The design of fiber reinforced composite materials for strengthening of existing structures

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The Design of Fiber Reinforced Composite Materials for Strengthening of Existing Structures

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Infrastructure in the United States is aging, creating a growing need for innovative, cost-effective methods for both retrofit and repair of existing structures. Fiber reinforced polymers (FRP) offer a high-strength, lightweight alternative to traditional methods of structural upgrade. These materials, also known as advanced composite materials or fiberwrap, consist of high-strength fibers in a polymeric matrix. The fibers provide the strength and stiffness and the matrix provides load transfer between fibers as well as environmental protection for the fibers.

Applications for externally bonded FRP

FRPs are designed as an externally bonded tension member. They can add shear strength and flexural capacity and provide confinement or axial tension to existing beams, slabs, walls, or columns. They are not designed to be stand-alone structural members, but to work in conjunction with the existing structure. They have been used as part of seismic retrofits, load capacity increases due to change of use, repair of damage caused by impact or corrosion, and construction anomalies (see Figures 1 and 2).

The process — This article focuses on externally bonded wet layup systems. These consist of dry fiber sheets that are saturated with resin at the project site. The "wet" fibers are then placed on the member to be strengthened and allowed to cure in place.

Once cured, the fiberwrap acts as a tension member, with the force in the direction of the fibers. The most common types of fibers are glass, carbon, and aramid; the most common type of saturating resin is epoxy. The design is based on the properties of the system, incorporating both the fibers and the matrix.

Figure 1 (left): Structure exhibits extensive corrosion caused by proximity to the ocean.
Figure 2 (right): Repaired Structure. Along with extensive concrete repair, the fiberwrap system was designed to provide additional shear and flexural capacity.

One of the advantages of using fiberwrap for structural strengthening is that it is light weight and its installation is low impact — small crews can accomplish the work with a typically small project site footprint. This allows for unique solutions to challenges that sometimes cannot be solved using traditional materials. For example, slab and beam strengthening projects can often be installed through existing drop ceilings and around existing HVAC equipment, minimizing any down time due to having to suspend operations. Strengthening of shear walls with fiberwrap adds minimal dead weight to a structure, avoiding the problems associated with transferring new loads down to the foundation. The final application is usually less than a half inch thick, so egress routes are not disrupted. In general, fiberwrap can be used to add tension capacity to an existing structural member.

During the last 20 years, the design practices for fiberwrap have advanced significantly. There are several design codes and recommendations that are available, both within the United States and internationally, which provide engineers reference information during the design process. In the United States, the American Concrete Institute's (ACI) 440 Committee is active in developing a variety of documents

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Learning Objectives

This article covers the design of externally bonded fiber reinforced polymers (FRP) for strengthening of concrete elements in shear, flexure, and confinement. After review of this material, readers should understand the following:

- Appropriate applications for externally bonded FRP strengthening;
- Basic design equations for shear, flexure, and confinement;
- Special considerations including fire protection; and
- Performance specifications.

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related to the use of FRP for structural strengthening (ACI, 2007). In Europe, Task Group 9.3 of the International Federation for Structural Concrete (fib) published a bulletin on design guidelines for externally bonded FRP reinforcement for reinforced concrete structures (fib, 2001). In Canada, the Canadian Standards Association (CSA S806) and ISIS (Neale, 2001) have developed guidelines for designing with FRP Systems.

Design process

The design of FRPs is based on allowable strain and modulus of the composite system. The design incorporates the principles of reinforced concrete and masonry design, with the fiberwrap acting as a tension member. The formulas below provide an overview of the design process for shear, moment, and axial load capacity calculations. However, each project incorporates specific details that cannot be covered in the limited space here. The designer is encouraged to consult the design references and fiberwrap engineers for more detailed information.

Shear strengthening

Fiberwrap can be used to provide additional shear capacity to an existing member. The shear capacity of the fiberwrap is added to the shear capacity of both the concrete and steel as follows:

$$\phi\, V_n = \phi\,(V_c + V_s + \psi_f\, V_f).$$

In this equation, V_f is the shear contribution of the fiberwrap, and V_c and V_s are the concrete and steel shear capacity, respectively, as calculated by existing building codes. This equation can be used for both beams and columns.

The following equation is used to calculate nominal shear strength enhancement, V_f, provided by the FRP (kip) (see Figure 3). The equations are from ACI 440.2R-08 Section 11. All formulas are for U.S. units.

$$V_f = \frac{A_{fv}\ f_{fe}\,(sin(\alpha) + cos(\alpha))\ d_{fv}}{s_f}$$

This equation is similar in principal to the equation used in ACI 318 to calculate the shear contribution of steel stirrups. Just as with steel, the equation for shear capacity is based on the area of the fiberwrap, the design stress, depth of the reinforcing, and the spacing (see Figure 4).

The area of fiberwrap is determined from the following:

- $A_{fv} = 2\ n\ t_f\ w_f$ = area of FRP shear reinforcement (square inches),
- n = number of layers of FRP reinforcement,
- t_f = FRP composite material thickness per layer (inches), and
- w_f = width of FRP reinforcing layers (inches).

The depth of the reinforcement and angle of the force is determined from the following:

- α = angle of fiber inclination (degrees) is applicable if the FRP is installed at an angle, and
- d_{fv} = effective depth of FRP shear reinforcement (inches).

The spacing of the fiberwrap is as follows:

- s_f = center-to-center spacing of FRP shear reinforcement (inches).

The design stress is determined from the modulus of elasticity and the effective strain as follows:

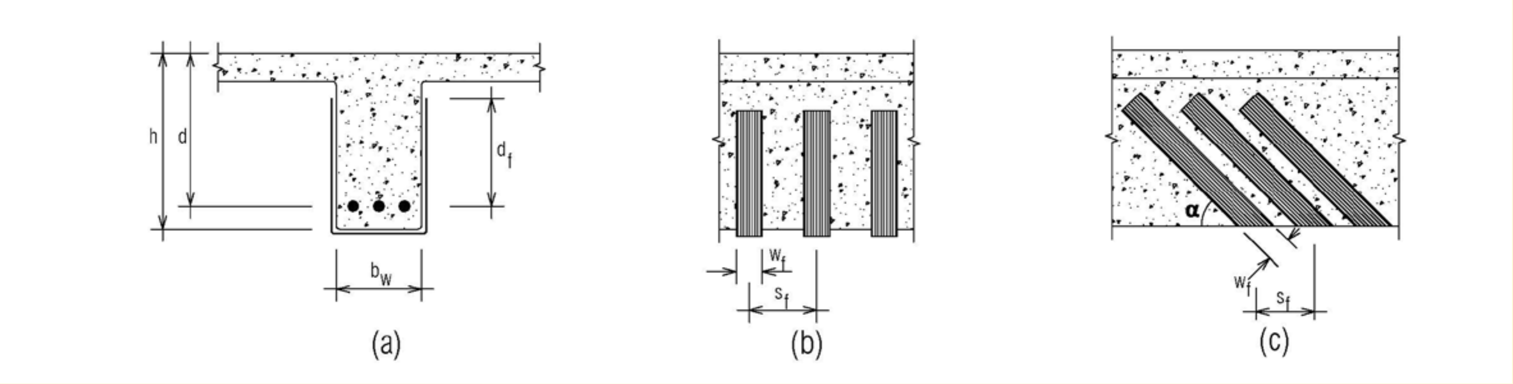
- $f_{fe} = E_f\,\varepsilon_{fe}$ = effective stress in FRP (ksi).

The design of fiberwrap is different from steel because it does not have one design stress that is used in every application, such as 60 ksi for grade 60 steel. The design stress of the fiberwrap must be calculated based on the modulus of elasticity of FRP material E_f (ksi).

This will vary by material and the data sheet of a specific product should be consulted for appropriate design values. The modulus of a carbon composite material is higher than the modulus of a glass composite material. However, the glass composite material has higher failure strains. All factors must be considered when choosing an

Figure 3: Carbon fiberwrap is installed over fiber anchors to provide confinement and shear capacity to beam end.

Figure 4: Variables used to calculate shear strengthening.



appropriate system.

The strain that is used in design is the most important step for fiberwrap design. For shear strengthening, this is based on the substrate strength and the geometry of the installation. The strain is limited to ensure that the force can be transferred through the bond into the concrete member.

ACI 440.2R-08 limits the strain based on several bond reduction coefficients as follows:

- $\varepsilon_{fe} = 0.004 \leq 0.75\ \varepsilon_{fu}$ effective strain in FRP reinforcement for fully wrapped applications. These are installations where the fiberwrap completely encases the concrete member. The most common application is column wrapping. The upper bound is set at 0.004 to ensure that the concrete substrate maintains aggregate interlock.
- $\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 0.004$ effective strain in FRP reinforcement for U-wrapped or two-sided applications. These installations do not completely wrap around the member, such as beam strengthening where a slab blocks complete confinement.

The κ_v is calculated using k_1, k_2, and L_e as follows:

$$\kappa_v = \frac{k_1\, k_2\, L_e}{468\varepsilon_{fu}} \leq 0.75$$

In this equation, k_1 is a function of the substrate strength since this directly affects bond strength as follows:

$$k_1 = \left(\frac{f'_c}{4000}\right)^{\frac{2}{3}}$$

And k_2 is a function of how the fiberwrap is installed. A three-sided U-wrap application is more effective than a two-sided application and this is accounted with this factor. Therefore, k_2 is derived from one of the two following equations: $k_2 = (d_{fv} - L_e)/d_{fv}$ for U-wrapped applications, or $k_2 = (d_{fv} - 2L_e)/d_{fv}$ for two-sided applications.

The final factor that is used in calculating κ_v is L_e, which represents an active bond length for the FRP. This is a function of the total force to be transferred from the FRP into the existing member. This is calculated using the number of layers n, thickness t_f, and design modulus of the fiberwrap E_f, as follows:

$$L_e = \frac{2500}{(n\, t_f\, E_f)^{0.58}}$$

Once V_f has been calculated, the final step to determining the additional shear capacity of the fiberwrap is to apply an additional reduction factor based on the installation geometry. The following factors are used depending upon the FRP application: $\psi_f = 0.95$ for fully wrapped applications, or $\psi_f = 0.85$ for U-wrapped or two-sided applications.

To ensure that the fiberwrap does not over strengthen the section and force a failure in the compression strut, the total shear strength provided by the existing steel shear reinforcement and the FRP shear reinforcement is limited to the following:

$$V_s + V_f \leq 8\sqrt{f'_c}\, b_w d$$

For this limit, b_w = web width (inches), d = distance from extreme compression fiber to centroid of tension reinforcement (inches), and f'_c = concrete compressive strength (kip).

Flexural strengthening

Designing fiberwrap to add moment capacity to beams and slabs is based on a design stress of the FRP, area of the material, and a moment arm. Once again, the concepts are similar to reinforced concrete design. The following equations are from The Fyfe Company Design Manual (2010). They highlight the design process presented in ACI 440.2R-08 Section 10. The condensed design process presented here is based on limiting the failure mode for analysis to debonding of the FRP. Due to space constraints, equations to calculate other failure modes, including FRP rupture and concrete crushing, are not presented here.

Nominal flexural strength enhancement M_f provided by the composite is determined by the area of the fiberwrap, the design stress, and the moment arm as follows:

$$\phi M_f = \phi\, A_f\, f_{fe}\, (jd)$$

In this equation, the area of the fiberwrap is calculated as follows:

- $A_f = n\, t_f\, w_f$ = area of FRP flexural reinforcement,
- n = number of layers of FRP reinforcement,
- t_f = FRP composite material thickness per layer, and
- w_f = width of FRP reinforcing layers.

The design stress, f_{fe}, in the fiberwrap is computed as follows:

- $f_{fe} = \varepsilon_{fe}\ E_f$ = effective stress in FRP, where
- E_f = modulus of elasticity of FRP material, and
- ε_{fe} = design strain in FRP reinforcement limited by section analysis or debonding such that the following limits are satisfied:

$$\varepsilon_{fe} \leq 0.083\sqrt{\frac{f'_c}{n\, E_f t_f}} \leq 0.9\varepsilon_{fu}$$

The moment arm for the fiberwrap is represented by the term jd, which is the distance from centroid of FRP to centroid of compression zone. The jd is calculated using an iterative process. A value for the neutral axis of the strengthened section is assumed, the strain level is calculated in each material (concrete, steel, and FRP) using strain compatibility, and the internal force equilibrium is checked. If the forces do not equilibrate, this process is repeated.

A final strength reduction factor, ϕ, is calculated, based on section ductility, as one of the following values:

- $\phi = 0.9$ if $\varepsilon_s \geq 0.005$, or
- $\phi = [0.65 + 0.25 (\varepsilon_s - 0.002)]/(0.005 - 0.002)$ if $0.002 \leq \varepsilon_s < 0.005$, or
- $\phi = 0.65$ otherwise.

In this case, ε_s = strain in tension steel reinforcement at ultimate compressive concrete strain.

The nominal flexural enhancement provided by the fiberwrap, ϕM_f, is added to the existing capacity of the section. This new nominal strength must be larger than the design ultimate moment.

Column axial load capacity enhancement

Fiberwrap systems can also be designed to increase the axial load capacity of columns. The design uses the tension capacity of the fiberwrap to confine the concrete in the column. By providing additional confinement, the apparent compressive strength of the concrete is increased. Thus, while still acting as a tension member, the FRP increases the axial load carrying capacity of the column. The fiberwrap also increases the displacement ductility of the member by increasing the strains the concrete can accommodate before failure.

The following design overview presents some of the equations from ACI 440.2R-08 Section 12 (ACI, 2008). These are intended to provide the overall concepts of the design process, not each individual calculation.

As mentioned above, the fiberwrap is used to increase the confined concrete compressive strength, f'_{cc}. The primary fibers of the fiberwrap are oriented transverse to the longitudinal axis of the column, just like the transverse or spiral reinforcing steel. In no case are the fibers oriented along the axis of the column and designed to act in compression.

Therefore, f'_{cc} is a function of the shape of the column (circular or rectangular), the existing concrete strength, internal vertical steel details, and the properties of the fiberwrap. Just as with shear and moment strengthening, a design strain of the fiberwrap is calculated in the design process. A confinement pressure, f_l, is calculated based on the design strain and modulus of the FRP. The existing geometry of the column is used to calculate a shape factor κ_a. This factor is one for circular columns and less than one for square/rectangular columns because it is less efficient to confine non-circular sections. Combined, these factors calculate the confined concrete compressive strength as follows:

$$f'_{cc} = f'_c + \psi_f 3.3\, \kappa_a f_l.$$

In this case, $\psi_f = 0.95$ is used as an additional reduction factor for the fiberwrap.

Once f'_{cc} has been calculated, the increase in axial load capacity is calculated with the following equation for columns with existing steel-tie reinforcement:

$$\phi P_n = 0.8\, \phi\, [0.85\, f'_{cc} (A_g - A_{st}) + f_y A_{st}]$$

All appropriate load factors and ϕ factors from ACI 318 should be used.

Special considerations

The current design documents provide the designer with the general design process. However, there are many projects that have aspects that require special consideration that are not well addressed in the current recommendations. This could include unique anchoring aspects, challenging installation requirements, and fire protection.

When completing a fiberwrap design, it is often required to design special fiber anchoring systems to meet the design goals. Fiber anchors consist of rovings of fibers combined with a system-compatible epoxy. The thickness and length are designed based on specific project conditions. They can be designed to anchor the externally bonded composite sheets. This allows higher strains to be used in the design process, leading to a more cost-effective installation. The anchors can also be designed to connect two structural members. For example, the anchors can have one end bonded to a roof slab and the other end bonded into the perimeter wall or column, thereby tying the system together. These types of fiber anchor systems are project specific and designed based on structural testing.

Installation of the fiberwrap system must also consider any existing conditions that might affect easy application of the material. This might be confined space requirements, work at extreme heights, limited access to the surface of the structural member, or short access times for installation (see Figure 5). Specialty contractors are well trained to address these issues and ensure the material is properly installed. They will perform site visits and feasibility analyses to ensure that the best solution is pursued.

Once considered a limiting factor for FRP design, fire protection coatings are now available to provide hourly ratings to fiberwrap-strengthened members. These systems work by protecting not only the composite strengthening, but also the steel and concrete of the existing structure. By providing fire protection to the entire structural system, the member can carry higher loads through a fire event. These fire coatings have been tested at the UL Laboratories per ASTM E119. If a project has a requirement for an hourly fire rating to meet local building codes, this should be addressed in the design phase to ensure that the proper safety factors are taken into account and the UL-approved fire coating is specified.

Performance specifications

It is important when moving ahead with a project using fiberwrap strengthening to have

Figure 5: Fiberwrap being installed on a chimney. Work is performed by small crews from scaffolding.

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a comprehensive performance specification. Effective specifications should include requirements for well-tested materials, competitive design procedures, skilled installation, and field quality control. Without these four components, the fiberwrap may not perform as designed.

Any strengthening system that is specified should have a well-documented history of both long-term durability testing of the system and large-scale structural testing for the intended application. In the United States, criteria for evaluating fiberwrap systems can be found in ICC-ES AC 125 (2007). 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. The designer should specify that the composite system — the fibers and matrix — has demonstrated durability that is consistent with the environment where it is to be used. Testing on the fibers or matrix themselves is not representative of the composite system. In addition to material testing, large-scale testing of the fiberwrap strengthening system should be required. If the project is for shear strengthening of a beam, the composite supplier should provide testing of its system for this application or supply an independent report (such as ICC Evaluation Service Report) showing that this type of use has been tested.

After ensuring that a well-tested fiberwrap material is required, the specifications should clearly state a design goal and required guidelines to be followed for design. The design goal is a quantified performance level that the fiberwrap will be designed to achieve. This may be required kips of shear or kip-feet of moment capacity. The performance target is coupled with design guidelines, such as ACI 440.2R-08. Without these guidelines, each FRP engineer may design the material in a different manner and the end results will not be comparable. Specifying a design goal and design guidelines ensures that all competitive bids meet the structural requirements.

The performance of externally bonded fiberwrap systems is highly dependent on the quality of the installation. As many of these applications rely upon the bond between the substrate and fiberwrap, surface preparation is critical. Without skilled contractors, this step may be overlooked, leading to inadequate force transfer between the members. An effective specification will require that the installation personnel have documented training and references. ICC AC 178 (2003) and ACI 440.2R-08 provide information on inspection and in-field material testing.

Once these components have been well described in the specification, the engineer of record may choose to require a deferred submittal. This submittal would require the specialty contractor to provide the engineer of record with calculations and shop drawings, stamped by an engineer familiar with fiberwrap design. This allows the designer to use fiberwrap strengthening without having to self-perform the design.

Conclusions

Externally bonded FRPs are an effective strengthening method for use in the retrofit and rehabilitation of existing structures. These fiberwrap materials have been used for civil engineering applications for more than 20 years and have a well-documented performance record. By understanding the basic engineering principles and practices needed to implement this technology, designers can feel more confident implementing its use. With the use of well-tested materials, expert installation crews, and proper design guidelines, fiberwrap will provide a unique solution to many structural problems.

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1. Which of the following statements is false about moment strengthening design?

a) The designer must consider the area of fiberwrap

b) The beam corners must have a rounded radius

c) The moment arm is used in the calculations

d) There is more than one failure mode that should be considered

2. Which of the following is an advantage to using fiber reinforced composite materials?

a) Light weight

b) High strength

c) Minimal project site footprint

d) All of the above

3. Which of the following are applications for externally bonded fiberwrap systems?

a) Adding additional moment capacity to a beam

b) Adding additional shear capacity to a section

c) Providing column confinement

d) All of the above

4. In writing a good performance specification for fiberwrap, which of the following does not need to be considered?

a) Clearly stated design goal

b) Well-tested fiberwrap materials

c) Local utility provider

d) Experienced specialty contractors

5. Which document provides design guidelines for fiber-wrap strengthening?

a) ACI 440.2R-08

b) ACI 222

c) ASTM D2974

d) ISIS 2780

6. What is a common type of fiber used in FRP strengthening systems?

a) Bamboo

b) Carbon

c) Concrete

d) Cotton

7. When performing a shear strengthening design, the engineer must consider:

a) Modulus of elasticity of FRP material

b) Effective depth of FRP reinforcement

c) Number of layers of FRP reinforcement

d) All of the above

8. Which of the following prevents the use of fiberwrap strengthening:

a) Required hourly fire ratings

b) Limited access around HVAC equipment

c) Concrete substrate

d) None of the above

9. The fiberwrap material is designed:

a) As an obelisk

b) As a compression member

c) As an externally bonded tension member

d) To conduct electricity

10. Which of the following statements is false:

a) Debonding of the fiberwrap is one failure mode to consider in design.

b) The design properties of the fiberwrap only consider the dry fibers.

c) The matrix material provides load transfer between the fibers.

d) The design of fiberwrap is based on allowable strain and modulus.

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