Fallingwater – structural intervention, in time

J.A. Matteo

*Robert Silman Associates, Washington, DC, United States*

**ABSTRACT:** A 65-year period of deflection and cracking at Fallingwater, evidence of a troubled structural history, frames a parallel history of analysis, monitoring and measured intervention. Complimentary investigation methods included the review of original documentation, the use of non-destructive techniques, the development of a finite element computer model, and remote sensor monitoring. The multi-faceted analysis found the main cantilever structure highly overstressed, and evidence of continued movement made the risk of structural collapse a reasonable concern. The final repair design employs a combination of steel and carbon fiber reinforcement, but is highlighted by the use of high-strength steel post-tensioning strands within the living room floor, external to the structure but internal to the historic architectural finishes. The stair to Bear Run suffered from severe material deterioration and was rebuilt using stainless steel framing and reinforcing within concrete elements. Carbon fiber sheet was also employed to strengthen the daringly cantilevered west terrace.

1 **INTRODUCTION**

Fallingwater, perhaps architect Frank Lloyd Wright’s greatest work, spans out over the mountain stream, Bear Run, and is perhaps the best example of Wright’s notion of “organic architecture” (Wright 1939) (Figure 1). The house structure, as it was built in 1936, consists of two primary materials. Reinforced concrete is used for wall footings and some foundation walls as well as for horizontal spanning floor and roof elements. Stone masonry, consisting of sandstone quarried on site, comprises most of the walls and vertical load-bearing elements. Select use of steel offered a secondary level of vertical support at discrete locations. Wright’s use of reinforced concrete for the two-level portion of the house which cantilevers over Bear Run presents two bands of structure separated by a largely transparent field of glass windows and doors.

The floor system developed for the main cantilevers worked favorably to achieve both architectural and structural goals, and proved useful in providing space for potentially concealed repairs (Figure 2). With the slab set low and structural members upturned, not only did Wright achieve a monolithic horizontal element that would perhaps most effectively reflect the landscape to which the house was integrally tied, but he also allowed for much-needed added stiffness and structural capacity by creating an inverted tee-beam, with the slab functioning as an increased compression flange for the cantilevered beams. It is this portion of the structure which caused greatest concern to the original owner (Edgar Kaufman, Pittsburgh department store owner) and subsequent historic home stewards (the Western Pennsylvania Conservancy), and which became the principle object of this investigation.

2 **THE PROBLEM**

Structural problems manifested themselves early in the construction process, with field reports as early as December 8, 1936 by the Metzer-Richardson Co.,
the steel reinforcement supplier, indicating that excessive deflections and cracking were apparent soon after the formwork was removed from the cantilevered portion of the house (Avery Library Archives, Columbia University, New York, New York). The largest cracks were apparent at the parapets of the second floor master terrace level (Figure 3). Though engineers were brought in to evaluate the apparent structural problems as early as 1937, no conclusive action was taken. From this early period up to 1955, regular monitoring documented the continuation of downward movement, with regular re-opening of structural cracks and corresponding surface treatments to cover the signs of structural distress (Hunting, Larson & Donnells, letter and report dated March 9, 1955 from Avery Library Archives, Columbia University, New York, New York). In 1995, The Western Pennsylvania Conservancy hired Robert Silman Associates to investigate this recurrent cracking at the master terrace parapets.

3 MULTI-FACETED INVESTIGATION UNCOVERS FALLINGWATER'S INGENUITY AND ILLUSION

It is perhaps inherent to the nature of reinforced concrete as a building material that side by side with the great potential for the expression of structural function is the illusory quality of a material which hides from view one of its primary load-carrying elements. Indeed Wright took great advantage of the freedom gained by forming structural concrete to a desired appearance, an appearance designed, in part, to express a fundamental structural idea—the cantilever. Like the projecting rock formations which pervade this wooded part of western Pennsylvania and upon which Fallingwater is built, the cantilever becomes a theme in the house design, which carries through from the basic structural configuration down to details of the furniture and finishes. Paradoxically, our investigation beneath the surface uncovered where the visual translation of apparent structural function belied the true structural behavior.

The ensuing investigation and design process represents a unique interplay between historically significant methods and materials with the “high-tech" potential of current construction technology. Parallel to the study of original construction drawings and documentation, the project took on a multi-faceted approach to investigation, employing non-destructive methods using impulse radar, metal detection, ultrasonic pulse velocity, and finite element structural modeling as well as a sustained program of monitoring using vibrating wire crack and tilt meters.

The objective of the largely non-destructive investigation was to confirm existing documentation and gather new information that would serve as the basis of a structural analysis and repair design, while minimizing the disturbance to the historic structure. Original drawings and limited specifications and construction correspondence provided some of the initial information, and gave the first indication that the reality of Fallingwater would be something other than what it presents on the surface. Comparing cross-sections through the cantilevered portion of the house, the architectural drawings depict two independent cantilevers with a clear level of glass between, while reinforcement fabrication drawings depict what is apparently a structural connection between the two levels consisting of embedded steel tee sections hidden within the thickened window mullions of the south living room windows. The upper level reinforcement layout indicated on the drawings is consistent with the interpretation of the master terrace being supported on the outer wall of the living room level below. Despite this apparently useful information, documented questions about the accurate correspondence between as-built and designed conditions necessitated that further steps be taken to confirm the existing structure.
With strong evidence that the two levels at the south end of the house were indeed structurally connected, with the upper level depending on the lower for support, a monitoring program was developed. Using vibrating wire crack meters and tilt meters measuring changes in crack width of as little as 0.0002 inches and angular changes of less than 0.003 degrees, the monitoring presented a clear picture of daily and season responses of the structure to temperature change, but more importantly also revealed a trend for continued downward movement.

Impulse radar, ultrasonic pulse velocity and high resolution metal detection were the primary non-destructive methods to “look” within the concrete with the ultimate goal of confirming the level of correspondence between the structural drawings and the as-built conditions. The results of the investigation both before and during construction revealed that the drawings did largely represent as-built conditions, with one noted exception. The investigation showed that as reported by the reinforcement supplier in a subsequent engineering report, the contractor did indeed double the amount of primary reinforcement in the main cantilever beams (Metzger-Richardson Co., letter and report dated June 1, 1937, Avery Library Archives, Columbia University, New York, New York). The non-destructive evaluation, alongside a series of destructive tests, also confirmed concrete strengths averaging greater than 5,000 psi (34 MPa).

Finite element structural modeling served in effect to create a time-history of the behavior of the reinforced concrete structure, and was developed using an iterative approach to model crack development, hinge formation, and subsequent force redistribution based upon member stiffness reduction. The modeling also allowed for the evaluation of structural behavior under multiple load-path scenarios, which supported the conclusion that the upper level could not support itself independently, but instead was dependent upon the support of the level below. This is in contrast to what is conveyed visually to the observer, that being two monolithic concrete cantilevers spanning independently with a “clerestory” of non-structural glass between.

With a new understanding of the structural behavior at Fallingwater, the conclusions of the investigation phase presented a structure that was significantly overstressed, and one which we could not guarantee would sustain its required loads safely in the near foreseeable future. The design and installation of temporary shoring down to the sandstone bed of Bear Run allowed for the continuation of normal visitor operations at Fallingwater while designs for permanent repairs were developed. RSA designed the shoring to support the full weight of the main cantilever and carry loads down the sandstone bed of Bear Run. The shoring was set back to align with the first interior rib to minimize the visual impact of the installation (Figure 4). In addition to shoring the cantilevered portion of the house, shoring was also placed beneath the cantilevered rock over which the signature waterfall of Bear Run cascades.

### 4 PRESERVING THE ILLUSION: STRUCTURAL REPAIR METHODS

Similar to Wright’s innovative use of reinforced concrete in a residential construction of the 1930’s, the repair methods employed were atypical for a structure of this nature. The final design employs a combination of steel, stainless steel, and carbon fiber reinforcement, but is highlighted with the use of high-strength steel post-tensioning, which both augments the tensile reinforcement of the cantilever beams while applying large forces on the structure which would counter the rotations and stresses associated with the long-standing loads (Figures 5 & 6). The post-tensioning concept developed in conjunction with Mario Suarez of Schupack Suarez, TDEG (Norwalk, Connecticut, USA) takes advantage of the interstitial space between the floor finish and the soffit slab to access the sides of the main structural members. Though the strengthening is set external to the structure, it remains visually unobtrusive by being internal to the architectural finishes. Transition points along the post-tensioning profiles are facilitated by reinforced concrete anchor and diverter blocks, which dowel into the existing beam by way of transverse post-tensioned thread bar.

The stressing of the strands with hydraulic jacks induced large forces on the floor structure which lifted the cantilever clear of its shoring, with maximum vertical movements on the order of \( \frac{1}{2}'' \) to \( \frac{3}{4}'' \). The primary north-south cantilever beams were strengthened with post-tensioning tendons on each side consisting of as many as 13 \( \frac{1}{8}'' \) diameter strands. Monostrand tendons were introduced in the east-west direction to
reinforce the cantilevered side terraces (Figures 6 & 7). V Structural LLC, the North American affiliate of VSL, were the contractors for the post-tensioning work. During the stressing process, extensive monitoring effort by both Structural Preservation Systems (Baltimore, Maryland, USA) and a research team from Penn State University under the direction of Professor Andrea Schokker measured movements and strains with each step in loading. The entire process, phased in gradual steps to avoid twisting or wracking the structure, was complete in less than three days.

To minimize potential damage, cracks in the main beams were epoxy-injected, which reduced the amount of upward movement associated with their closing during the post-tensioning. As such, the work preserved both the deflected shape as well as the appearance of the unsupported cantilever over Bear Run, one of the great defining elements of Wright’s design.

5 STAIR RECONSTRUCTION

Following upon the strengthening of the main cantilever, RSA also served as engineers for two other important components of the historic design. The stair from the living room down to Bear Run was suffering from significant corrosion deterioration in its mild steel tread hangers and structural posts. Deterioration was so severe that repair and maintenance approaches were deemed infeasible and full reconstruction was selected as the best option.

The investigation phase revealed details of the stair’s own troubled structural history. Though it appears from original drawings to have been the architect’s intent to have the stair suspended from the cantilevered structure above, early photographs reveal that there were larger vertical steel members at the bottom landing which linked the underside of the east terrace with the sandstone bed of Bear Run (Hoffmann 1993). Subsequent historical account discuss repeated failures and modifications to these elements, which appear to have been gradually evolving structurally into their current role as vertical supports for the east terrace (Metzger-Richardson Co., letter and report dated May 21, 1940, Avery Library Archives, Columbia University, New York). It appears that these columns suffered failures as the result of the combined effects of a failing cantilever structure above, incapable of self-support, and the infrequent but severed lateral loads imparted by a build-up of debris in the flooding current of Bear Run (Hoffmann 1993). In 1955, these main supporting stair columns were significantly strengthened with the addition of new steel angle sections made to work compositely with the existing tee sections (Hoffmann 1993). No structural problems have been documented since this reinforcement and structural analysis by Robert Silman Associates found the existing columns to have adequate capacity.

The stair reconstruction was designed to match, and in some respects improve upon, the structural capacity of the existing system, were it not suffering from material deterioration. In addition, it was important to minimize the potential for recurrence of the material
decomposition which had weakened the structure over time. To meet this objective, the hangers and reinforcement within the concrete treads and landing were stainless steel. So too were the replacements for the structural columns which supported the east terrace. The use of stainless steel type ASTM A276, Type 316L, was selected for the steel replacement to allow for substantially increased corrosion resistance while allowing for field weldability in the selection of a low carbon alloy.

6 WEST TERRACE STRENGTHENING

Work at the western-most terrace, referred to as Edgar Kaufman Sr.’s terrace, employed carbon fiber sheet to augment the existing reinforcing of a doubly cantilevered reinforced concrete structure. Here once again, Wright shows sensitivity to working within the natural context with the insertion of beam ends through a naturally occurring bolder, while at the same time exhibits a willingness to push limits and to experiment with structure to great architectural advantage. The finite element modeling of the structure took a similar approach to that of the main living room cantilever, wherein an iterative process of stiffness reduction, to represent the redistribution of forces as the reinforced concrete structure would crack and deform. The doubly cantilevered system required multiple iterations as loads would in theory shift back and forth based upon the relative stiffnesses. Structural analysis determined the west terrace to be generally overstressed, but not nearly to the level that was found at the living room. With these lower levels of overstress, the thinness and simplicity of carbon fiber proved to find excellent application for Wright’s cantilevered beams. Structural Preservation Systems (Baltimore, Maryland, USA) installed SikaWrap Hex 103C, by Sika Corporation, over the top and side faces of the reinforced concrete cantilevers, which required increases in both flexural and shear capacities.

7 CONCLUSION

With the completion of both living room strengthening and stair reconstruction, the shoring below the main
cantilevers was removed. And with the reapplication of Wright's exterior surface treatments, little trace is left of the extensive repair work implemented to preserve the image of this icon. Though the need for this work originates in the structural weaknesses of the design, it ultimately highlights and bears witness to the incredible achievement of the architect, who tested equally the limits of physical materials and aesthetic perceptions as he reshaped the course of American architecture in the early 20th century.

REFERENCES