STRUCTURAL ROOF STRENGTHENING TO SUPPORT NEW GREEN ROOFS

BY TAREK ALKHRDAJI

In the race to build green, many building owners and contractors have turned to an unlikely place: the roof. A green roof is a green space created by adding a growing medium and plants on top of an existing or new roofing system. Green roofs are vegetated roof covers with growing media and plants taking the place of bare membrane, gravel ballast, shingles, or tiles. The number of layers and the layer placement vary from system to system and green roof type, but a typical green roof includes a single or multi-ply waterproofing layer, drainage, growing media, and the plants, covering the entire roof deck surface. A distinction should be made between a green roof and traditional roof garden. A roof garden is typically done with containers and planters located on a roof terrace or deck, whereas a green roof system is made of several layers that are installed directly on the roof. Green roofs have been shown to reduce heat loss and energy consumption in winter conditions and help keep temperatures down during hot weather—particularly in urban areas.

Green roofs have many environmental benefits. Chief among the benefits is the ability to better regulate storm-water runoff, help keep temperatures under control—both inside and outside the building, filter dust and smog particles, provide a habitat for wildlife, insulate against noise, and increase the life span of the roof. For property owners seeking Leadership in Energy and Environmental Design (LEED) certification, a green roof can contribute several credits toward green certification of new and existing buildings. In addition, many cities currently offer tax credits for green roof construction. Because of these factors, green roofs are currently experiencing a boom in popularity in urban environments. Many green roofs are designed like gardens, with pathways and manicured landscapes, and are popular amenities for office buildings, hotels, and condominiums looking to create green spaces for tenants and guests. What was a fad a few years ago is now developing into a quantifiable building improvement for natural aesthetics, lower utility costs, and reduced rainfall runoff into local watersheds.

TYPES OF GREEN ROOFS

There are two types of green roofs: intensive roofs, which are thicker and can support a wider variety of plants, and extensive roofs, which consist of a light layer of a growing medium and vegetation. Intensive green roofs are generally heavier, include a deeper layer of growing medium, and have greater needs for irrigation and maintenance. These roofs are designed as amenity space that can be used by building tenants or the general public. Soil depth for intensive green roofs varies from 6 to 24 in. (150 to 610 mm) or more and can weigh from 80 to 200 lb/ft^2 (391 to 976 kg/m^2). Extensive green roofs, on the other hand, are generally designed to be lightweight to maximize the performance and environmental benefits for the least increase in design loads. Extensive green roofs feature a layer of growing medium that is 6 in. (150 mm) deep or less and weigh 15 to 50 lb/ft^2 (73 to 244 kg/m^2). They have low maintenance requirements, but are generally not maintenance free. Extensive green roofs are not designed for public access and require less initial investment, making them ideal for owners who are simply looking for the energy benefits a green roof can provide.

Green roofs can also be classified as integrated or modular. Integrated green roof components are installed as a series of layers. Modular green roofs are partially assembled off-site and are installed in units. Some modular systems feature plastic or metal trays that are filled with growing medium and placed on the rooftop.

Similar to green roofs, the term "blue roof" has been coined to refer to roof systems that focus on rainwater collection. This relatively new term was used by New York City, which has recently pushed past its green roof initiative to include blue roofs in its new campaign for a cleaner city. Blue roof systems minimize the amount of storm water that a building site sheds to the rest of the city by using catchment pools, rain barrels, and more discreet water-hungry plantings. Blue roofs are less costly than green roofs and can also provide sustainability benefits through rooftop cooling.

Before any installation can take place, it is very important to hire a licensed structural engineer to determine if the existing structure can support a green roof. The consultant will analyze the building and will need to know the following information to complete the structural analysis:

- Green roof type, layout, and loads;

- Type and condition of the existing roof membrane;
- Existing and required electrical and water supply;
- Roof accessibility for installation and maintenance; and
- Current structural system capacity.

Green roof loading is one of the main factors in determining both the viability and the cost of a green roof installation. For a green roof installed on an existing building, the design can be limited to the load-carrying capacity of the existing roof, or the existing roof system can be upgraded to support the new green roof loads. Typical green roofs weigh between 30 and 100 lb/ft^3 (481 to 1603 kg/m^3). This is a heavier load, considering that most existing roofs are typically designed for a live load of 30 or 40 lb/ft^2 (146 or 195 kg/m^2). In general, the more complex the green roof system, the more extensive and intrusive the required structural upgrade. The following strengthening solutions have been successfully used to increase the load-carrying capacity of structural systems and are typical considerations for green roof installation projects.

STRENGTHENING SOLUTIONS

There are different methods available to strengthen existing buildings, including externally bonded fiber-reinforced polymer (FRP) composites, span shortening, externally bonded steel plates, external post-tensioning systems, and section enlargement. A thorough analysis of the existing capacity and the effects of the new loads onto the roof structure including slabs, beam, and columns is a critical first step. The selection of the strengthening techniques will depend on the specific requirements of the project in regard to the type of deficiency (flexure, shear, axial, and so on), magnitude of strength increase, constructibility issues, aesthetics, and economics. The following is a brief description of some of the most common structural strengthening methods that have been used to address similar conditions.

CARBON-FIBER REINFORCED POLYMER (CFRP) COMPOSITES

CFRP systems are carbon-fiber fabric sheets or pre-cured bars and sheets that are externally bonded to concrete members with adhesive resin and can increase the member's load-carrying capacity. CFRP sheets are typically very thin (30 to 60 mil [0.76 to 1.5 mm]), yet they have a tensile strength up to eight times that of steel, allowing it to add considerable capacity to the structure without impacting the appearance. Due to its noncorrosive nature, the use of CFRP reinforcement is ideal for green roof applications as it requires minimum to no maintenance and provides a durable long-term solution. As tensile reinforcement, CFRP systems must be bonded to a properly prepared concrete surface to achieve the desired composite behavior. For applications where the top side of the roof slab requires upgrade, the thin CFRP system is very advantageous, as it will not interfere with the green roof components and is very durable. In some cases, high-strength CFRP rods are glued into slots cut in the concrete member—a technique known as near-surface mounting (NSM). Using externally bonded CFRP reinforcement, the bending capacity of beams and slabs, shear capacity of beams and joists, and axial capacity of columns can be increased; however, there are a few limitations and design and detailing requirements should be achieved in accordance with ACI 440.2R design guidelines to ensure adequate system performance.

Installation of CFRP sheets on the underside of the slab

Installation of NSM carbon rods on the top side of the slab

EXTERNAL POST-TENSIONING

With external post-tensioning, active external uplift forces can be applied to the structural member to offset new roof loads. Post-tensioning is the introduction of external forces to the structural member using high-strength cables, strands, or bars connected to the existing member at anchor points (typically located at the ends of the member) and profiled along the span to produce high and low points. End anchors can be made of steel fixtures bolted to the structural member or cast-in-place reinforced concrete blocks. When stressed, the tendons will produce upward forces (at low points) or downward forces (at high points) to create a reverse loading condition on the member. As with any strengthening system, there are several design, detailing, construction, and durability issues that must be considered when designing a post-tensioning strengthening system.

While sufficient post-tensioning should be provided to achieve the desired strength increase, care should be taken not to overstress the member at service condition and to ensure proper transfer of post-tensioning force to the structure. Forces generated at the anchor points can be quite large and should be properly addressed in the design of the system. The design and detailing of post-tensioning strengthening systems should be developed by experienced engineers with a focus on structural strengthening and the use of post-tensioning systems.

SECTION ENLARGEMENT

This method of strengthening involves placing additional "bonded" reinforced concrete onto an existing concrete member in the form of an overlay or a jacket. Achieving composite action between the existing member and the new enlargement is critical to allow for full use of the enlarged member. The bond between the new and existing concrete can be achieved by roughening existing concrete surfaces (typically 0.25 in. [6.4 mm] of surface amplitude) and the use of shear dowels that are epoxy or mechanically anchored to the existing substrate. The American Concrete Institute (ACI) 318 Building Code provides criteria for design of horizontal shear transfer and profiling requirements. To ensure full composite behavior, the additional concrete must be placed in the formwork under pressure to ensure consolidation around the new reinforcement for optimum surface bond. This method of concrete placement is known as the form-and-pump technique. A minimum of 2 psi (0.01 MPa) pressure must be produced inside the formwork during pumping to ensure adequate bonding between existing and new concrete. This internal pressure is different from the pressure that is typically measured at the concrete pump truck and should be verified by measuring the pressure inside the formwork.

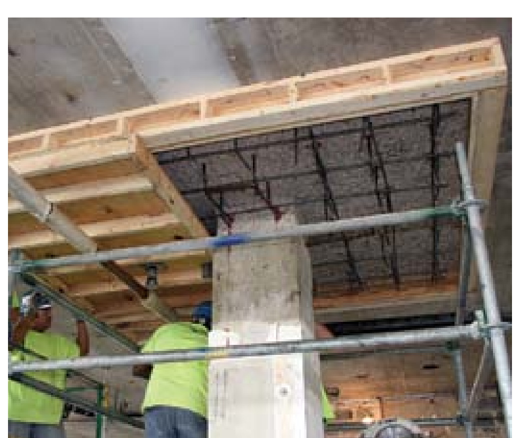
Section enlargement can be used on columns, beams, slabs, and walls to increase their load-carrying capacity. A section enlargement can be as thin as 2 in. (50 mm) for slabs and 4 in. (100 mm) for beams and columns. In some cases, the enlargement may use post-tensioning tendons as reinforcement within the new concrete.

A thinner and stronger layer of structural section enlargement can also be achieved by using an ultra-high-performance ductile concrete consisting of high-strength cementitious matrix reinforced with multiple layers of bidirectional steel micro-mesh. The micro-reinforcement is uniformly distributed in the cross section, creating a homogenous composite material with superior strength and ductility characteristics. This strengthening material results in a durable strengthening system with high compressive strength and abrasion resistance as well as exceptional resistance to aggressive chemicals. Similar to most structural concrete enlargements, this material must be installed using the form-and-pump technique to ensure composite behavior with the existing structure.

SPAN-SHORTENING/ SUPPLEMENTAL SUPPORTS

This technique involves adding supports underneath existing members, thereby increasing the structural load-carrying capacity by reducing the length between spans or by directly supporting the

Installing reinforcement for concrete drop-panel enlargements



Installing forming for concrete drop-panel enlargements

Completed concrete drop-panel enlargements element. Typically, structural steel members are used. Although it employs basic materials, challenges with this technique include material handling, structural connections, reduced headroom inside the building, and load transfer to the existing structural system.

SELECTING THE PROPER STRENGTHENING SYSTEM

In many cases, selection of the roof strengthening system will be governed by a system that can provide the required strength increase without interfering with the use, aesthetics, and operation of the structure. The structural engineer typically decides which type of strengthening system is best suited for the project based on the structural analysis of the existing roof system, as well as constructibility, cost, and strength increase considerations. In some instances, thorough analysis of the roof structure can reveal that there are certain roof areas where loading can be increased more than others, which will allow for certain areas to accommodate deeper growing medium and larger plants (combination of extensive and intensive roof systems). The structural engineer should make the owner and building manager aware of the roof's loading restrictions to avoid future improper relocation or additional plantings in areas that cannot accommodate the weight.

WHAT ABOUT COST?

A properly designed and installed green roof system can cost \$12 to \$20 per ft^2 (\$129 to \$215 per m^2) for extensive green roofs and \$20 to \$40 per ft^2 (\$215 to \$430 per m^2) for intensive green roofs. The cost depends on the green roof design specifics, climate, and plant selection; however, there are additional costs associated with strengthening the existing roof structural system to support the new green roof loads. The cost of strengthening the structural system will vary from \$20 to \$50 per ft^2 (\$215 to \$538 per m^2), depending on the complexity of the structural system and size and level of strength increase required, as well as the type of strengthening system.

Although renovating an existing roof system to install a green roof requires an initial investment, the increased longevity of the roof and savings on energy expenditures outweigh the initial cost.

GREEN ROOFS IN ACTION

Today's savvy owners are looking to add green roofs to their properties to enhance value. One example is an eight-story office building at 1225 Connecticut Avenue in downtown Washington, DC, owned by Brookfield Properties. In September 2008, the building was undergoing a complete renovation. The owner originally registered the project as LEED EB (Gold) certification, but decided to add a green roof to complement the new penthouse and to earn enough credits for a Platinum rating—the highest allowed under the LEED system. A strengthening program was needed to address the increase in required capacity from 30 to 75 lb/ft^2 (146 to 366 kg/m^2), part of which came from the 4 to 6 in. (100 to 150 mm) of saturated growing medium. It was determined that a CFRP system could supply up to 100 lb/ft^2 (488 kg/m^2) of service load capacity or 10 lb/ft^2 (49 kg/m^2) superimposed dead load and 90 lb/ft^2 (439 kg/m^2) live load.

STRENGTHENING

The strengthening contractor worked to develop a solution using the following:

- CFRP sheets on the underside of the slab;
- CFRP rods on the top side of the slab;
- Concrete drop panel enlargements designed for optimum structural enhancement; and
- Column enlargement.

In general, projects involving strengthening of an existing structure offer different challenges than new construction. A significant challenge with this project was access to the roof. A crane was not used during the project; therefore, all equipment and material (including thousands of bags of concrete) were taken up to the roof via a small service elevator. Some of the equipment had to be dismantled to fit in the elevator and then reassembled on the

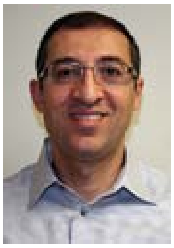
Completed green roof at 1225 Connecticut Avenue in downtown Washington, DC. The project helped the owner attain LEED Platinum rating roof. Three mobilizations were required to accommodate the overall project schedule.

Several other challenges were addressed and the solutions implemented with great success. The building now has a green roof that not only enhances the value of the property but also helped the owner attain LEED Platinum certification.

KEY TO A SUCCESSFUL GREEN ROOF

Depending on the type of green roof system, installation can be a major undertaking. Upgrading a roof for additional capacity requires careful consideration of existing conditions to ensure the structure is capable of supporting the additional load. Because every element of the existing structure carries a share of the load, the effects of strengthening or removing part or all of a structural element must be analyzed carefully to determine its influence on the global behavior of the structure. Failure to do so may cause overstress to other structural elements and cause serious problems. In addition, performing work on an existing structure requires attention to critical issues such as access to the work area, noise and dust control, and compatibility of construction materials with existing systems.

Because of these many considerations, it is important for owners, engineers, and architects to engage a company with experience in structural upgrades. Specialty firms familiar with the critical aspects of structural strengthening can ensure the most cost-effective and long-lasting results, making the green roof an enhancement and valuable addition to the property.



***Tarek Alkhrdaji**, PhD, PE, is an Engineering Manager with Baltimore, MD-based STRUCTURAL TECHNOLOGIES. He has been involved in numerous projects involving structural repair and upgrade as well as full-scale load testing. He is an active member of ACI Committees 437, Strength Evaluation of Existing Concrete Structures; 440, Fiber-Reinforced Polymer Reinforcement; and 562, Evaluation, Repair, and Rehabilitation of Concrete Buildings, as well as a member of ICRI and the American Society of Civil Engineers. He may be contacted at (410) 796-5000 or via e-mail at talkhrdaji@structural.net.*