

Post-Tensioned Retrofitting Maintains Landmark's Aesthetics

Team effort, sophisticated technology solve problems at famed architect Frank Lloyd Wright's *Fallingwater* creation

BY JAMES LOPER AND JASON HUGHES

When selected by the Western Pennsylvania Conservancy to renovate *Fallingwater* (Fig. 1)—one of Frank Lloyd Wright's most famous architectural home designs—VSL (a post-tensioning contractor) became part of a team focused on saving the ailing structure. In 1995, the Conservancy retained Robert Silman Associates (an engineering firm specializing in the restoration of historical structures) to lead the efforts by providing a cutting-edge analysis of the existing structure and engineering recommendations for its restoration. Additional team members included Schupack Suarez/TDEG (post-tensioned concrete consultant), Pennsylvania State University (deflection monitoring), GBG, Inc. (nondestructive testing), and Structural Preservation Systems (concrete repair).

Silman Associates and the Conservancy fostered teamwork among the participants, which led to a number of excellent ideas. Although the project had many special features—nondestructive testing, section enlargement, carbon fiber reinforcement, epoxy crack injection, and deflection monitoring—the feature that set this project apart from typical restoration projects was the delicate operation required during installation of the external post-tensioning.



Fig. 1: View looking up at *Fallingwater* from stream below. The home is comprised of a series of concrete cantilevered trays. From downstream, water appears to pour out of the structure

THE PROBLEM

A series of four large bolsters, built into a natural sandstone ledge, comprise the structure's foundation. Three of the bolsters are made of reinforced concrete and one is made of stone masonry. Three-ft-wide (1 m) concrete girders cantilever outward from the bolsters approximately 15 ft (4.6 m) over the stream and are the primary support for the main terrace (Fig. 2 and 3). Four-in.-wide (100 mm) concrete joists, spaced 4 ft (1.2 m) on center, span between the girders to support wooden planking and stone flooring.

By the time the house celebrated its 50th anniversary in 1987, the Conservancy had concerns about cracking and deflection observed at the cantilever terraces. The most notable concerns were cracks in the upper level parapet walls and vertical deflections of up to 7 in. (175 mm) over the cantilever span of the main terrace. A review of historical information containing deflection data indicated that the vertical movement was active and progressively worsening.

THE CAUSE

The underlying cause of the cracking and deflections was the structural capacity of the cantilever girders at the main level. Bar reinforcement is generally placed in the top of cantilevered members to carry tension stresses created by dead and live loads. Such loads at the master and main terraces include stone flooring, furniture, people, and snow. While the cantilever girders at the main level contained up to sixteen, 1-in.-square (25-mm-square) bars each, engineers found that the girders were inadequate for the design loads, causing both terraces to sag.

INSPECTION AND EVALUATION METHODS

To accurately evaluate the structure, engineers needed to gather, inspect, and analyze information on four primary features—material properties, as-built conditions, load paths, and member capacities. Structural shop drawings from the original construction provided insight about the geometry and reinforcement used to build the home. Nondestructive testing methods, such as impulse radar and magnetic resonance, helped to determine as-built conditions. Metallurgical testing on small pieces of reinforcement recovered from the Conservancy indicated that its yield strength was about 41 ksi (283 MPa). Tests on the concrete's in-place strength revealed a compressive strength of approximately 5000 psi (35 MPa).

Pennsylvania State University furnished and installed an electronic monitoring system that they attached to the parapets to measure crack widths over an 18-month period. After adjustments for seasonal changes, data indicated that the cracks were progressively widening. Engineers conducted a comprehensive computer analysis on the structure to evaluate its capacity and found that the main and master level terraces are interdependent and that the stress in the primary girder reinforcement was approximately at its material yield strength. Realizing that stresses were at critical levels and deflections were worsening, engineers began developing a repair strategy.

STRENGTHENING AND REPAIR SYSTEMS SELECTION

Based on results from the engineering analysis, and given the great amount of concern for public safety, the

HISTORICAL SIGNIFICANCE

While Frank Lloyd Wright designed many notable commercial and residential structures during his illustrious career, *Fallingwater* is arguably his greatest achievement. Wright blended each facet of the structure seamlessly into the natural surroundings. Several structural and architectural features set this structure apart from his other works. One of the home's signature features is the soffit slab. The slab works integrally with the girders as a load-carrying inverted T-beam while providing an aesthetically pleasing smooth finish on the structure's underside. Another unique feature is the master bedroom terrace that cantilevers approximately 6 ft (1.8 m) further out than the main level terrace. Four vertical window mullions span upward from the main level to support the bedroom terrace cantilever. At the time of construction (1937), these types of ideas were considered revolutionary.

Fallingwater was originally constructed as a weekend home for the Kaufmann family who owned a successful department store at the time in nearby Pittsburgh, PA. The structure is comprised of a series of concrete cantilever trays approximately 30 ft (9.1 m) above a waterfall on a mountain stream called Bear Run. The lower tray is the first floor (main) terrace and the upper tray is the master bedroom terrace. From a downstream view, the terraces appear to hover over the water and water appears to pour out of the structure. Approximately half the living space at each terrace is indoors, the other half is outdoors.

In 1963, the family entrusted *Fallingwater* to the Western Pennsylvania Conservancy, which maintains the structure, surrounding landscape, and original furnishings within the home. Today, approximately 60,000 people visit the site per month during peak tourist seasons.

Conservancy prudently chose to install temporary shoring beneath the main level terrace until a permanent strengthening solution could be designed and installed. Primary requirements for the permanent system were strength and aesthetics; it would need to be strong enough to halt vertical deflections while being relatively unobtrusive to visitors.

The owner and engineer considered several options for permanently strengthening the under-reinforced cantilever girders. One option was to simply leave the shoring in place permanently. This option was discarded because it was considered to be too obtrusive to the aesthetics of the structure. The team also considered other options such as section enlargement and carbon fiber strengthening. After careful review, the design team selected external



Fig. 2: One of the primary girders at the main level that cantilevers over the stream and supports the south parapet wall (background). Note the four structural window mullions at the parapet and the dead-end anchorages with spiral reinforcement and grout vents (foreground)

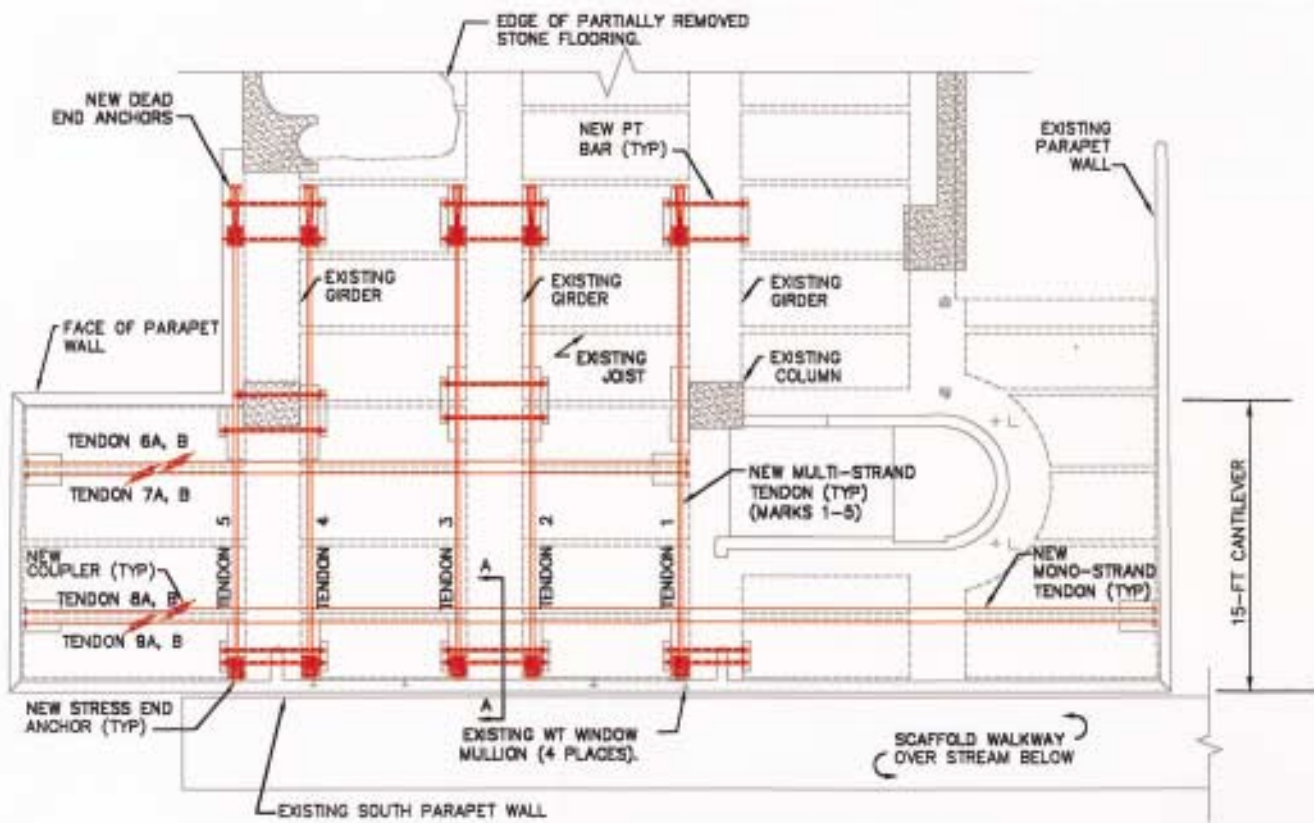



FIGURE 3 - FIRST FLOOR TENDON LAYOUT 

NTS

Fig. 3: Plan view of the first floor showing the tendon layout. The 3-ft-wide (1 m) girders cantilever from the bolsters about 15 ft (4.6 m) over the stream. The monostrand tendons were stressed from within the structure using special splice couplers

post-tensioning for several reasons. The strands, anchorage assemblies, and concrete anchor blocks proved to be relatively lightweight and did not add a significant amount of additional dead load to the already overstressed girders. Also, post-tensioning was aesthetically favorable because it would be hidden in the floor cavity between the girders and invisible to passersby.

Once the team selected the repair systems and the owner awarded the construction portion of the project to the post-tensioning contractor, the next step was to remove the existing stone flooring. Unfortunately, no one knew exactly what conditions would be found.

UNFORESEEN CONDITIONS

After the Conservancy carefully removed and cataloged the stone flooring, engineers and technicians began exploring the structural framing. They found severe deterioration of the existing joists and surrounding support members on the eastern side of the main terrace. Four of the joists were badly cracked and appeared to be pulling away from the main support. It is believed that this damage may have occurred when a tree hit the structure during a major storm several years prior to the current project. This and other deteriorated areas were carefully evaluated and added to the scope of repairs for this project.

REPAIR PROCESS CHALLENGES

The construction team faced several challenges on this unique renovation project. Due to the historical significance of the structure, the owner wanted to preserve the existing building elements and to minimize incidental damage during renovation. As “gently” as possible, the construction team chipped and drilled pockets and openings for the new reinforcement.

The waterfall and stream beneath the structure posed two challenges. First, there were special safety requirements related to working over the stream. Second, the team had to take special interest in keeping construction debris from falling into the stream. This was especially important because the stream’s water quality is extremely high.

Cold-weather conditions were a challenge during placement of concrete anchor blocks and grouting of post-tension tendons. The team was particularly careful to comply with ACI and PTI guidelines for cold-weather concreting and tendon grouting, respectively.

Due to the delicate nature of this project, the post-tension stressing sequence and staging operations also provided unique challenges. The team needed to develop a system whereby the effective post-tension forces would be large enough to meet the requirements specified by the engineering analysis. The forces would also need to be low enough to avoid excessive upward vertical deflections and member stresses.

VSL prepared detailed stressing and elongation calculations with input from the post-tensioning

consultant. Careful consideration was given to tendon curvature, friction losses, creep, shrinkage, anchor set, and the age of the structure. The post-tensioning contractor and Pennsylvania State University installed a data acquisition system to monitor strain and vertical deflections at various points around the structure during stressing.

Tendons were incrementally stressed to facilitate the introduction of relatively uniform post-tensioning forces and to allow for the careful monitoring of deflections and strains in the structure.

EXECUTION OF REPAIRS

Execution of the repairs via a step-by-step process and close coordination between all team members were essential to the successful completion of this project. Construction documents called for multistrand post-tensioning (using 0.5-in.-diameter [13-mm], 7-wire low relaxation strand) of the three primary cantilever girders spanning in the north-south direction. Thirteen-strand tendons were placed on each side of two of the girders. One 10-strand tendon was positioned on the western side of the third girder (access on the eastern side of this girder was not available). Eight monostrand tendons (0.6-in.-diameter [15-mm], 7-wire strands) were slated for the east-west direction.

The first step was layout and placement of the monostrand and multistrand tendons and their anchorage blocks. The team paid special attention to the amount and location of dowels, spirals, and transverse post-tension bar reinforcement at the anchorage blocks (Fig. 4 and 5).

Craftsmen doveled new reinforced concrete blocks into the sides of the existing girders to anchor and profile the post-tensioning. Small openings were sawcut into the existing south parapet wall to gain access for multistrand tendon stressing (Fig. 4). Dead-end anchors were placed at the north end of the girders.

Similar anchor blocks were positioned for the monostrand tendons that spanned in the east-west direction. The post-tensioning contractor stressed the monostrand tendons from within the structure using special splice couplers (Fig. 3). This was done to avoid the need for cutting additional access openings in the parapet walls.

Based on nondestructive testing methods, the contractor found delamination of the concrete at the existing support girders. High-strength post-tensioning bars 8 ft (2.4 m) long were doveled vertically through the girders and into the foundation below to provide additional strengthening. Craftsmen took extreme care to avoid drilling through the existing reinforcement in the girders.

The next step was to stress the tendons. Stressing operations were carefully staged and sequenced. The post-tensioning contractor stressed the four monostrand tendons in the east-west direction and then the five multistrand tendons in the north-south

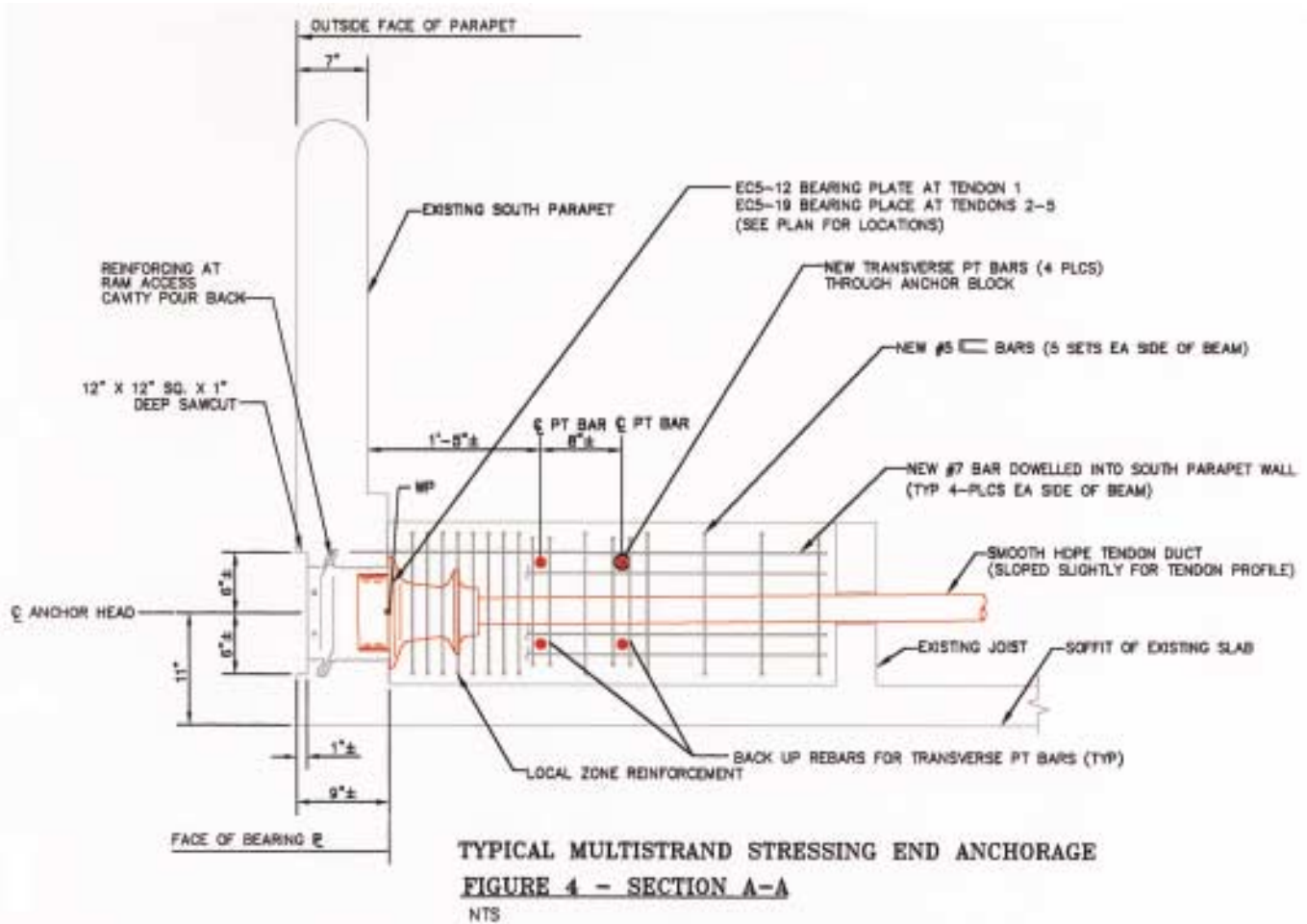


Fig. 4: Typical reinforcement detail for a multistrand stressing end anchorage. Small openings were sawcut into the existing south parapet wall to gain access for stressing

direction (Fig. 6). Stage loading was beneficial because it allowed engineers to visually inspect the structure and monitor strains and deflections periodically.

The monostrand tendons were tensioned to jacking forces of approximately 43 kips (191 kN) each. Technicians post-tensioned the 10-strand and 13-strand tendons to jacking forces of 300 and 390 kips (1335 and 1735 kN) each, respectively. They then grouted the multistrand tendons with a high-quality, low-bleed cementitious grout mixture. VSL Project Manager Dennis Sanschagrín noted, “The knowledge and procedures we developed during several recent major bridge projects—especially regarding materials, installation techniques, and quality control—benefited us during the tendon grouting phase of this project.”

Pennsylvania State University and the post-tensioning contractor installed a data acquisition system to measure strains and deflections during stressing. The data acquisition system consisted of a series of deflection monitoring devices placed on the main terrace slab soffit and wired to a central computer for monitoring. Technicians also placed strain gages on the window mullions and concrete girders. Measured upward deflections in the main terrace due to



Fig. 5: View of a typical multistrand stressing end anchorage for one of the three primary cantilever girders spanning in the north-south direction



Fig. 6: Multi-strand tendons were carefully stressed in stages using a hydraulic ram. Here, technicians position extender nosing (left) and ram over the strand tails in preparation for stressing

post-tensioning ranged from nearly zero to approximately 3/4 in. (19 mm). Pennsylvania State University Civil Engineering Professor Andrea Schokker explained, "This system was extremely useful because it provided immediate and continuous feedback during stressing operations and helped us to cross reference estimated deflections from the engineering analysis. In fact, we were able to use strain gage data to make slight adjustments during the final stage of post-tensioning. This fine-tuning helped ensure relatively uniform stresses across the structure."

At the upper level terrace, craftsmen cut grooves into inside faces of the parapet walls running in the north-south direction. They then epoxied 3/8 in.-diameter (10 mm) carbon fiber rods, which were placed perpendicular to the vertical cracks observed in the parapets, into the grooves.

SUMMARY

The unique features of this project are the variety and complexity of repairs required. Special features included nondestructive testing, external post-tensioning, section enlargement, composite strengthening, epoxy crack injection, and data acquisition. Silman Associates project engineer John Matteo added, "While these tools have been used on many past projects, the complexities added by the age, pristine surroundings, and historical significance of this structure offered unique challenges."

The success of this project, which recently won an ICRI Award of Excellence for Outstanding Concrete Repair Projects, was due in large part to the team atmosphere and

a forward thinking approach to problem solving. Close coordination between the owner, the engineer of record, the post-tensioning consultant, and the repair contractor was required to complete the project on budget, within a reasonable schedule, and with high quality.

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Selected for reader interest by the editors.



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