Structural repair and reinforcement using carbon fiber reinforced polymer (CFRP)

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Carbon fiber materials have been used extensively in the aerospace, marine, and high-performance automobile industries for years. Now, with the development of new manufacturing processes, the field of carbon fiber reinforced polymer (CFRP) reinforcement has expanded into the construction industry as well.

These materials work well in concrete because they can carry high tensile loads with little strain. In addition, acids, alkalis, and high temperatures do not affect carbon fiber. The advantages of a noncorrosive, non-intrusive method of reinforcement provides a cost-effective renovation and/or repair solution for existing structures.

Presently, CFRP is used as external tension reinforcement for masonry and concrete, and it may be used in the near future for applications with wood. It can be field-applied to fairly rough surfaces, and roughening a surface provides a greater area to which it can adhere. Carbon fiber reinforced polymer has tremendous adhesion, conforms to both straight and curved surfaces, and can add significant tension capacity to masonry or concrete — neither of which have much tension strength of their own unless previously reinforced.

Carbon fiber reinforced polymer is an especially relevant product for the repair and reinforcement of masonry walls because the straps can be applied in vertical or horizontal strips to provide almost any required tension capacity (see Figure 1).

Figure 1. Applying vertical strap to reinforce masonry wall.

By adding CFRP tension strips to the outside face of an unreinforced masonry wall, it is possible to increase its bending strength by 30 times. A typical tensile strength value for pre-cured carbon fiber is 270 ksi, well above most steel. The tensile capacity is primarily limited by the amount of bond or contact area (the "development length" or area) on the substrate rather than by the tension capacity of the straps.

The outside face of the block or concrete is the most advantageous position for reinforcement. It provides a moment-resisting couple consisting of the carbon fiber on the tension side and block or concrete in the compression block on the opposite side. Further, carbon fiber does not rust or corrode like reinforcing steel.

For projects involving masonry basement or retaining wall repairs, carbon fiber can completely eliminate the need for soldier beams — a common repair method. Unlike soldier beams, this method does not create an obstacle in the room that reduces floor space. Also, it doesn't require special effort to finish.

Carbon fiber reinforced polymer technology lends itself readily to major retrofit projects in older industrial, commercial, and other buildings in seismic regions where unreinforced brick and CMU walls and parapets are problematic. Narrow strips of CFRP applied vertically at four foot to eight foot on center could greatly reduce damage. The use of a similar technique could apply to all sorts of plain concrete and block structures.

This system can be field-applied without expensive equipment and with only limited training. It is important to maintain a clean site, to keep adhesive off the personnel, equipment, and surroundings, and it does require moderate (but not difficult) quality control to assure a clean substrate and to avoid bubbles, trapped air, or other impurities.

Current methods of applying carbon fiber include wet lay-up and pre-cured carbon fiber straps. The pre-cured straps come in two forms — pultrusion plates and carbon tapes. All three methods are described in detail below. The strength of the system is highly dependent on the type of method used and how well the method is performed. Carbon fiber has an inherent strength within the fibers; however, once laminated in an epoxy matrix, the filaments have a lower tensile strength than the dry filaments. For example, a typical tensile value for dry carbon filaments is 600 ksi. Once laminated, the tensile strength drops to 300 ksi, and flaws in the lamination process could drop the tensile strength to 150 ksi.

Differences between the three methods

The wet lay-up method uses flexible carbon fiber that can easily be molded to various shapes; however, its advantage of flexibility is a disadvantage in terms of reliability. Because the individual fibers in the fabric are not pretensioned, the placement of the fibers is highly dependent on the ability of the installer. All inconsistencies in the fabric (wrinkles) will reduce the strength of the system.

Pre-cured carbon fiber straps (including pultrusion plates and carbon tape) are pre-tensioned so that the individual fibers of the strap remain straight during installation — providing a more reliable system. Because carbon tape is thinner than pultrusion plates, they can bend to conform to curved surfaces better, but they still aren't as flexible as the dry carbon fiber.

Differences between installation procedures

All three methods are similar. For all three methods, the installer grinds the accepting surface to assist with the mechanical bond to the carbon and treats it with an epoxy, which is then applied to the carbon strip. With wet lay-up, the installer applies the epoxy to the cloth with an impregnator and positions the cloth on the prepared surface. With the pultrusion plates, a roller is needed to apply pressure to remove air bubbles. The fiber tape is a bit different. The application method involves the use of a vacuum lamination system. The system uses atmospheric pressure to apply continuous pressure to the strap in order to disperse the epoxy evenly and to provide a good bond. The tape is designed to conform under pressure even to cylindrical concrete substrates.

Wet lay-up

Wet lay-up of the composite laminate consists of applying a liquid polymer resin to a carbon fabric made with a designated fiber (carbon fiber, Kevlar™, et cetera). The resin polymerizes to become a solid matrix surrounding the fibers in the fabric. The fibers in the composite carry the loads imposed on the laminate while the resin holds the fibers in position, distributing loads among the fibers and protecting them from physical and chemical attack.

Types of resin – Three types of resin are used in the majority of wet lay-up lamination projects. All three are thermoset resins; that is, they form into a solid plastic as a result of a non-reversible chemical reaction. All three resin types have two components — a resin and a catalyst or hardener. When the two components are mixed together, an exothermic chemical reaction begins and the liquid components become solid in a controllable amount of time.

Polyester resin – This resin has been used commercially for decades with fiberglass. Laminates made with polyester and fiberglass have been thoroughly tested, both in the laboratory and the field, and are well understood. The resin is inexpensive, wets out fiberglass cloth well, and the rate of reaction is easily controlled. However, polyester resin is not particularly versatile. It adheres to a limited number of fabrics and substrates, and does not withstand fatigue very well.

Perhaps the biggest drawback of using polyester resin is its Hazardous Air Pollutant (HAP) content. Styrene monomer, one of the components of polyester resin, is a highly volatile material. Styrene vapors are extremely flammable, cause narcotic effects when the concentration is too high, and have recently been classified by the Environmental Protection Agency as "a possible human carcinogen." Ventilation must be substantial — many manufacturers using polyester resin aim for 50 ppm exposure for their workers. Because of the styrene content, areas with stringent air emission standards may not allow its use on large-scale projects.

Epoxy resin – Epoxy is the most versatile of the three resins listed, and it is also the most expensive. It is used for projects that require good fatigue performance and/or good adhesion to a variety of fibers and substrates. Because epoxy resin adheres to a large number of materials, it is used not only to wet out the commonly available fabrics but also to bond them to a number of substrates. For this reason, epoxy is used to make most of the carbon fiber laminate currently used. The volatile, organic compound emissions are low for epoxy, making it a top choice for wet lay-up applications, especially in confined areas.

Vinyl ester resin – Vinyl ester resin is a hybrid of polyester and epoxy, and this resin has physical characteristics that fall between those two. It performs better than polyester resin, especially in applications that are subjected to fatigue cycles. It is also a styrenated resin and, as a result, has the same air quality issues of polyester.

Advantages of wet lay-up – Wet fabric easily conforms to substrates that have irregular geometry. Wet fabric will often conform to misalignment in cracked concrete and it will negotiate radii as tight as ¼ inches.

Wet lay-up lends itself to laminating in tight quarters. It is possible to carry dry fabric and a bucket of resin into almost any area. The technique is also useful for small-diameter pipeline repairs where it is not possible for a person to enter. The process does not require expensive manufacturing equipment, and while some training is necessary to be a good laminator, a high level of skill is not needed.

Disadvantages of wet lay-up – Even under the best circumstances, wet lay-up is a messy operation. The people doing the lamination and the area around the work site have to be protected from spills and drips. Workmanship becomes important in keeping the fabric fibers aligned and consolidating the layers of fabric. Strength and stiffness drop considerably once the load direction falls off the fiber direction. It is extremely important to minimize air entrapment and resin content in a laminate. These factors are directly related to the skill of the installer.

The fiber alignment and void content can vary in a hand lay-up, therefore the ultimate strength of a laminate is generally not as good as pre-cured, machine made laminates like those described below. Wet lay-up wastes resin because there isn't much control over how much resin is added to the fabric. The use of a resin impregnator can minimize this problem, but buying and setting up a machine at the site is costly.

Proper temperature and humidity levels must be maintained while laminating. The temperature must be between 68 and 70 degrees Fahrenheit, and the relative humidity must be below 70 percent to assure proper saturation of the fibers. This may require building temporary structures around the work area to maintain suitable conditions. If styrenated resins are used, ventilation must be in place. This is often not easy as a jobsite.

Pre-cured carbon fiber straps

In addition to the wet lay-up method, pre-cured straps are available in the form of pultrusion plates or carbon tape. Installing a pre-cured strap is easier and faster than installing a wet lay-up. The epoxy used to bond the strap to the substrate can be mixed and delivered through a static mixer. The carbon strap can then be cut to length with a grinder or scissors and glued to the wall. Once the epoxy cures, the process is complete.

Pultrusion plates – The plates are made from a process called pultrusion. This process involves pulling continuous filaments of dry fiber through a resin bath and then through a hot die. The heat from this process cures the epoxy, and the result is a rigid plate of straight, continuous carbon fibers. Once cured, these plates can be wound on large spools and made available to contractors. The pultrusion method displays several advantages, including consistent resin content throughout the plate, and fibers and straight fibers in the direction of the plate because of mass production techniques and substantial labor savings during installation.

Pre-cured carbon fiber tape – The pre-cured carbon fiber tape is also manufactured in