Cantilevers

To thoroughly understand the Renick Building requires background knowledge of cantilever structures. A cantilever is described as a projecting beam or a member supported at only one end. This cantilevered beam\(^1\) is supported by two columns. A balancing weight is used to counteract the force of gravity at the end of the cantilever. The critical location indicates where bending and shear forces are greatest on the cantilever member.

There are many examples of cantilevers. For instance, at any Olympic-size swimming pool, most diving platforms are cantilever structures. Usually, the diving platforms are supported by large concrete columns and consist of reinforced concrete slabs, which could include pre-stressing or post-tensioning bars for extra strength. However, these platforms rarely see any live load that compares to their own self-weight, making design less complicated.

Another example, that might not be as obvious, is cantilevered bridges. They have been used all over the world and can span some stunning distances. Perhaps the most impressive cantilever bridge to date is the Forth Railway Bridge in Queensferry, Scotland. Built in the 1880s, it spans approximately one and a half miles across the Firth of Forth. One of the first bridges built primarily of steel was designed shortly after Scotland suffered a disastrous bridge collapse that killed seventy-five people. For this reason, Scottish engineers were encouraged to design a structure that not only endured, but appeared visibly infallible. The result was costly, involving 54,000 tons of steel, 194,000 cubic yards of concrete, 21,000 tons of cement, and almost seven million rivets. Although the structure was over-designed using repetitive truss members, it still provides a great example of how a cantilever structure is supported.

\(^1\) Colors represent members in cantilever visualization, this page
The diagram below describes the arrangement of loads in a cantilever bridge. The secret is maintaining balance, especially during construction. The supports are built first from the base upwards. Then, two cantilever arms, one in each direction, are constructed horizontally outwards from the main towers. These are supported by diagonal members projecting from the top and bottom of the towers. The only catch is they must be erected symmetrically and simultaneously to keep from accumulating an overturning moment on the structure. Below are some different shapes and sizes of cantilever bridges designed in the past.
Fallingwater

Arguably the most intriguing cantilever structure in the world is Fallingwater, located in southwest Pennsylvania. Designed by Frank Lloyd Wright, the building has two cantilevered balconies that dangle out over a waterfall on the Bear Run. Fallingwater's lower cantilever extends nearly 15 feet outward from four large bolsters which were constructed into Bear Run’s natural sandstone ledge. Three of the bolsters, the building’s primary foundation, are made of reinforced concrete while the other, for architectural purposes, is stone masonry. The bolsters support three-foot wide reinforced concrete girders, the primary support for the main level terrace. Running parallel to the girders are four-inch wide concrete joists spaced at four-feet-on-center. Wood planking rests on the joists, ultimately carrying the weight of a stone floor. A soffit slab, found under the floor system, was used for both structural and architectural reasons. It provides extra strength because it works collectively with the girders like a t-beam to carry the cantilevered loads. Also, it helps to keep water from splashing up and damaging the wood flooring. The upper terrace, including the master bedroom, extends another six feet beyond the main level cantilever. Four vertical structural steel t-shaped members support the master bedroom terrace, connecting it to the main level terrace below. However, it was not taken into account initially that the main level would not only be carrying its own weight, but also the master bedroom level from above. It was assumed that the master bedroom cantilever would support itself, and therefore the four steel t-members would just create a frame for the unobstructed windows which provide an incredible view of the surrounding landscape.

1 See Fallingwater Sections, next page
The problem in the structure ended up having to do with the lack of bar reinforcement located in the top of the cantilever girders. The tension stresses created by the weight of the stone flooring, furniture, people, and snow over the years caused the balconies to deflect. The original design called for sixteen one-square-inch strands of rebar in each girder, which was just recently determined to be inadequate for the design loads. The deflections in the cantilevers were not only active, but progressively worsening. The displacement had reached seven inches at some locations, which caused visually noticeable tension cracks in the parapet walls located at the master bedroom terrace level. What made this worse was that
until the 1990s, these tension cracks were only cosmetically patched, which just temporarily hid the primary failure in the structure.

Engineers at Robert Silman Associates of New York drew up a solution, post-tension the concrete cantilever members. If properly placed, high-strength post-tensioning tendons would be sufficient at fortifying the cantilevers without external shoring. This would keep Frank Lloyd Wright’s daring prairie-style, cantilever architecture intact.

The main level terrace cantilever girders needed to be strengthened with bonded post-tensioning tendons parallel to the cantilever length and unbonded tendons in the transverse direction. The tendons are placed near the bottom of the end of the cantilever, gradually rising up over the length of the beam until mid-span. This way, when the post-tension force is released into the strands, the stressed tendons will create a positive bending moment in the cantilever. They will try to flex back into a straight bar, counteracting the gravity forces that have caused major deflections over the past.

The structure also requires some improvements at the master bedroom level, just to ensure a proper transfer of forces from the upper terrace to the post-tensioned beams. The remedy was to bolt steel channel beams to both sides of the concrete floor joist at the upper level, directly above the four t-shaped mullions that adjoin the upper and lower levels. These channels, similar to the post-tension cables in the girders below, will be concealed within the floor cavity.

The entire process was a very costly repair job. The stone floors and built-in furniture had to be removed and the wood planking had to be pulled up in order to make room for construction of the new post-tension members. The cables were then anchored in new concrete blocks, shown here, which were attached to the girders. It was also necessary to drill holes in the outside wall of the living room to allow room for the opposite ends of the tendons to be secured.

One thing we can learn from the repairs at Fallingwater is that pre-stressing or post-tensioning is a very effective way of controlling deflections in cantilever structures. With the extra positive bending moment across the beams, deformations are not detrimental.
In recent years, architects have been attempting to replicate the precision in a cantilever that Frank Lloyd Wright had designed. A building that Axis Design Group, of Newark, New Jersey, is currently working on is the U-shaped Chongqing Public Library. Located in Chongqing, China, this six-story, 540,000 square foot structure is constructed primarily out of normal weight, reinforced concrete.

One of the highlights of this building is a 54’ wide cantilevered classroom wing that spans 80’. The structure of this section is under consideration, but two possible layouts are the focus of discussion. Both assemblies consist of two reinforced concrete trusses, like those found in concrete bridge design. The Chinese metric system explains the odd sizes of the truss chords and supporting columns, at 1’-3½” x 1’-11” (1 meter x 1½ meters). Concrete is capable of withstanding large compression forces, however very little in tension. For this reason, tension members must be eliminated in a concrete truss and more strength should be concentrated into the compression members. The following pages show the two structural arrangements.
Scheme one introduces two main diagonal braces balanced by a main column. There is an additional 2'-0"x1'-3\(\frac{3}{8}\)" tie brace that runs down from the roof to the ground. The roof girder is where the worst case tension loads will be found, which explains why its size matches that of the truss chords and main column.
Scheme two disrupts the architecture of the cantilever, but is just as affective at supporting the weight of the structure. There is less tension in the roof which allows for decreased roof girder sizes. Also, no tie bracing is necessary to help distribute the loads.