

# RETROFITTING HIGH-RISE STRUCTURES USING FRP COMPOSITE MATERIALS

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**F**iber-reinforced polymer (FRP) composite materials have become a viable and accepted means of upgrading, strengthening, and rehabilitating structures over the past three decades. They provide many advantages over conventional materials due to their exceptional physical and mechanical properties. Among these advantageous properties are high strength, light weight, noncorrosive, extremely durable, and ease of installation. In addition to being used on heavy civil engineering structures such as bridges, dams, and various infrastructure projects, composites have also been used successfully on high-rise structures in applications such as façade and balcony repairs, seismic upgrades, changes in use, building modifications, and blast hardening. The most prevalent types of composite materials used for building repairs are carbon, glass, and aramid fibers, while epoxy resins are the most commonly used adhesive due to their tenacious bond to most construction materials, long track record, and excellent durability characteristics.

Structural engineers will typically design with FRP composites in accordance with ACI 440.2R, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening

Concrete Structures.”<sup>71</sup> In addition, ACI 562, “Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings,”<sup>72</sup> allows for the use of FRP composites as long as the designs are consistent with ACI 440.2R guidelines. For projects governed by the International Building Code (IBC), the model building code developed by the International Code Council (ICC),<sup>3</sup> it is important to use products that are tested in accordance with AC 125<sup>4</sup> and have a published Evaluation Services Report (ESR) verifying compliance with the code. Various fire protection systems are also available ranging from intumescent coatings to guard against flame spread and smoke development (ASTM E84)<sup>5</sup> to fire-resistive mortars that insulate and protect the FRP composites and reinforced concrete up to 4 hours in accordance with ANSI/UL 263<sup>6</sup> and ASTM E119.<sup>7</sup>

The International Concrete Repair Institute (ICRI) also has several documents on structural strengthening systems for concrete and masonry structures using FRP composites: ICRI 330.1, “Guide for the Selection of Strengthening Systems for Concrete Structures,”<sup>8</sup> and a Special Publication, “Strengthening and Stabilization of Concrete and Masonry Structures.”<sup>9</sup>



Fig. 1: Building façade repairs using CFRP fabrics

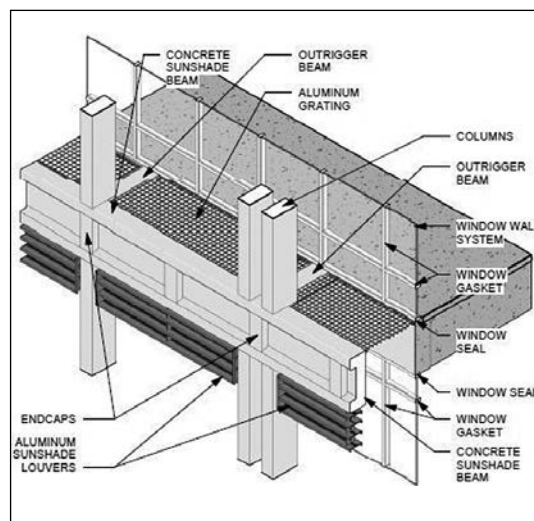


Fig. 2: Isometric view at midlevels on north and south building façades (Diagram courtesy of Johnston, LLC Architects, Houston, TX)



Fig. 3: Shear cracking adjacent to post-tension anchorage zone



Fig. 4: Double-bias CFRP fabric installed on sunshade beams (Photo courtesy of Structural Concrete Systems, LLC, Houston, TX)

## FAÇADE REPAIRS

A 10-story government office building (Fig. 1) in downtown Houston, TX, was constructed in 1978 with a reinforced concrete slab supported by post-tensioned concrete beams. It was showing signs of distress including spalling and cracking, causing pieces of concrete to come loose and fall off. A series of “sunshade” perimeter beams supported by “outrigger” beams that cantilever beyond the window wall perimeter to support the sunshade beams (Fig. 2) were also showing signs of deterioration. The precast concrete end caps that protected the button-head anchorages of the post-tensioned system were compromised and shear cracks developed adjacent to the anchorage zone (Fig. 3). After a comprehensive diagnosis of the building was completed, a series of concrete repair solutions was undertaken that included the removal and replacement of deteriorated concrete and end caps, epoxy injection of cracks, application of a surface-applied corrosion inhibitor, and removal/replacement of the exterior sealant and glazing gaskets.

In addition, a series of FRP repairs were made to repair and strengthen the building façade and the sunshade and outrigger beams. A unidirectional carbon fiber-reinforced polymer (CFRP) fabric was installed longitudinally along the flanges of the sunshade beams. A  $\pm 45$ -degree, double-bias CFRP fabric was installed on both faces of the web to provide shear reinforcement and intersect the pre-existing cracks (Fig. 4). This same fabric was also used on the outrigger beams for added stability at the corners (Fig. 5). Once the FRP repairs were completed, an elastomeric, anti-carbonation coating was installed over the entire façade to provide protection against the elements and for improved aesthetics (Fig. 1).



Fig. 5: CFRP fabric adds stability at beam intersection



Fig. 6: New curtain wall installed over CFRP repairs at office building

## BLAST HARDENING

A 600,000 ft<sup>2</sup> (55,740 m<sup>2</sup>) reinforced concrete office building (Fig. 6) in Metropolitan Washington, DC, was gutted to its core and completely

renovated to achieve LEED Gold Certification. In addition, the building was blast hardened to meet Department of Defense (DOD), Department of Justice (DOJ), and General Services Administration (GSA) security requirements. The renovation



Fig. 7: Roof slab strengthened with CFRP laminates for blast hardening



Fig. 8: Perimeter edge slabs strengthened with CFRP fabrics



Fig. 9: Slab at column retrofitted with CFRP laminates to reinforce for punching shear

included demolition of the building core, building systems and building envelope. The entire façade was removed and replaced with a new precast concrete curtain wall (Fig. 6). A series of CFRP repairs were made during the renovation to structurally enhance the building and provide blast protection for future occupants.

The entire concrete roof and floor slabs were reinforced with externally applied, pre-cured carbon fiber laminates to resist the potential for uplift pressures from an explosion (Fig. 7). The perimeter slab edges were reinforced with CFRP fabrics prior to the replacement of the new curtain wall system (Fig. 8). In addition, the column perimeters were retrofitted with CFRP fabrics to reinforce the area for punching shear (Fig. 9). In total, 28 miles (45 km) of CFRP pre-cured laminates and 25,000 ft<sup>2</sup> (2325 m<sup>2</sup>) of CFRP fabric were installed to enhance and upgrade this Class A space.

## BUILDING MODIFICATIONS

It is not uncommon for building owners to modify or alter their interior space over the life of the structure. This sometimes involves making cut-outs in the structural elements to accommodate these changes. However, whenever a reinforced concrete slab or wall is penetrated, this can change the load paths and possibly make the building unsafe. One way to reinforce the cut-out area is to add structural beams to carry the redistributed loads. While structurally sound, this solution is often undesirable because the new beams are difficult to install in an occupied space, impossible to hide, and take away from the functionality and aesthetics of the finished space. Another option is the use of externally bonded FRP plates, or in some instances, the use of near surface-mounted (NSM) carbon-fiber rods. For example, a condominium owner on Central Park West in New York City was combining two apartments into one and wanted to add a new octagonal shaped staircase into the units to allow direct access between the two units. Prior to saw cutting into the floor slab, a series of CRFP pre-cured plates were epoxy bonded into grooves cut into the concrete slab on both the top (Fig. 10) and bottom surfaces. The new CFRP laminates structur-



Fig. 10: Octagonal cut-out in slab reinforced with CFRP laminates



Fig. 11: Shear cracks in critical support beam

ally enhanced the opening and replaced the tensile forces that were removed when the existing reinforcing bar was cut out for the new opening. By placing the CFRP plates around the perimeter of the opening, the stresses were redistributed and the owner was able to install the new staircase without the need for a new structural beam. Not only was this a less-expensive repair option, but it was much less obtrusive to the client and the space.

### SEISMIC RETROFIT

One of the earliest uses of FRP composites in infrastructure applications was for seismically upgrading bridge structures, many of them built pre-1950s. The California Department of Transportation (Caltrans) initiated a program in the mid-1990s to evaluate and test advanced composite materials as a column wrap alternative to steel jacketing and pressure grouting. The lack of sufficient shear reinforcement and inadequate lap splice lengths created an unsafe condition for thousands of bridges on the West Coast in high-seismic regions.



Fig. 12: Concrete beam wrapped with CFRP fabrics and "rope" anchors for seismic strengthening

In fact, many bridges and buildings collapsed from the 1989 Loma Prieta and 1994 Northridge earthquakes in California, creating billions of dollars' worth of damage and causing dozens of fatalities.

One example of a high-rise structure strengthened with the use of FRP composites was an 11-story medical office tower in Beverly Hills, CA. This reinforced concrete building was built in 1963 and seismically retrofitted in 2014-2015. Shear cracks were identified in some of the critical support beams (Fig. 11) and crack monitors were installed to measure the movement over an extended period of time. A structural analysis was performed by the

structural engineers and identified a deficiency in the concrete beams. The structural cracks were pressure injected with a low-viscosity epoxy resin to fill the void and stabilize the movement. New concrete shear walls were added to further stabilize the building. Finally, the concrete beams were U-wrapped with carbon fiber fabrics to provide enhanced shear reinforcement and added ductility. Specially designed CFRP “rope” anchors (Fig. 12) were installed to provide anchorage and assist with the through-slab connections. Finally, the repairs were over-coated with an ultraviolet (UV)-stable and waterproof coating to provide enhanced durability and improved aesthetics to the client.

## SUMMARY

FRP composites offer many advantages to owners, architects/engineers, and contractors for making modifications or alterations to building structures; undertaking upgrades for seismic, wind or blast loading conditions; as well as strengthening



Fig. 13: Strengthening of foundation wall during original construction



Fig. 14: CFRP fabrics bonded to roof slab to support additional loads

of structural elements (Fig. 13 and 14). FRP composites have been used successfully over the past three decades in the United States and abroad and have significantly replaced the traditional methods of adding new support beams or externally bonded steel plates or jackets. Not only do FRP composite materials offer higher strength than steel and concrete, they are extremely lightweight and noncorrosive, which provides for long-lasting repairs and sustainable structures. The industry has published design codes, guidelines, and approval criteria which enable structural engineers to safely determine which structures are candidates for FRP repairs and how to best design and detail a repair solution.

## REFERENCES

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