Perched on a hillside in southwestern Pennsylvania, about 72 miles from Pittsburgh, is one of the world's most famous houses. Fallingwater, the stunning creation of architect Frank Lloyd Wright, has been an American icon since its construction in 1937. More than two million tourists have visited the site and stared in awe at the building's concrete terraces hanging over a clear, swift-running stream. Architecture critics have extolled Fallingwater as Wright's greatest achievement. In fact, in 1991 the American Institute of Architects voted it the best work ever produced by an American architect.

Yet this incomparable structure has a critical flaw. Wright's design did not provide enough support for the portion of the house that hangs over the stream. As a result, Fallingwater's famed terraces began to droop as soon as they were built, causing large cracks to appear in the concrete. What is more, the sagging gradually increased over the next six decades. In 1995 the Western Pennsylvania Conservancy, which owns Fallingwater, was concerned enough to hire our engineering firm, Robert Silman Associates in New York City, to examine the house's structural problems. The results of our investigation indicated that the beams supporting the house were continuing to bend and that the building would eventually collapse into the stream below if nothing was done.

In 1996 the conservancy prudently decided to shore up Fallingwater with temporary steel beams and columns. At the same time, our office began to draw up a plan to permanently repair the house. We had previously worked on two other buildings designed by Wright—the Darwin D. Martin House in Buffalo, N.Y., and Wingspread in Racine, Wis.—but Fallingwater posed a unique challenge. To determine how to relieve the stresses that were threatening the house, our engineers probed the building with radar and ultrasonic pulses, then performed a rigorous structural analysis. Along the way we also tried to retrace the thinking of Wright and his apprentices. We now have a plausible theory to explain how the design of Fallingwater went awry.

The story of Fallingwater begins with Edgar Kaufmann, Sr., who owned a successful department store in Pittsburgh in the 1930s. His son, Edgar Kaufmann, Jr. (he always spelled "junior" with a lowercase "j"), spent a short time as an apprentice in Wright's studio at Taliesin, the architect's estate in Spring Green, Wis. Kaufmann, Jr., convinced his father to retain Wright to do some work at the store and later to design a weekend house for the family on a site that had formerly been

The Plan to Save Fallingwater

This breathtaking house designed by Frank Lloyd Wright was in danger of collapse until an engineering firm found a way to stop it from falling down.
a summer recreation camp for the store's employees.

The wooded property features a small stream known as Bear Run that cascades over a series of rocky ledges. The Kaufmanns had always assumed that their house would be located downstream from the ledges, at a point where the waterfalls could be viewed from below. But it was Wright's genius to site the house above the falls, on top of a large sandstone ledge that overlooks the stream. The building was designed in 1933, and construction started in 1936. The design work was conducted at the Taliesin studio, with Wright's apprentices Bob Mosher and Edgar Tafel participating significantly. The structural calculations for Fallingwater were done in the same studio by engineers Mendel Glickman and William Wesley Peters.

Wright and his apprentices designed the house so that the section over Bear Run acts as a cantilever. Like a diving board, it has a fixed end and a free end. The fixed end consists of four large bolsters, three of reinforced concrete (that is, concrete with steel bars embedded in it) and one of stone masonry. These bolsters rise from the sandstone ledge to the building's first floor [see illustration on pages 74 and 75]. Each one supports a horizontal reinforced-concrete beam that extends some 4.42 meters (14.5 feet) beyond the bolster, jutting southward over the stream. The beams are connected to one another by concrete joists, each 100 millimeters (four inches) wide. Together the beams and joists create a rectilinear grid. Above this grid are wooden two-by-fours and planking, which support the stone floor of the house's living room and the first-floor terraces.

Beneath the joists and cantilever beams is a concrete slab that serves as the finished underside of the structure. Wright chose this design to give the house's exterior a monolithic look, but it also had a structural purpose. In engineering terms, a cantilever has a negative bending moment—the load at the free end of the horizontal beam is resisted by tension in the beam's upper side and by compression in the lower side. (In contrast, a bookshelf has a positive bending moment—the weight of the books is resisted by compression in the shelf's upper side and by tension in the lower side.) Wright's decision to put the concrete slab under the cantilever beams turned them into inverted tee beams—each shaped like an upside-down T—thereby raising their resistance to compression and enabling them to support a greater load.

Fallingwater has more than one cantilever, though. Terraces extend from
INTERIOR VIEW of Fallingwater’s living room shows the stone floor that rests on the house’s cantilever beams. The windows at the south end of the room are divided by four steel mullions that help support the weight of the second floor.

out than the first floor does, extending an additional 1.83 meters (six feet) southward [see left illustration below]. Four T-shaped window mullions rise from the south edge of the living room to the terrace above. At first glance these steel mullions appear to be merely decorative, but we would eventually learn that they, too, play a key role in Fallingwater’s structure.

Concerns about the soundness of Wright’s design arose even before construction started. Metzger-Richardson, the Pittsburgh engineering firm that supplied the steel bars for the reinforced concrete, insisted that there were not enough bars in the cantilever beams below the living room. To make the beams strong enough to resist bending under their load, the firm doubled the number of one-inch-square bars in each beam from eight to 16. Wright was furious when he learned about the change. He believed that the additional steel bars would increase the weight of the beams too much and thus weaken the structure. In an angry letter to Kaufmann, Sr., he wrote: “I have put so much more into this house than you or any other client has a right to expect, that if I don’t have your confidence—to hell with the whole thing.”

Kaufmann, Sr., appeared his architect by asserting his confidence in him. But Wright was clearly wrong about the cantilever beams: if Metzger-Richardson had not slipped in the extra steel bars, the beams surely would have failed. Even the greater amount of reinforce-

The Plan to Save Fallingwater

ment was not enough, as the builders discovered during Fallingwater’s construction. When workers removed the wooden formwork from beneath the concrete of the first floor, they recorded an instantaneous downward movement of 44.5 millimeters. It is not unusual for a small amount of deflection to occur when the scaffolding is removed from a concrete structure, but in this case the bending was especially pronounced. Mosher, the apprentice on site, telephoned Glickman at the studio in Taliesin. After a quick check of his calculations Glickman is reported to have exclaimed, “Oh my God, I forgot the negative reinforcement!”

Glickman was referring to the reinforcement needed to balance the negative bending moment, which causes compression in the lower part of each cantilever beam and tension in the upper part. In any beam made of reinforced concrete, the concrete resists the compression on the beam and the steel bars in the concrete resist the tension. Fallingwater’s cantilever beams could handle the compression caused by the negative moment, but there were not enough steel bars in the upper parts of the beams to balance the tension.

The problem became even more apparent after the completion of the second floor. Soon after workers removed the formwork from the concrete of the master bedroom terrace, two cracks appeared in the terrace’s parapets. In 1937 Metzger-Richardson conducted load tests of the structure and calculated that the stresses in the cantilever beams were near or even exceeded the margins of safety. The engineering firm recommended placing permanent props in the streambed to support the first floor and thus reduce the length of the cantilevers. But Wright stubbornly defend-
ed his design. Once again he forced Kaufmann, Sr., to choose between him and Metzger-Richardson. Kaufmann, Sr., decided to go ahead with the house as originally planned.

Still, the house's owner remained concerned about the tilting of the terraces, so he commissioned a surveyor to measure the deflections of the terrace walls by recording the elevations of the tops of the parapet walls. This was done from 1941 until 1955, when Kaufmann, Sr., died. In 1963 Kaufmann, Jr., presented the house to the Western Pennsylvania Conservancy. Between 1955 and the time our firm was retained in 1995, only one or two random measurements of the terrace deflections were recorded.

Engineers as Detectives

The conservancy initially asked our office to evaluate the structural adequacy of the master bedroom terrace, the part of the house that historically had the most severe visible cracks. Work was ongoing to repair Fallingwater's facade, including the terrace's cracks, and the conservancy wished to know whether it was wise to continue repairing these cracks cosmetically without performing a structural review and, if necessary, repairs. We soon realized that we had to broaden our investigation to include the living room below, because the two floors are structurally interdependent.

Our first question was, "Have the deflections stopped, or are they still growing?" Using an instrument called a water level, we took height readings at more than 30 locations and attempted to relate them to the survey readings done earlier. Our measurements showed that the edge of the west terrace had sagged by as much as 146 millimeters and the edge of the east terrace by as much as 184 millimeters. The deflection of the south end of the master bedroom terrace was about 114 millimeters. We then installed electronic monitors to measure very small movements of the terraces and changes in the width of the cracks in the terrace's parapets. The results over more than one and a half years, corrected for daily and seasonal temperature variations, confirmed that the cracks were still growing and the terraces sagging ever lower.

The next step was to examine the structure's as-built condition to see how closely it conformed to Wright's plans. In particular, we needed to verify the actual number, size and location of the reinforcing bars in the cantilever beams and other structural elements. We organized a program of nondestructive evaluation, employing instruments that used impulse radar, ultrasonic pulses and high-resolution magnetic detection to plumb the interiors of the beams, floors and parapets. The tests also provided data on the quality of the house's concrete. The work was performed by GB Geotechnics of Cambridge, England. To investigate the main cantilever beams, the technicians had to remove several paving stones from the living room floor so that they could gain access to the hollow space below.

Our engineers then conducted an independent structural analysis of the house. Metzger-Richardson had done such an analysis in 1936 and 1937, but we wanted to make our own determination of how the structure functioned.
Using a computer model of Fallingwater, we tested three hypotheses: that the master bedroom terrace can support itself through cantilever action; that the living room is a self-supporting cantilever; and that the living room supports both itself and the master bedroom terrace. For each scenario we calculated the bending moments that would be caused by the dead load of the house. Then we calculated the resulting stresses in the steel and concrete of the supporting beams, as well as the amount of deflection that these loads would induce.

If our computer model predicted stresses that were significantly higher than the yield strength of the steel or concrete, we knew that some of our assumptions had to be incorrect, because such overstressing would have resulted in the immediate collapse of Fallingwater. Tests of the house's concrete indicated an in situ strength of about 34 megapascals (5,000 pounds per square inch). We also recovered a small piece of reinforcing steel from the building and sent it to a metallurgical laboratory; the results of the mechanical analysis showed a yield strength of slightly more than 283 megapascals (41,000 pounds per square inch).

First, we tested the hypothesis that the master bedroom terrace could support itself through cantilever action. If this were the case, our calculations revealed that the stress in the reinforcing bars in the terrace's parapet would be 1,195 megapascals, or more than four times the steel's yield strength. This scenario is therefore not possible. Next, we examined whether the living room is a self-supporting cantilever. Our analysis indicated that the weight of the living room alone would induce toler-
The maximum stress induced in them would be 64 megapascals, which is well below their allowable strength of 112 megapascals (assuming that they are braced by the concrete of the living room parapet). What is more, it is this extra weight supported by the mullions that has raised the stresses on the main cantilever beams to critical levels. Although we cannot know for certain what led to this design flaw, the structural evidence suggests a possible chain of events. According to this scenario, when Wright's engineers realized that the master bedroom terrace could not support itself, they redesigned the window mullions to carry some of the load. The engineers failed, however, to redesign the main cantilever beams to support the extra weight.

**Fixing Fallingwater**

When the conservancy's trustees received the results of our analysis in May 1996, they were naturally concerned. Our study indicated that the stresses in Fallingwater's main cantilever beams were great enough to raise questions about the house's safety. The trustees decided to commence the design of permanent repairs. We advised them that during the construction phase it would be necessary to shore the ends of the main beams while repairs were under way. Because the house would ultimately have to be shored, the trustees wisely chose to do it immediately and thereby eliminate the fear that the building might collapse or that some structural element might fail before repairs could be made.
teract the negative moment caused by cantilever action, lowering the tension in the upper part of the beam and the compression in the lower part. We will also connect post-tensioning cables to the parapet edge beams in the east and west terraces to relieve the stresses in those beams. On the second floor, we plan to reinforce the overstressed concrete joists just above the steel window mullions, either by bolting steel channels to each side of the joist or by bonding carbon-fiber plates to it. At the conclusion of the project, we will patch and paint the holes in the parapet, replace the stone floor and remove the temporary shoring.

We anticipate that the structure will lift slightly off the temporary shoring when the post-tensioning forces are applied, but we do not intend to restore the cantilever beams to their original horizontal level. We will fill the cracks in the tops of the beams prior to jacking to limit the amount of upward movement. When the repairs are completed, the terraces will still be tiled, but they will not sag any further. The deflected structure will illustrate the history of the building and the problems that it has encountered over its lifetime.

The repairs are scheduled to take place during the winter of 2001–02 as part of a larger restoration project that also includes the waterproofing of the entire house. This work will be supervised by Wark Adams Slavin Architects of New York City. The conservancy is also upgrading the water supply and sanitary facilities at the property.

The strengthening of Fallingwater’s cantilever beams will guarantee the structural stability of the house for years to come. Moreover, the plan stabilizes the house without the need for permanent props rising from Bear Run. Thanks to state-of-the-art technology, we can preserve the most striking architectural element of Fallingwater, its cantilevered terraces stretching gracefully over the rushing stream.

The Author

ROBERT SILMAN is president of Robert Silman Associates, P.C., Consulting Engineers, a structural engineering firm with offices in New York City and Washington, D.C. Since its founding in 1966, the firm has worked on more than 7,300 projects, including the restoration of 303 designated landmark buildings. Among these are the U.S. Supreme Court Building, Carnegie Hall, George Washington’s mansion at Mount Vernon and six other Frank Lloyd Wright buildings. Silman received a bachelor’s degree in government from Cornell University and bachelor’s and master’s degrees in civil engineering from New York University. He is a fellow of the American Society of Civil Engineers.

Further Information

FALLINGWATER: A FRANK LLOYD WRIGHT COUNTRY HOUSE