforcement is a complex process that requires a full understanding of the materials and the existing structural conditions, as well as accurate design and detailing practices. This article provides an overview of different FRP systems and their applications, limitations, and design considerations, and presents international design guidelines that have been driven by the state of the practice.

FRP Materials

FRP composites are advanced materials that consist of continuous fibers—such as carbon, glass, aramid, basalt, or natural materials—embedded in a polymer matrix. The fibers are the primary load-carrying components, whereas the polymer resin acts as a binder that transfers forces among the fibers and protects the fibers. FRP composites are available in various forms, including thin strips and bars that are both typically made by pultrusion, and flexible, dry-fiber sheets, which are typically saturated with resin on site during installation.

FRP composites are orthotropic materials with properties that can vary in different directions. Both unidirectional and multidirectional FRPs are available; unidirectional FRPs are the most common for structural applications. The overall properties of FRP materials depend on the mechanical properties of the fibers, mechanical properties of the matrix, the interaction between the fibers and matrix, and the method of manufacturing. Moreover, because the fibers are the main load-carrying components, the type of fibers, fiber-volume fraction, and orientation of fibers are key factors that dictate the stiffness and tensile strength of the material.

FRP materials exhibit a linear-elastic stress-strain relationship up to failure when loaded in direct tension, with no yielding or plastic behavior. This behavior is contrary to that of elastoplastic steel; therefore, standard methods used for

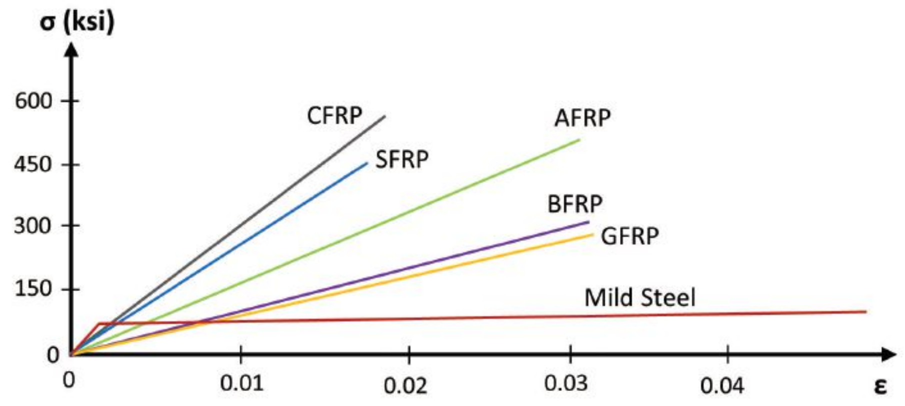

Figure 1. Typical stress-strain relationships of mild steel and different types of fiber-reinforced polymers. Note: AFRP = aramid-fiber-reinforced polymer; BFRP = basalt-fiber-reinforced polymer; CFRP = carbon-fiber-reinforced polymer; GFRP = glass-fiber-reinforced polymer; SFRP = steel-fiber-reinforced polymer. Source: Adapted from reference 2.

design to determine the amount of steel reinforcement do not apply to FRP reinforcement, where more complex procedures and design methodologies are involved. In general, FRP composites have a higher ultimate strength than steel but a lower modulus of elasticity and strain at failure. **Figure 1** shows typical stress-strain diagrams for different types of unidirectional FRP composites compared with mild steel reinforcement. The different types of FRP depend on the type of fibers and are noted on the figure; for example, carbon-fiber-based FRP composites are referred to as CFRP and glass-fiber-based FRP composites are referred to as GFRP. The modulus of elasticity can vary for the same type of FRP because the modulus is a function of the fiber modulus, matrix modulus, and fiber-volume ratio. The most common FRP systems for structural applications are CFRP composites because of their superior mechanical properties, including higher tensile strength, stiffness, and durability, compared with GFRP and other types of FRP composites.

Figure 2. Strengthening of concrete bridge elements using carbon-fiber-reinforced polymer systems bonded to the concrete, which appear as black bands or wraps in the photo. Photo: Simpson Strong-Tie.

FRP Strengthening Systems and Applications

The increased use of FRP materials in structural engineering for strengthening and rehabilitation of existing structures is mainly due to the advantages of FRP composites compared with traditional materials and techniques. These advantages include corrosion and chemical resistance, high tensile strength, design versatility, and, most importantly, their light weight and the variety of available forms (different sizes, geometry, and dimensions), which allow easy and rapid application of the system while minimizing labor costs and disruption of use, as well as enabling use in areas with limited access.

FRP systems have been successfully used for different strengthening applications such as flexural strengthening, shear strengthening, column confinement, and seismic retrofitting (**Fig. 2**). The most common types of FRP strengthening systems include surface-bonded FRP reinforcement (precured or cured on site) and near-surface-mounted FRP reinforcement. Each of these systems requires a specific installation and material selection process. Therefore, it is critical that engineers follow reliable guidelines when selecting suitable FRP systems for specific strengthening projects. For example, prefabricated (or precured) strips are typically stiff and cannot be bent; therefore, they are best suited for straight surfaces such as the top or bottom surfaces of slabs and beams. In contrast, flexible fabrics cured on site can be tailored to fit any geometry and can be adhered to straight surfaces or wrapped around almost any profile (**Fig. 3**). Near-surface-mounted FRP strengthening systems are suitable for applications where the FRP should be protected or if improved bond conditions between the concrete and FRP are necessary.[1]

Figure 3. Flexible carbon-fiber-reinforced polymer sheets can be wrapped around and bonded to almost any concrete element profile. Photo: SURFPREP.

Limitations and Design Considerations

Although FRP composites offer many advantages, these systems do have certain disadvantages and limitations that should not be neglected by engineers. Examples of such limitations are the linear-elastic behavior of FRP composites, which leads to reduced ductility of the material; different thermal expansion coefficients for FRP materials compared with concrete; and their low maximum temperature threshold, specifically related to the epoxy resins, which could cause premature degradation in case of fire. Additionally, careful consideration should be given during design to determine reasonable strengthening limits for the FRP composite system. The design guides and codes described in the following section outline the required minimum capacity of the unstrengthened structural member and other guidelines regarding the condition of the structure. For example, the American Concrete Institute's (ACI's) *Guide for the Design and Construction of Externally*

Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R)[1] recommends that the existing strength of the unstrengthened structure should be sufficient to resist a level of load as described by the following equation:

$$(\phi R_n)_{existing} \geq (1.1S_{DL} + 0.75S_{LL})_{\text{new}}$$

where

R_n = nominal strength of a member

ϕ = strength reduction factor

S_{DL} = dead load effects

S_{LL} = live load effects

Moreover, the cost of FRP materials is high compared with conventional materials such as steel. However, due to their high strength-to-weight ratio, the cost of using FRP systems can be favorable if the structure is properly designed, because they can be more cost effective over the life of the structure.

According to the *fib* (International Federation for Structural Concrete) Bulletin 90, *Externally Applied FRP Reinforcement for Concrete Structures*,[2] FRP materials for strengthening and repair applications should not be blindly used as a replacement for conventional materials. Instead, proper evaluation of their advantages and drawbacks, accurate design processes, a good understanding of the existing structural conditions, and appropriate detailing should all be considered when making the final decision regarding their use.

Guides and Codes for Externally Applied FRP Reinforcement

Several guides that address the design and construction aspects of externally applied FRP reinforcement systems for concrete structures have been published. In the United States, ACI published the latest edition of the previously mentioned *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (ACI 440.2R) in 2017.[1] Later, ACI published a code for the repair of existing structures, *Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures* (ACI 562),[3] which permits the use of FRP materials and refers to several documents by ACI Committee 440. In 2012, the American Association of State Highway and Transportation Officials (AASHTO) published *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*,[4] which was intended to supplement the *AASHTO LRFD Bridge Design Specifications*.[5]

In 2019, *fib* published the aforementioned *Externally Applied FRP Reinforcement for Concrete Structures,*[2] which provides supplementary provisions for FRP-strengthened concrete structures. The bulletin discusses the design of reinforced concrete members strengthened with externally applied composite materials, as well as currently available composite materials, durability, and proper installation techniques. It focuses on strengthening and seismic retrofitting with FRP in the form of externally bonded or near-surface-mounted reinforcement and provides all necessary information to ensure the overall structural safety of the strengthened member.

Conclusion

Externally applied FRP reinforcement systems have gained significant popularity and have been successfully used to strengthen concrete structures including bridges, buildings, and tanks. Their advanced properties and design versatility have caught the attention of both design professionals and researchers, who have carried out several studies to demonstrate the material's efficiency and have contributed to the development of design guides and specifications. The higher cost of FRP materials is counterbalanced by lower life-cycle costs and reduced costs of labor, installation time, and equipment; as a result, using FRP materials is often more cost effective than traditional strengthening techniques. Finally, understanding the properties and limitations of FRP systems is an important step in developing adequate design solutions and using the proper system for each application.

References

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