A PROFESSOR'S PERSPECTIVE

# The Role of Analytical Tools in Innovation

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Computers and their software are both the boon and bane of our profession. The boon is easy to recognize: Computers save enormous amounts of time that were previously spent doing tedious, repetitive calculations. They also make possible much more sophisticated structural models, which are capable of predicting behavior more closely than could ever have been achieved with previous computational technologies, like hand calculators, slide rules, and pencils. (To those of you with youth on your side: google "slide rule.")

So, what is the bane? The problems probably lie not so much with the machines as with us. The machines do so much that we come to rely heavily on them, and it becomes harder to recognize the point at which we should start to question their electronic wisdom. We should also ask how we can best harness their powers for our benefit. These are the issues I would like to explore here, in the context of innovation.

Innovation is the engine of progress. And if we do not innovate and build that better mousetrap, someone else will, and we will find ourselves at a disadvantage. Furthermore, new challenges are constantly arising, and they call for appropriate, and often new, solutions. Bridge engineers carry an enormous responsibility for public safety and cannot afford to undertake risky innovations. That responsibility differentiates the profession from, say, builders of apps for tracking exercise regimens, but the pressure to innovate is there in both cases. Innovation in engineering takes a combination of a strong understanding of the underlying behavior, a thick skin (getting used to being called crazy), and the tools to develop the idea to fruition.

The first floating bridge across Lake Washington in Seattle, Wash., (**Fig. 1**), provides an example. Homer Hadley worked for the cement industry and saw that the lake was too deep and wide, and its bottom too muddy, to build a suspension bridge economically. So, he approached the state bridge engineer with the idea of using a series of hollow concrete pontoons to build a floating bridge. It would be anchored to the lake bottom with inclined cables. History does not relate the number of times that he was told he was crazy to think that concrete would float, but eventually, in 1940, the bridge was built, although it was named after the state bridge engineer, and not Hadley. It was followed over the course of time by three other such bridges in the region, using the same principles. The Interstate 90 (I-90) Lake Washington Floating Bridge sees relatively modest wave loading and was designed without computers. The Hood Canal replacement floating bridge, built in the early 1980s, also in Washington state, experiences more onerous loading; it crosses salt water and sees a 12 ft tidal range as well as dynamic loading from larger waves. Computing power provided much improved modeling capability and was clearly important for the design of this bridge.

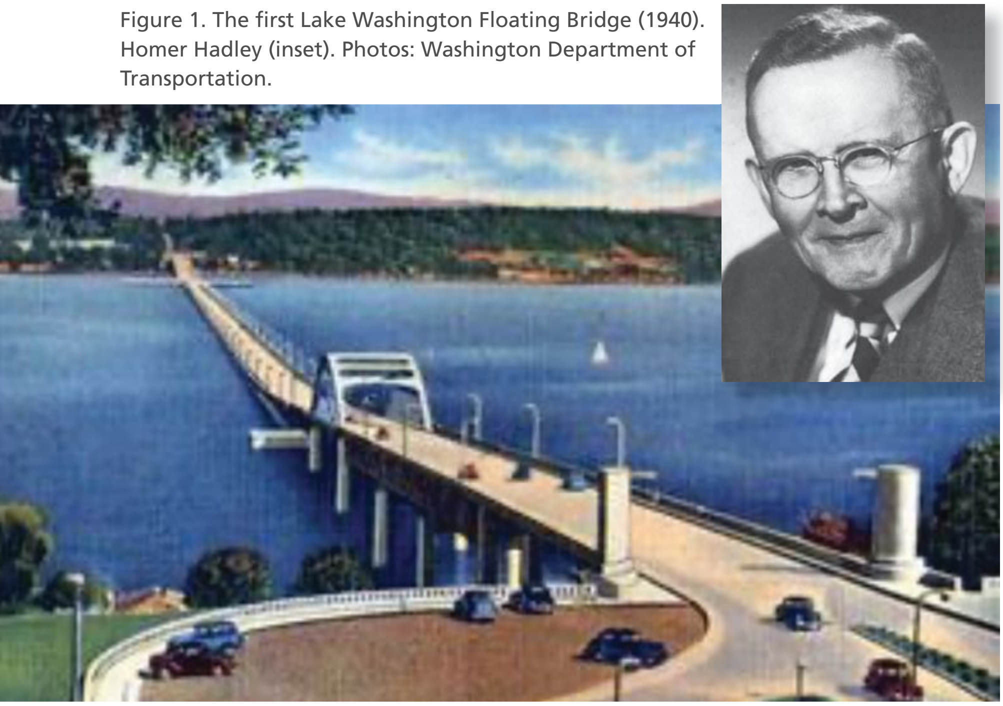

Figure 1. The first Lake Washington Floating Bridge (1940). Homer Hadley (inset). Photos: Washington Department of Transportation.

More recently, the floating bridge provided the need for another innovation. Sound Transit planned to extend its light rail network from Seattle, over Lake Washington, to Bellevue. The obvious route was over the I-90 floating bridge. But the lake level rises and falls, controlled physically by the locks to Puget Sound, and administratively by the Army Corps of Engineers. Elevation changes require a transition span at each end to serve as a "gangplank" from "ship to shore," and the hinges at their ends undergo concentrated rotations as the water level rises and falls. The rotations are barely noticeable for rubber-tired vehicles, but they pose a real problem for fixed steel rails. Enter Andy Foan, who thought up a way of spreading the rotation over a length of rail great enough that it could be accommodated by elastic bending while at the same time vertically supporting the rails at the standard 30 in. tie spacing.[1] It is a clever three-dimensional (3-D) solution to a 2-D problem where no

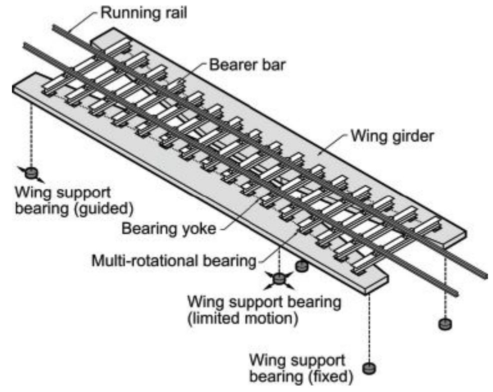

Figure 2. Curved-element-supported rail system at hinge in the existing Lake Washington Floating Bridge accommodates multidirectional movement for the new Sound Transit light rail extension. The concept was first modeled by Andy Foan using coffee stir sticks. Figure: Travis Thonstad.

adequate 2-D solutions could be found (**Fig. 2**). Foan claims to have dreamed up the idea when he was stirring his coffee at a coffee shop, and his first model was indeed made from coffee stir sticks. That was followed by a lot of head-scratching, sophisticated computer analysis, and proof-of-concept testing before the idea could be accepted and the prototype designed and then tested at full scale. It is, as yet, the only application of the idea worldwide. In this instance as in many others, the innovation was kick-started without computers. But, because of the geometric complexities, computing technology was almost essential to verify it and conduct detailed design.

How can we foster innovation? Measures should start in universities (or earlier), where "failure" costs nothing. We should provide students with opportunities to let their imaginations run free in developing concept designs for structures (such as bridges), and then apply basic tools of analysis to evaluate for themselves whether the design will work. It is humbling to prove that your own brilliant idea will not work, but the lessons learned through such trial and error stay with you for life, and they build the store of knowledge that is the basis for that elusive quality we call "judgment." This approach requires that the students have the tools to do the analysis. I would argue that, at this stage, simple tools are better than sophisticated software, because of the risks of using the latter inappropriately and coming to a wrong conclusion. The time for the advanced software comes later, during detailed design.

A second feature of innovation is a willingness to question conventional wisdom, and to reject it if reason finds it wanting. This is hard for both students and practitioners to do because much of conventional wisdom is embodied in codes and specifications. Students are bedazzled by today's codes (the American Concrete Institute's *Building Code Requirements for Structural Concrete* [ACI 318][2] has grown in length by a factor of approximately 8.6 since 1963, and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[3] are much longer), and practitioners often find themselves bound by them. But questioning the code is the engineering equivalent of natural selection in biological systems, and it is essential for improvement. Of course, the right to question comes only with the obligation of listening to the answer.

An example is provided by the serendipitous birth of the use of unbonded post-tensioning for recentering of structures under seismic loading. A 10-story concrete frame building was constructed near Seattle in the early 1980s. The designer had provided the necessary reinforcing steel in the beams for the seismic and gravity forces, but they had added some unbonded post-tensioning to the beams, ostensibly for deflection control. For complicated reasons that are beyond the scope of this article, the owner had his own building condemned and then sued the builder and designer for code violations. The basis was that ACI 318 prohibited the use in seismic frames of steel with a yield strength greater than 78 ksi. A laboratory test of an exterior beam-column-slab joint was eventually arranged and was conducted at the University of Washington.[4] Despite the many inappropriate details of the test specimen, such as top beam bars hooked upward and in the front face of the column, rather than downward at the back face, the beam-column system performed remarkably well. It was clear to the team that the unbonded post-tensioning gave the system real potential, even though it clearly violated a well-meaning code provision. From that inauspicious start, the concept of deliberately using unbonded post-tensioning to recenter a seismic system was developed. It gained recognition in the Precast Seismic Structural Systems (PRESSS) program[5] and has been copied and adapted by the steel and timber industries for moment frames, shear walls, and braced frames. This innovation is now used in many countries susceptible to earthquakes (the United States, New Zealand, Japan, Italy, and various Central and South American countries). ACI 318 now recognizes and permits such systems. The moral of the story is that there is no formal route to innovation—sometimes, it is started by an accidental finding. Question conventional wisdom, even in codes.

The foregoing examples make the case for iconoclastic thinking and simple models of behavior to initiate innovation. If we all behaved like that all the time, the profession would be an unruly place. The initial, simple models should be thought through carefully, but frequently they alone are not enough. This is particularly true of statically indeterminate structures, in which the material behavior, including creep and cracking, plays a significant role. (Of the three pillars of structural mechanics—equilibrium, compatibility, and constitutive laws—constitutive laws are by far the most difficult). Large post-tensioned box-girder bridges, constructed using the balanced-cantilever method, provide a good illustration.

Podolny's comprehensive paper[6] describes many of the problems that can occur, most of which are associated with the changing distribution of stresses in the indeterminate structure. For example, Bazant and coauthors[7] discuss the Koror-Babeldaob Bridge in Palau, which collapsed after displaying large creep deflections.

In Seattle, the West Seattle Bridge, which was opened to traffic in 1984, was closed in March 2020 because ominous cracks had appeared in the webs and bottom flange (**Fig. 3**). The cause has now been traced back, with a high level of certainty, to the fact that creep strains and deflections caused the inflection points in the main span to migrate outward toward the main piers, thereby increasing the length of the positive moment region. That region eventually grew to encompass the anchor locations for the positive moment tendons, and the stress concentrations there initiated the cracking. This behavior could be identified in principle with a pencil and paper, but demonstrating it beyond a reasonable doubt was possible only with

Figure 3. Epoxy-injected cracks in the West Seattle Bridge (2020). Photo: John Stanton.

a sophisticated finite element model that included time-dependent constitutive behavior. Such tools are indispensable for complex problems of this sort.

We need both sophisticated analytical tools and simple tools, and we need them for different purposes. But let us not become so enraptured by the sophisticated ones that we lose the mental models of structural behavior that are one of the main engines of innovation.

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## EDITOR'S NOTE

***The West Seattle Bridge was one of the early segmental concrete box-girder bridges constructed in the United States. When the structure was designed, it was still not well understood how such bridges should be designed and detailed to deal with long-term effects. Unfortunately, the design and details for the West Seattle Bridge did not allow the structure to accommodate an inexact prediction of long-term behavior. Designers have since developed solutions for those issues that are now standard practice. This is a further demonstration of the need to understand underlying behavior and the limitations or variabilities of our numerical models.***