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Report on Spray-Up and Continuous Strand Glass Fiber-Reinforced Concrete (GFRC)

Reported by ACI Committee 549



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Report on Spray-Up and Continuous Strand Glass Fiber-Reinforced Concrete (GFRC)

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Report on Spray-up and Continuous Strand Glass Fiber-Reinforced Concrete (GFRC)

Reported by ACI Committee 549

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Glass fiber-reinforced concrete (GFRC) is a popular construction material used to manufacture precast concrete products in architectural and civil engineering applications. GFRC products have desirable aesthetics and physical properties, including durability, strength, toughness, moisture resistance, dimensional stability, and fire resistance. This report summarizes the processes, properties, and applications of GFRC made by the spray-up process, and processes that use continuous strands and woven, knitted, or bonded textiles.

Keywords: alkali-resistant glass fiber; architectural panels; cement boards; composites; concrete panels; ductility; durability; fiber-reinforced concrete; filament winding; formwork; glass fiber-reinforced concrete; glass-reinforced concrete; mesh reinforcement; permanent formwork; premix; precast concrete; spray-up process; textile-reinforced concrete; toughness.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Glass fiber-reinforced concrete (GFRC) is a composite of alkali-resistant (AR) glass fibers embedded in a cementitious mixture, which could be a paste, mortar, or concrete, possibly with additives and admixtures added for improved processability, properties, or both. The fibers could be short individual fibers or monofilaments; bundles of fibers, which are often referred to as chopped strands; continuous strands or roving, or textiles (Fig. 1.1). Textiles are also synonymously called scrims, fabrics, or meshes.

Only AR glass fibers should be used in GFRC composites, to which this report is confined. There are four processes used to manufacture GFRC:

- 1) Premix
- 2) Spray-up, which usually contains a minimum of 4 percent chopped AR glass fiber roving strands by mass of the composite traditionally referred to as GFRC
- 3) Textile-reinforced concrete (TRC), which uses continuous structured AR glass fibers in woven (typically leno weave), knitted, and bonded constructions such as fabrics, scrims, or meshes
- 4) Continuous strands in oriented patterns such as filament winding

This report covers Items 2 through 4 and is a companion to [ACI 549.3R](#), which covers Item 1.

GFRC is not just a single material, but rather a variety of materials with different properties and performance characteristics. Because GFRC in any of its forms does not contain steel reinforcing bars, there is no need of extra concrete cover to protect steel against corrosion. This allows it to be produced in thin sections, typically 0.5 to 1.0 in. (13 to 25 mm), which makes GFRC products much lighter in weight compared to conventional concrete products, which are usually 2 in. (50 mm) or thicker, although both are similar in density.

GFRC products have several significant advantages over conventional precast concrete products. They are lightweight, easy to handle and install, and have high toughness. Being lightweight offers cost-effective concrete-based alternatives in applications where the heavy weight of conventional precast concrete would make it unsuitable.

Research on GFRC composites began in the 1960s and has been in successful commercial use for over 40 years. This is proof that, if designed and manufactured to accepted, recom-



Fig. 1.1—Alkali-resistant glass fiber roving, chopped strands, and textile (bonded scrim).

Table 1.2a—Chemical composition of selected glasses, percent of total by mass

Component	A-glass	E-glass	AR glass #1	AR glass #2
SiO ₂	73.0	54.0	62.0	61.0
Na ₂ O	13.0	—	14.8	15.0
CaO	8.0	22.0	—	—
MgO	4.0	0.5	—	—
K ₂ O	0.5	0.8	—	2.0
Al ₂ O ₃	1.0	15.0	0.8	—
Fe ₂ O ₃	7.0	0.3	—	—
B ₂ O ₃	—	7.0	—	—
ZrO ₂	—	—	16.7	17.5
TiO ₂	—	—	1.0	—
Li ₂ O	—	—	—	1.0

mended practices, GFRC has a durability and longevity to be an acceptable building material. Its properties have been thoroughly researched, probably as much as, if not more than, any other material. Further research and development of new applications and mass production processes will move GFRC into the next phase of large-scale use.

1.2—History

Much of the original research performed on glass fiber-reinforced cement paste took place in the early 1960s. This work used conventional borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass). The chemical compositions, densities, and mechanical properties of E- and A-glass are listed in Tables 1.2a and 1.2b. Glass compositions of E- and A-glass were found to lose strength quickly because of the high alkalinity (pH ≥ 12.5) of portland cement-based materials. Consequently, early A- and E-glass cementitious composites were unsuitable for long-term use ([Larner et al. 1976](#)). Some E-glass products have been developed with alkali-resistant (AR) coatings, but

Table 1.2b—Properties of selected glasses

Property	A-glass	E-glass	AR glass No. 1	AR glass No. 2
Specific gravity	2.46	2.54	2.70	2.74
Tensile strength, ksi (GPa)	450 (3.1)	500 (3.45)	360 (2.48)	355 (2.45)
Modulus of elasticity, ksi (GPa)	9400 (64.8)	10,400 (71.7)	11,600 (80.0)	11,400 (78.6)
Strain at break, %	4.7	4.8	3.6	2.5

these should be viewed with caution because glass filaments are very fine, with typical diameters of approximately 56×10^{-5} in. (13 microns). If the coating is degraded physically or chemically, the exposed reinforcing filaments will be quickly degraded away. Also, the ends of the fibers in chopped strands are exposed, and alkalis can wick along the fibers and attack them.

Continued research resulted in the development of AR glass fiber, which improved the long-term durability of glass fiber-reinforced concrete (GFRC). The alkali resistance of AR glass fiber derives solely from its glass composition and is not dependent on surface coatings.

The specifications for AR glass fiber are given in **ASTM C1666/C1666M**. Alkali resistance significantly increases with increasing zirconia contents up to 16 percent, but only increases slightly with a further increase in zirconia content (**Majumdar and Laws 1991**; **Bentur et al. 1985**).

Chemical compositions and properties of commercially available AR glass fiber are provided in Tables 1.2a and 1.2b, respectively. Since the introduction of GFRC in 1970, a wide range of applications in the construction industry have been established. Although much of the research and development was completed in the 1970s and 1980s, more recent work on technology, material, and application developments was presented at the biennial congresses organized by the Glassfibre Reinforced Concrete Concrete Association (**1998, 2001, 2003, 2005, 2008, 2011, 2015**).

1.3—Scope

This report provides practical information about alkali-resistant (AR) glass fiber-reinforced concrete (GFRC), including a comprehensive compilation of international data and references oriented toward increasing the awareness of producers, engineers, architects, and end users about GFRC technology and its use in a variety of applications. The fundamental principles of materials, mixture proportions, properties, manufacturing processes, and applications of GFRC are reviewed in this report. This report offers an overview of current design practices with references to design guides. The various industrial applications of GFRC include architectural panels, permanent formwork, utility poles, textile-reinforced concrete, and standard panel products.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

F_d	=	ultimate design load, or factored load
F_k	=	service load
f_u'	=	assumed (aged) modulus of rupture or ultimate flexural strength, psi (MPa)
f_{ur}	=	average 28-day modulus of rupture strength of 20 consecutive tests (each test being the average of six individual test coupons), psi (MPa)
f_{yr}	=	average 28-day proportional elastic limit strength of 20 consecutive tests (each test being the average of six individual test coupons), psi (MPa)
k_1, k_2	=	reduction factors
t	=	student's t —a statistical constant to allow for the proportion of tests that may fall below f_u ; the value is 2.539 for the recommended 20 tests
R	=	resistance
S	=	actions
s	=	shape factor
V_f	=	volume fraction of fibers
V_u	=	coefficient of variation of the modulus of rupture test strengths
V_y	=	coefficient of variation of the proportional elastic limit test strengths
ϕ	=	strength reduction factor
γ	=	ratio of compressive and tensile modulus
γ_f	=	load factor
γ_{iv}	=	factor to account for variations in thickness of glass fiber-reinforced concrete
γ_b	=	factor to allow for difference in bending behavior between test coupon and full-size section
γ_c	=	factor to account for mode of collapse and consequence of failure
γ_m	=	partial safety factor

2.2—Definitions

acrylic copolymer—acrylic thermoplastic copolymer is a resinous substance made by reacting acrylic monomers together; the type of copolymer used in concrete and glass fiber-reinforced concrete is an emulsion of submicron-size polymer particles dispersed in water.

alkali-resistant glass fiber—glass fiber using at least 16 percent zirconia by mass.

characteristic strength—value of a strength; for example, flexural, above which 95 percent of the population of all possible measurements of that strength are expected to lie.

creel—framework designed to support roving or bobbins of yarn while being fed into a weaving loom or filament winding machine.

externally bonded fabric-reinforced cementitious matrix—composite material consisting of a sequence of one or more layers of cement-based matrix reinforced with dry fibers in the form of open single or multiple meshes that, when adhered to concrete or masonry structural members, forms a fabric-reinforced cementitious matrix system.

filament—single glass fiber, sometimes called a monofilament.

filamentizing—dispersion of a multifilament strand into individual filaments.

flex-anchor—L-shaped rod or bar that connects the glass fiber-reinforced concrete skin to the panel frame.

glass fiber-reinforced concrete—cementitious mixture containing at least 4 percent alkali-resistant glass fiber by total mass of composite; usually manufactured by the spray-up process.

glass fiber-reinforced concrete premix—mixture of prechopped alkali-resistant glass fibers; cementitious materials; water; chemical admixtures; fine aggregate; and, if required, coarse aggregate.

glass fiber strand—group of filaments of predetermined quantity—50, 100, 200, or 400 filaments per strand—bundled together to resist splitting (filamentizing).

gravity anchor—rods, bars, or plates that transfer the weight, or gravity load, of the glass fiber-reinforced concrete panel to the supporting frame.

high integrity—describes a characteristic of particular glass fiber strands that are difficult to break down into individual filaments during processing or mixing.

leno weave—weave structure in which paired warp yarns, or strands, are intertwined in a series of figure eights and filling yarn, or strand, is passed through each of the interstices so formed, producing a firm, open mesh.

proportional elastic limit—limit of stress beyond which the strain is not wholly recoverable.

roving—number of parallel, continuous, not twisted, glass fiber strands bundled together and wound to form a cylindrical package.

scrim—structured form of glass fiber reinforcement in which continuous strands or yarns are laid down to produce a nonwoven grid pattern; also known as mesh.

textile-reinforced concrete—fiber-reinforced concrete composite in which the alkali-resistant glass fiber is a bonded scrim or woven fabric.

yarn—bundle of glass fiber strands that are twisted together.

CHAPTER 3—APPLICATIONS

3.1—Glass fiber-reinforced concrete architectural cladding

One of the first applications for glass fiber-reinforced concrete (GFRP), which was introduced in 1970, was architectural panels. GFRP architectural panels can be either standard products or customized. Standard products are usually basic flat or simply shaped panels with an applied or molded finish that can be cut to size. Standard panels can be made on an automated line, typically 8 x 4 ft (2.44 x 1.22 m) or 10 x 4 ft (3.05 x 1.22 m) and color is applied after the panel has cured. Figure 3.1a shows an example of a standard panel with a simulated split-face concrete block appearance, and Fig. 3.1b shows a building that used the same standard flat and curved panels. Installation of the panels is usually made with a proprietary connection system.

Customized GFRP architectural panels are invariably made by the hand spray-up process as described in 4.1. The



Fig. 3.1a—Standard GFRP panels with split-faced block finish.



Fig. 3.1b—Standard flat and curved GFRP panels.

Precast/Prestressed Concrete Institute (PCI) gives full details of these types of architectural panels (PCI MNL-128), so only a summary description will be given herein.

The spray-up process allows the shapes, returns, and surface features or textures usually required in architectural panels to be easily achieved. It also makes maximum fiber content possible, providing the maximum strengths needed, particularly in large panels; 15 x 20 ft (5.2 x 6.1 m) is the maximum recommended size. High-quality GFRP manufacturing requires that manufacturers have the required physical plant and equipment, trained personnel, and quality-control procedures that ensure consistent quality (PCI MNL-128). The plant should:

- a) Be clean
- b) Contain an enclosed area for spraying or casting operation
- c) Be capable of maintaining temperatures for adequate curing
- d) Have well-maintained equipment for proportioning and mixing materials
- e) Have the necessary equipment to deposit materials to forms
- f) Establish a comprehensive quality-control (QC) program for monitoring composite materials in-process manufacturing operations, and finished product

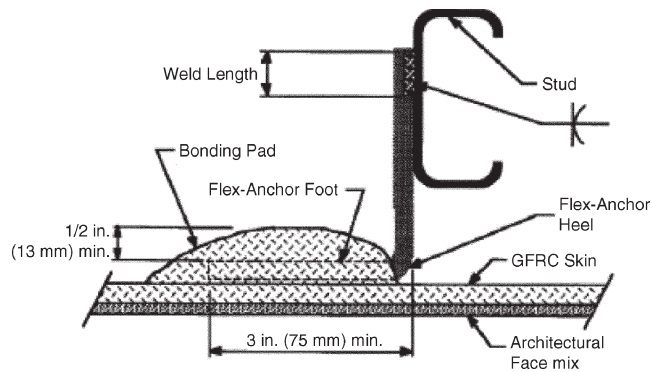


Fig. 3.1.1a—Flex-anchor connection with bond pad.

g) Have in place a comprehensive testing program to determine production composite properties and a system for maintaining QC records (PCI MNL-128; Daniel et al. 1989; Hanson et al. 1990).

Since the introduction of GFRC panels in the early 1970s, three basic panel types have been manufactured—sandwich, integral rib, and steel-stud/flex-anchor. Since the early 1980s, the majority of cladding panels manufactured in the United States are steel-stud/flex-anchor versus sandwich and integral rib type.

3.1.1 Steel-stud framing system (PCI MNL-130; PCI MNL-128)—The steel-stud frame should be fabricated in accordance with the Metal Lath/Steel Framing Association (2009). The studs are generally placed at 16 to 24 in. (0.4 to 0.6 m) on center with the flex-anchors (3.1.2) spaced 16 to 36 in. (0.4 to 0.9 m) on center, based on design considerations. The prefabricated stud frame will be moved several times before and after skin attachment; therefore, welded, rather than screw, connections are more desirable, although both systems are acceptable. With welding, studs are usually a minimum of 16 gauge (1.52 mm nominal) material. Touch-up paint or coatings should be applied to accessible welds of the light-gauge material after the stud frame has been fabricated.

Environmental conditions will usually determine to what extent steel framing needs corrosion protection. Steel studs are available with a red oxide paint or galvanized finish (before slitting and forming). Flex-anchor and gravity anchors (3.1.3) may be zinc- or cadmium-plated, before or after fabrication, and painted with a zinc-rich coating, or they may be stainless steel, where the additional cost is justified by severe environmental conditions. After fabrication, the stud frame is ready to attach to the GFRC skin after it has been sprayed and roller compacted to its design thickness. The stud frame is positioned over the skin with jigs to fix its location. Flex-anchors sometimes telegraph through and show on the face of the panel, so they are usually set at least 1 in. (25.4 mm) away from the surface of the GFRC skin (Fig. 3.1.1a). With some finishes, they may touch the surface of the GFRC skin. A bonding pad (Fig. 3.1.1a and 3.1.1b) is used to attach the flex-anchor to the GFRC skin. They are made either from GFRC spray-up material or GFRC premix. Operators hand apply the bonding pads over the foot of the

Stud Frame System



Fig. 3.1.1b—Flex-anchor connection with bond pad.

flex-anchor and knead them into the GFRC skin. Time delay between final roller compaction of the GFRC skin and the placement of the frame and the bonding pads should be kept to a minimum. This is necessary to ensure monolithic bonding of the bonding pads. If there is a significant time delay, initial set of the skin could prevent the bonding pad from achieving monolithic bonding to the skin, creating a potential for subsequent delamination (Daniel et al. 1989; Jones 2009). The bonding pad thickness over the top of the flex-anchor contact foot should be a minimum of 1/2 in. (13 mm) with a bonding area of 18 to 32 in.² (13,000 to 20,000 mm²). Care should also be taken not to build up the bonding pad over the heel of the flex-anchor, which would add undue restraint to skin movement. The bonding pad over the cross piece of the flat bar tee gravity anchor should be sized to adequately support the tributary weight of the GFRC skin. Sizing of bonding pads should be based on actual axial and shear pull-off tests of bonding pads in the fully aged condition (ASTM C1230).

3.1.2 Flex-anchor connections (PCI MNL-130; PCI MNL-128; Harmon and Molloy 1991)—GFRC can exhibit high drying shrinkage so the method to attach the metal stud frame to the GFRC skin should avoid undue restraint on the GFRC panel from shrinkage and thermal movement. Although the flex-anchor method was designed to the required flexibility, it is capable of transferring stresses between the GFRC skin and stud frame. The GFRC skin weight is transferred to the steel-studs by the bending strength of the flex-anchors. To ensure structural integrity, the anchors should have the strength to carry their tributary gravity and wind loads, while remaining flexible enough to allow relatively unrestrained thermal or moisture movements of the skin. This method is recommended for panels small enough that the flex-anchor can carry the weight of the GFRC skin and not allow the skin to sag.

If the skin is too heavy for the flex-anchor to carry the weight and provide satisfactory flexibility, gravity anchors (3.1.3) would then be required. They should be flexible in the horizontal direction, but rigid enough to carry the gravity loads of the GFRC skin. Flex-anchors are usually made with a smooth, round rod no less than 1/4 in. (6 mm) in

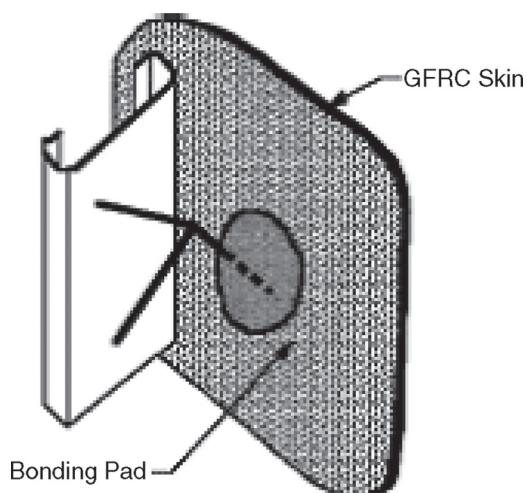


Fig. 3.1.3a—Round rod trussed gravity anchor.

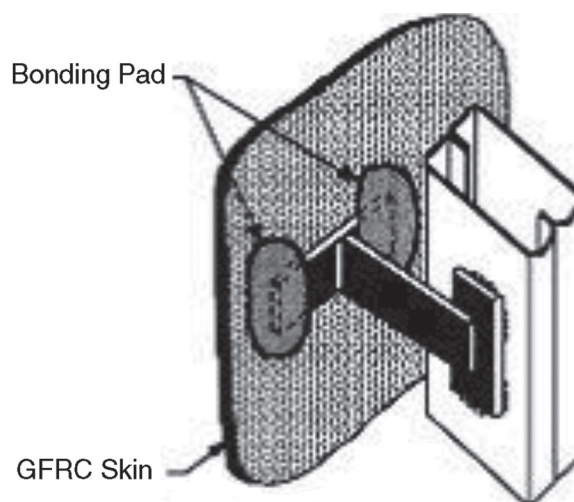


Fig. 3.1.3b—Tee plate gravity anchor.

diameter, although square bar can also be used if preferred. Diameter choice is influenced by the clear length of flex-anchor from the weld to the bonding pad and by determining if a separate gravity anchor is provided. They are welded to the stud at the top of the leg of the flex-anchor for flexibility. A plastic sleeve can be placed over the anchor foot to minimize restraint. Anchor orientation with toes positioned toward the center panel is advisable, allowing for initial drying shrinkage, which has a tendency to move the flex-anchor away from, rather than toward, the stud. Rigid fire protection or thermal insulations should be installed so as not to inhibit skin movement.

The unsupported edges of GFRC panels can bow or warp from moisture or temperature effects, presenting a problem with panel alignment and an unsightly joint. The edge distance to the end steel-stud, therefore, should be kept small to minimize warping.

3.1.3 Gravity and seismic anchor connections (PCI MNL-130; PCI MNL-128)—In larger, heavier panels, if the GFRC skin is attached to the steel-stud frame with flex-anchors only, the size of the flex-anchors could cause excessive restraint and over stress the skin. If the dead load is carried separately by special gravity anchor connections, the flex-anchors can be made smaller (1/4 in. [6 mm] minimum diameter), thereby substantially reducing the in-plane restraint.

In its plane, the skin is rigid. If the steel-stud frame is made rigid with diagonals or heavy upper tracks, lower tracks, or both, or if the frame is uniformly supported by the structure, the gravity load of the skin can be carried with a series of gravity anchors. This is usually accomplished with the trussed round bar gravity anchors (Fig. 3.1.3a) located on every, or every other, typical steel-stud. If the frame is supported at two points, it may be convenient to support the skin's dead weight at the two corresponding locations. This allows the in-plane rigidity of the stud frame to be lower because the skin weight is carried only by the panel connector studs or tubes directly to the building connections. The connector studs or tubes may need strengthening locally for full height. The remaining typical studs then act

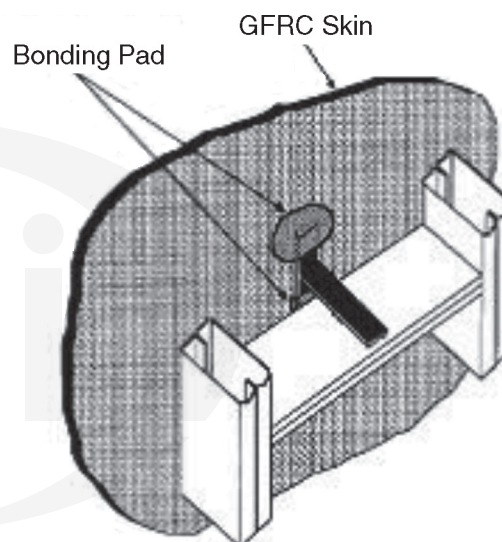


Fig. 3.1.3c—Tee plate longitudinal seismic anchor.

as floating stiffeners. This is usually accomplished with the flat plate tee gravity anchor shown in Fig. 3.1.3b. By adjusting the plate height and thickness, vertical strength of the anchor is achieved without sacrificing horizontal flexibility. In seismic areas, the longitudinal-seismic-force resistance requirements should be achieved without excessive restraint. When using flex-anchors alone or a flex-anchor/gravity anchor system, stiffness of the steel-stud along the weak axis should be considered. With a flat-plate tee system, it is advisable to strengthen only one of the two gravity anchors to carry the seismic load. A horizontally-oriented flat-plate tee anchor can be used to carry the longitudinal seismic force to the stud frame (Fig. 3.1.3c). There will be rotational forces that the anchor system should carry if the seismic anchor system is not colinear with the center mass of the skin. Because gravity anchors provide the fixed point to or from which way the GFRC skin moves, it may be advantageous to place the gravity anchor system mid-height for vertical panels. This also has seismic advantages from

reduced overturning moments. Permanent tensile stresses are produced because the bottom half of the panel is hanging from the gravity anchors. Generally, it is preferable to have permanent stresses, due to weight, be compressive, although they would have to be weighed against the seismic stresses. Stresses in both directions may also have to be considered at times (Schultz et al. 1987; Hanson et al. 1990; PCI MNL-128).

3.1.4 Connection test (ASTM C1230)—Each producer should perform a sufficient number of tests to develop a database from which an allowable design load can be determined for each type of flex- or gravity anchor. Seven test specimens made in an identical manner to the panel anchors should be tested. The highest and lowest values should be eliminated, and the average of the five remaining values should be used for determining the allowable design load (PCI MNL-128). Preferably, tests on representative artificially aged specimens should be performed so that long-term material property variations are accounted for in design. Tests of artificially aged connections and bonding pads indicate strength reductions of 25 to 50 percent with the failure plane occurring typically at the bonding pad/panel interface or as a shear wedge above the flex-anchor foot (Daniel et al. 1989; Hanson et al. 1990). A conservative safety factor of 4 to service loads should be used on the aged test results. For unaged test specimens, a safety factor of 5 to service loads is used on test results.

3.1.5 Steel-stud frame/GFRC panel design approaches (PCI MNL-128)—Whereas Chapter 6 describes design procedures for the GFRC skin, this section covers the entire panel frame, steel stud with GFRC skin attached.

Depending on the panel configuration and skin attachment system, stud frames might need to provide in-plane rigidity comparable to the GFRC skin so that each stud can support its tributary portion of vertical loads. The frame should also have sufficient rigidity perpendicular to its plane to resist skin bowing forces caused by restraint of skin shrinkage. Bowing tendencies are generally greatest when the GFRC skin and the bonded face mixture are not dimensionally compatible. Some designers have insufficiently recognized the effects of differential shrinkage and thermal expansion when panels are faced with a material that has different volume-change properties than GFRC (Pilkington Brothers Ltd. 1979). If polymer addition is used in GFRC, it should also be used in the face mixture when possible to ensure compatibility and increase the aggregate-to-cement bond. For integrally bonded facings, these effects can be minimized when the facing materials are selected to establish compatible material properties. Careful consideration of the induced stresses should be recognized in the design to ensure no cracking. For applied facings, the use of flexible adhesives or bond breakers and flexible anchors is recommended. Properties used in analyses and design should always be confirmed by each manufacturer through materials testing. The GFRC skin should not be relied on to provide bracing for stud stability. Depending on stud dimensions, support conditions, interior finish, and other factors, bridging could be required to prevent stud buckling. The steel-stud frame for a GFRC

panel can be analyzed by several methods. The GFRC skin spans between flex-anchors can be analyzed as one of the following:

- 1) Simple beam between flex-anchors
- 2) Continuous beam over a row of flex-anchors
- 3) Two-way slab system over an area of flex-anchors

In most cases, the edge GFRC skin is unsupported and should be checked by the designer. The GFRC skin load is transmitted through the gravity and flex-anchors to the steel studs. From the studs, the load is transmitted by horizontal tracks and vertical connector studs to the building connections, and then to the structure. If the steel-stud frame loads exceed the strength of a single stud, the steel studs should be welded together or a rolled structural steel shape used. Depending on the skin's gravity-transfer system and its relationship to the panel-bearing connectors, diagonal braces or strengthening of the horizontal tracks could be required. Increased stud strength is required at the connection locations because they resist loads collected by the horizontal tracks. Increased strength is usually accomplished by using a rolled structural shape or double or boxed studs. To eliminate indeterminate reactions and additional lateral non-load-bearing connections, the stud frame is generally attached to the structure with two load-bearing connections. At the steel-stud frame-to-structure connection, to achieve better load distribution, it is common to supplement the light gauge steel-stud framing by welding heavier plate or angle assemblies to the studs. In designs where welding is impractical or uneconomical, rolled structural shapes can be used in place of steel studs. Because freedom from restraint of the GFRC skin is achieved by flex-anchors, the stud-to-structure connection usually addresses only typical building movements such as floor deflections and wind and seismic drift. Horizontal deflection perpendicular to the panel plane should be limited to prevent damage to interior finishes or windows that are attached to the steel-stud frame.

3.1.6 Surface finishes (PCI MNL-128)—Most types of surface finishes used successfully with architectural precast concrete are acceptable on GFRC panels. The absence of large coarse aggregate in the GFRC mixture allows it to closely follow the surface texture or mold pattern. Many surface patterns and textures can be achieved by casting the panels against form liners, although it is advisable whenever possible to incorporate chamfers or radii at inside corners of the form and avoid sharp angles and thin projections. Although a smooth, off-the-form finish may be the most economical to use, it is not recommended. Color uniformity of gray, buff, or pigmented surfaces can be difficult to achieve and the cement film on the GFRC could develop surface crazing or fine, random hairline cracks. This crazing has no structural or durability significance, but may become visually accentuated when dirt settles in the cracks. The esthetic limitations of smooth GFRC could be minimized by the shading and depth provided when creating profiled surfaces such as fluted, sculptured, or board finishes; by subdividing the panel into smaller surface areas; or using white cement or applied coatings. Panels should be faced with a 1/8 to 3/8 in. (3 to 9 mm) thick face mixture with

decorative aggregates. The aggregate may be exposed by retarders, sand or abrasive blasting, acid etching, or honing and polishing to produce the desired effect. Light, medium, or deep exposure of aggregates is possible.

Differential shrinkage between the face mixture and the GFRC backing is important and should be considered in the mixture proportions. Mixture proportions should be developed so that moisture and thermal-related movements between the bonded face mixture and GFRC backing are dimensionally compatible. The cement matrix also offers many color choice variations with gray, white, or buff-colored portland cements or color pigments. Vapor-permeable concrete coatings or stains can be applied after adequate surface preparation. When the GFRC panel surface has two or more different mixtures or finishes, a demarcation feature is necessary. Different face mixtures should have reasonably similar shrinkage behaviors to avoid cracking at demarcation features from differential shrinkage. Natural stone veneers such as limestone, marble, or granite in narrow strips; small squares and rectangles; or regular-sized ashlar pieces can also be attached to the GFRC skin. A bond breaker between the veneer and GFRC skin is necessary to minimize panel bowing from differential shrinkage. Clay products, such as thin brick veneer, facing tile, and architectural terra cotta (ceramic veneer) can be attached to GFRC as long as the differential moisture and thermal movements of the clay product facing and GFRC backing are considered. Exact replicas of original ornamental work such as terra cotta from historic buildings can be made from GFRC. Sample panels of adequate size may be necessary to translate design concepts into realistic production requirements. With any integral or attached surface-finishing material, consideration should be given to the thermal- and moisture-induced dimensional changes and their compatibility, as well as aged properties of the GFRC.

3.1.7 Benefits of GFRC cladding panels—The benefits offered by GFRC for architectural concrete include:

a) Their thinness, which can be 0.5 to 1.0 in. (13 to 25 mm) compared to precast concrete and stone, usually over 2 in. (75 mm), which leads to additional benefits such as:

- i. They can often be less than one-fourth the weight of other masonry materials, with commensurate savings in structural steel; for example, the Marriott hotel in San Francisco, CA (Fig. 3.1.7a), which has 340,000 ft² (31,587 m²) of GFRC panels, thereby reducing the structural steel requirements by 330,700 lb (150 tonnes), in comparison to being clad in precast concrete.
- ii. The thinness of GFRC also means that GFRC panels can take up less of the area of the slab for installation than stone or precast concrete, which offers more leasable floor for the owner; this adds up in expensive real estate markets such as London, UK. For example, The Crédit Lyonnais building (Fig. 3.1.7b), the first major project completed in GFRC in 1974, resulted in 5 percent more leasable area, which was a significant factor in the economic viability for a building in this pricey real estate area.



Fig. 3.1.7a—Marriott Hotel, San Francisco, CA.



Fig. 3.1.7b—Crédit Lyonnais, London, UK.

b) Faster erection provides shorter building schedules, which was the case in the Stanford University Business School buildings, CA (Fig. 3.1.7c), completed in 2011. Stucco on lath was first considered for this project, but GFRC offered a shorter schedule and was comparable in weight, eliminating the need to modify the structure. Additionally, the color, texture, and quality of finish were more acceptable to the architect and owner.

c) The light weight of GFRC panels makes it advantageous in earthquake-prone areas.

d) Glass fiber-reinforced panels can be designed for hurricane requirements (3.2).