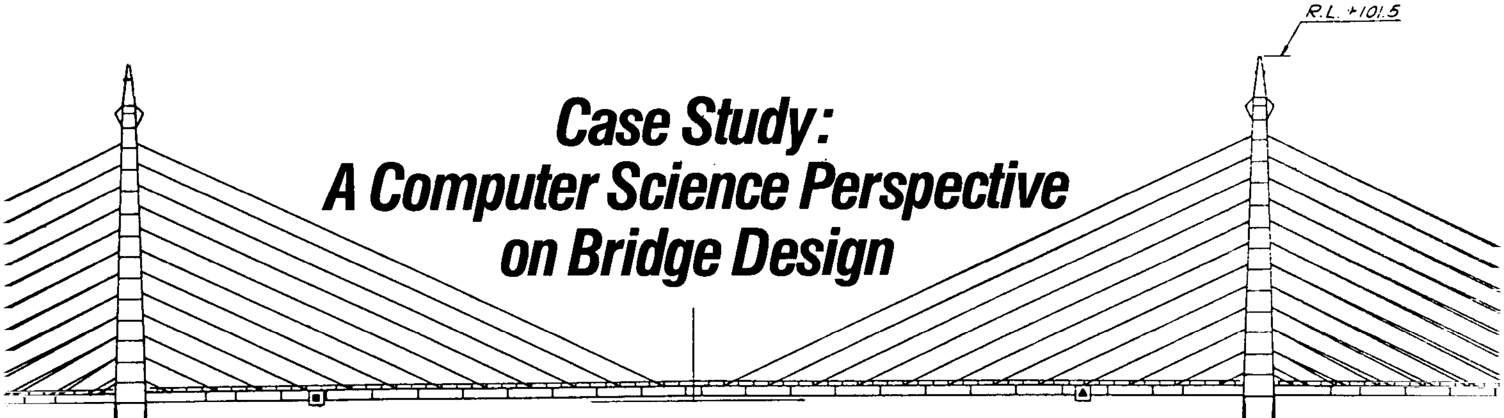
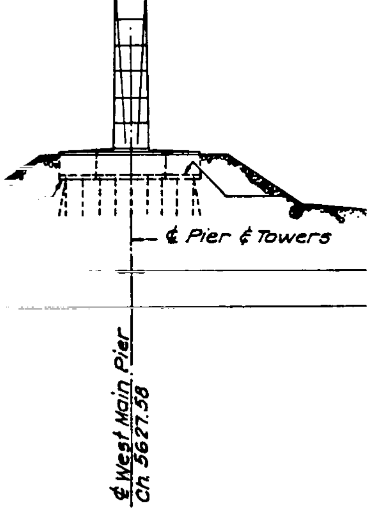
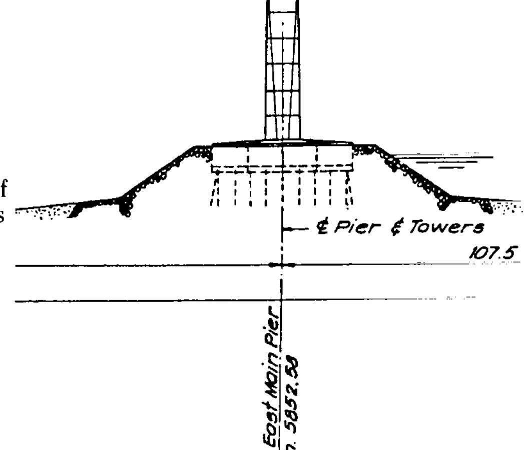
Case Study: A Computer Science Perspective on Bridge Design

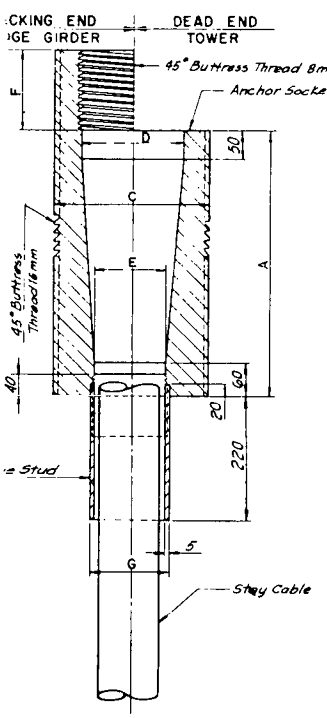




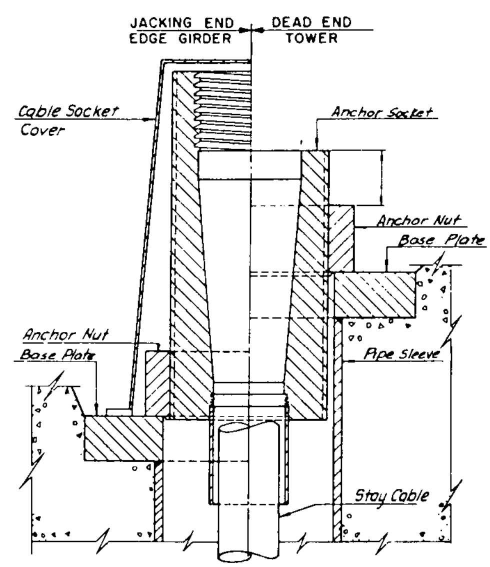


Engineers have been designing bridges and other complex structures for millennia. Civil engineering is one of the most classical of the engineering disciplines—it has well-developed designs, procedures, and tools at its disposal. Bridges rarely fall down. In contrast, computer systems design is one of the least classical of the engineering disciplines, and its products are often poorly understood, unmanageably complex, and unreliable. Though some computer systems are more complex than even the largest bridges, there is a wealth of experience and insight in the older discipline that can be of use to computer systems designers, particularly in such areas as specification, standardization, and reliability. There is also the opportunity, in the consideration of two kinds of design, to learn something about design in general.

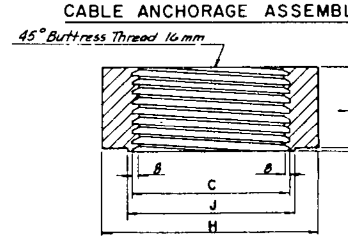
In November 1985, case-study editors Alfred Spector and David Gifford spoke with Gerard F. Fox, a partner in the consulting engineering firm of Howard, Needles, Tammen, and Bergendoff (HNTB). Fox has been a structural engineer specializing in the design of bridges for 38 years. He is also an adjunct professor at Columbia University, where he teaches a course on bridge design. HNTB has designed many bridges and approximately half the toll roads in the United States. Fox has been involved in the design of many important bridges, including the Delaware Memorial Bridge, the Rio Niteroi bridge in Rio de Janeiro, and the Penang Bridge in Malaysia. He is currently working on the Dame Point Bridge, now under construction in Jacksonville, Florida, which is to be the longest concrete cable-stayed bridge in the United States. The analogy between bridge design and computer systems design is implicit in the interview; the editors' conclusion provides a more explicit summary and analysis of many of the major issues that were discussed.



CABLE SOCKET



CABLE ANCHORAGE ASSEMBLY



ANCHOR NUT

Not to Scale

A COMPUTER SCIENCE PERSPECTIVE OF BRIDGE DESIGN

What kinds of lessons does a classical engineering discipline like bridge design have for an emerging engineering discipline like computer systems design? Case-study editors Alfred Spector and David Gifford consider the insight and experience of bridge designer Gerard Fox to find out how strong the parallels are.

ALFRED SPECTOR and DAVID GIFFORD

AS **Gerry, let's begin with an overview of bridges.**
GF In the United States, most highway bridges are mandated by a government agency. The great majority are small bridges (with spans of less than 150 feet) and are part of the public highway system. There are fewer large bridges, having spans of 600 feet or more, that carry roads over bodies of water, gorges, or other large obstacles. There are also a small number of superlarge bridges with spans approaching a mile, like the Verrazzano Narrows Bridge in New York.

AS **What are the requirements for a bridge?**
GF There are several categories of requirements. For instance, there are *functionality* requirements: The lanes should be sufficiently wide, the bridge should have safe barriers to deflect cars back onto the roadway, and the lighting should be sufficient. There are *serviceability* requirements: We don't want the bridge to vibrate excessively and scare people, and we don't want large cracks in concrete bridges. Of course, there is the *ultimate strength* requirement: We don't want the bridge to fail. Then there is an *aesthetics* requirement: The bridge should be pleasing to the eye. There's also a *long-term maintainability* requirement, which involves corrosion protection of various elements. For example, cables tend to be very susceptible to stress corrosion, and therefore their protection is very important. Finally, there is the *cost-effectiveness* requirement: The finished product should meet all of the above requirements at the best possible cost.

THE DESIGN PROCESS

AS **What is the procedure for designing and constructing a bridge?**
GF It breaks down into three phases: the *preliminary design phase*, the *main design phase*, and the *construction phase.* For larger bridges, several alternative designs are usually considered during the preliminary design phase, whereas simple calculations or experience usually suffices in determining the appropriate design for small bridges. There are a lot more factors to take into account with a large bridge: aesthetics, method of construction, cost of materials, etc. The preliminary design report for a large bridge usually describes three or four alternative bridge types, estimates their costs, and provides a rendering of what the bridge will look like. Usually, the designer recommends one of the alternatives to the client. There would also usually be hearings to get the public's reaction.

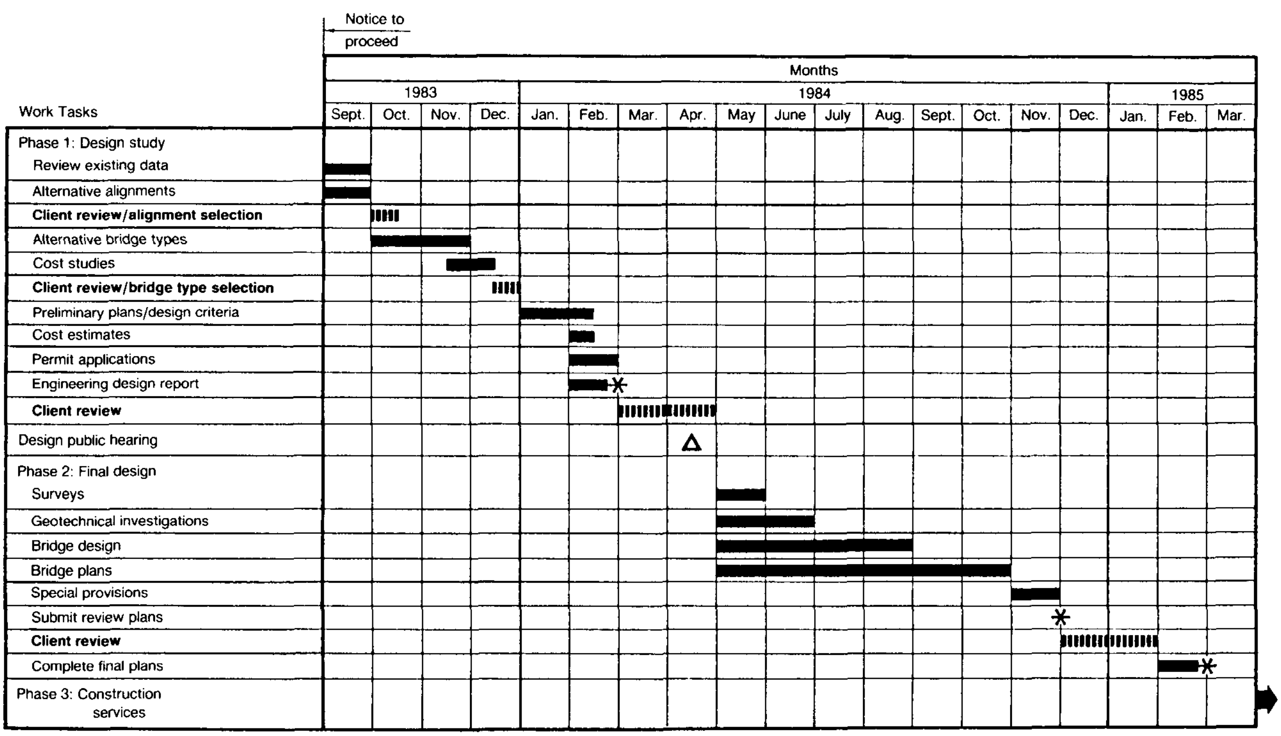
DG **Do you estimate both the initial cost and the life-cycle cost for each of the alternatives?**
GF Life-cycle costing is not in wide use for bridges, although I think it should be. For example, consider the life-cycle cost of a bridge's deck, the portion of the bridge that comprises the riding surface. One alternative is to design an orthotropic steel deck, which can support traffic and also help to carry the weight of the bridge itself. The alternative is a concrete slab deck, which costs a lot less initially, but does not last nearly as long as a steel deck. Since the initial cost is the primary thing that clients look at today, most new bridges in this country are being built with concrete decks. At the same time, many

major bridges in this country, including the Golden Gate Bridge, the George Washington Bridge, and the Benjamin Franklin Bridge, are being rehabilitated with orthotropic steel decks.

AS **Who does the preliminary design?**
GF A consulting engineering firm like HNTB generally handles both the preliminary design phase and the main design phase, although some state highway departments actually do their own design work. The main design phase involves a complete structural design, making drawings, and writing specifications that describe the tests that materials must pass before they can be used, their quantities, and some of the construction techniques. In effect, the bridge is completely specified during the main design phase.

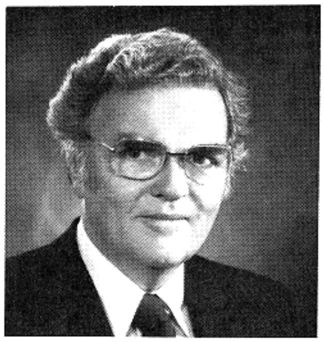
AS **How is a consulting firm chosen?**
GF The government body in charge of the project usually selects three or four consulting engineering firms to make presentations. A selection board makes a decision based on the firms' experience, how quickly they will be able to do the work, the key people they will be assigning to the project, their respective approaches to the project, etc. Usually the firm that is selected does both the preliminary and the main design. Traditionally, these selections have not taken the costs of the design process into account, but that seems to be changing, slowly. Unfortunately, it's difficult to be very specific about the scope of the design process in advance. A firm might decide to study three basic designs that vary in complexity by a factor of two or three. The parties involved have always understood that the quality of the design is more important than its cost, particularly as construction costs generally dwarf design costs. Construction firms, on the other hand, are selected on the basis of competitive bidding, at least in the United States.

DG **Can the construction firm work just from the drawings and specifications the designer provides? Is the specification that complete?**



This document was prepared by HNTB as part of a presentation for a proposed Mississippi River bridge at Burlington, Iowa. The government body in charge of selecting a design firm considers the candidates' experience, how quickly they will be able to do the work, and the key people they will be assigning to the project. Traditionally, design cost is not a factor in the decision. In the schedule, solid lines indicate work by the designer, broken lines indicate client review, asterisks indicate points at which the designer delivers drawings and specifications to the client and/or contractor, and the triangle indicates that the design public hearing takes place sometime in April.

FIGURE 1. Proposed Design Schedule for a Large Bridge



GERARD F. FOX

A partner in the consulting engineering firm of Howard, Needles, Tammen, and Bergendoff, Fox has been a structural engineer specializing in the design of bridges for 38 years. He is also an adjunct professor at Columbia University where he teaches a course on bridge design.

GF Yes. This is somewhat in contrast to the building industry, where some details are left to the contractor.

***DG* How large are the preliminary and the main design documents, and what do they contain?**
GF The preliminary design document could be as long as 100 pages, depending on the size of the structure. Of course, it would be much shorter for small bridges. For large bridges, the preliminary design describes the various alternative structures that were considered, estimates the costs of each alternative, and usually recommends one of the designs. The final design could contain a minimum of 10 drawings and a few hundred pages of standard specifications for a small bridge. A large bridge would have 50 to 200 separate drawings and perhaps 50 pages of additional special provisions. The additional specifications would be for defining special materials and construction procedures.

***AS* What happens once the construction firm has your specifications in hand?**
GF They take our drawings and prepare their own set of even more detailed drawings, which are called shop drawings. They might make two to five drawings from each of our originals, with every dimension and bolt hole mapped out. The original design firm has to review these shop drawings for accuracy. In some cases, the design firm is actually responsible for reviewing the construction process, in which case it will have inspectors on the job to verify that the contractor is implementing the design as originally conceived.

RESOURCES

***DG* How do you measure the various resources that go into building a bridge?**
GF We break it all down into time, money, and person-years. I'll start with time. The preliminary phase takes little time for smaller bridges, and up to nine months for the largest bridges. There is also a review period for large bridges during which the client considers the designs and sometimes obtains a response from the public. So there might be a year between the beginning of the preliminary design phase and the beginning of the main design phase. The main design phase for a small bridge wouldn't take any more than three to six months. A large bridge with spans of over 600 feet and long approaches (to raise the bridge higher, for example) might take two or three years to design, depending on its complexity. The construction phase for the smaller bridges would take about six to eight months; the larger bridges take as long as three or four years to construct.

A handle on the construction cost of bridges is the cost per square foot of bridge surface. The range today is from $30 to $200 per square foot, with the largest bridges at the high end of the range. The total costs then run anywhere from $250 thousand to $80 million. A very large bridge, like a new East River span in New York, would probably cost over $400 million, not counting property acquisition. Design costs usually account for less than 6 percent of total cost, and even less for larger bridges—most of the rest is for construction. In what I'm calling "design cost," only about a quarter to a third is for the actual design process—the rest is for producing the drawings and specifications.

The third metric is person-years. I would say that a small bridge can be fully designed in anywhere from 1 to 5 person-years; large bridges may take anywhere from 10 to 30 person-years, and very large bridges could require up to 150 person-years.

PROJECT ORGANIZATION

***DG* How is a design project organized at HNTB?**
GF A partner or an associate is completely in charge of each job, with responsibility for client contact. Under this partner or associate is a project manager, who usually devotes full time to the project, if it's of any size. This project manager is responsible for the various budgets associated with the project and for monitoring the technical competence

of the people working on the job. For example, we don't want a highway engineer doing what a bridge engineer should be doing.

The project manager also oversees the design section and the detailing section, as well as at least one person who is responsible for writing the specifications for the bridge. The design section is headed by a chief designer, who is responsible for the engineers doing the actual design work, on regular grid calculation paper. The detailing section in turn is headed by a chief detailer, who is responsible for the engineers and technicians who make the drawings for the design, either manually or on CAD workstations.

DG **Are the chief designer and detailer dedicated to only one bridge at a time?**
GF The chief designer might be in charge of a few other bridges as well. The chief of the detailing section is usually assigned to only one job at a time.

DG **Do you make it a point to isolate your technical people from administrative concerns?**
GF The technical people are isolated from administrative activities that relate to actually running the business. They're not isolated from budgets. They're probably the first ones to prepare item-by-item budget sheets, and to determine how long it will take to design components and make drawings for piers, abutments, the superstructure, etc.

PRELIMINARY DESIGN

DG **How do you come up with alternative designs in the preliminary design phase?**
GF For a large bridge, we start with a group of two or three people at a roundtable discussion. They sketch ideas and consider the advantages and disadvantages of the various possibilities. This process might last for a few days. We then try to put some meat on the ideas, in order to determine whether the designs are feasible. Finally, we narrow our focus to maybe three or four designs. Optimization is used to obtain the best possible design for span lengths, depth of structure, etc., with cost as the usual objective function.

There's usually not a lot of very complex analysis involved, unless the project represents a significant departure from experience. For example, if we were designing a new type of very light structure, we would have to pay close attention to the response of that structure to the wind. We might even subject a model of the bridge to wind-tunnel testing, although that would be unusual. As a result, we might opt for a particular type of cross section that we wouldn't have used otherwise.

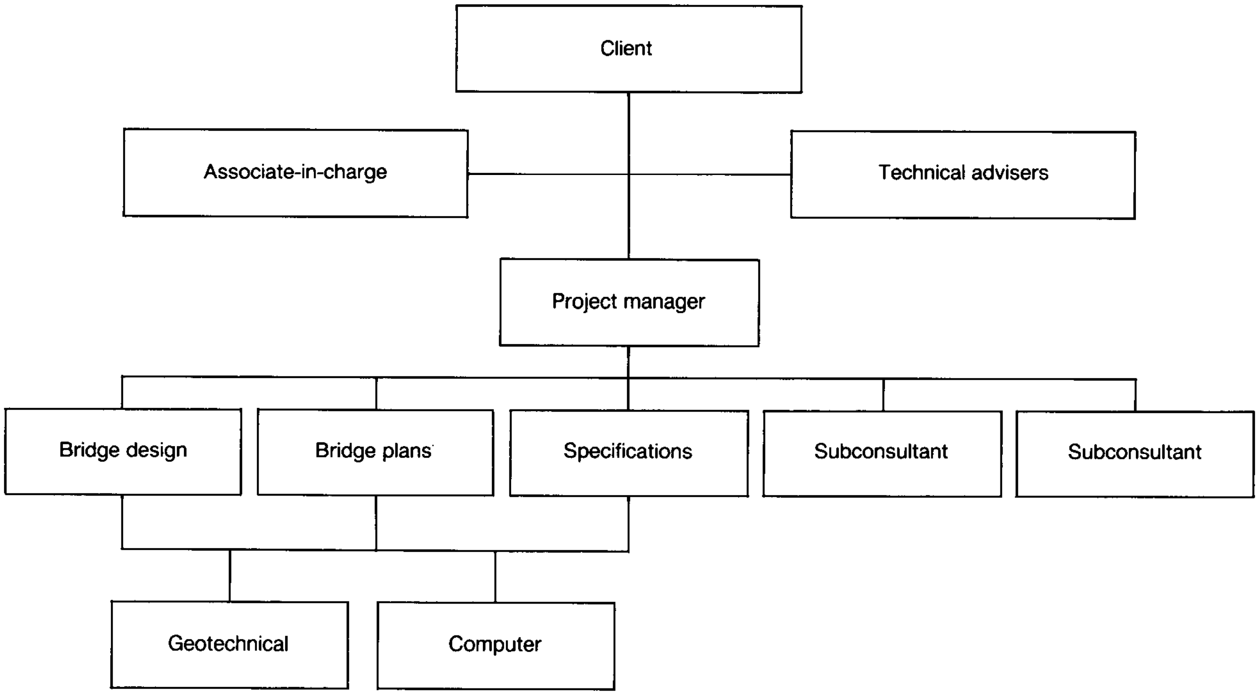


FIGURE 2. Project Organization Chart for a Large Bridge

The final selection is made after an evaluation of several pertinent factors that are either qualitative or quantitative: aesthetics, cost, redundancy, constructability, schedule of completion, maintenance, etc. An evaluation matrix is set up with different weights assigned to each of the factors.

MAIN DESIGN

***AS* Let's move on to the main design process. What are some of the major milestones in putting a design together?**
GF The first thing a team does is to review the amounts of the various resources that are going to be necessary. The first milestone is preparing design criteria for the project. There is a major design specification in this country for highway bridges that provides standard values for the allowable stresses and loadings for a bridge, and so forth. It's written by the American Association of State Highway and Transportation Officials (AASHTO). Each state is generally represented on this committee by its chief bridge engineer. This specification is revised annually.

***AS* What does the AASHTO specification contain?**
GF The overall objective is design standardization. It prescribes load capacities for vehicular traffic in terms of weight, number, and frequency. It gives design loads for wind and outlines procedures for obtaining seismic loads. It sets allowable stresses for steel, concrete, and other materials, and details design rules for such components as stiffeners, columns, etc. It indicates what tests are necessary for various materials before they can be approved for use. Most of the individual specifications are component specifications, although some specifications are given on a system basis: For instance, the overall stability criteria for a pier might be specified.

Naturally, the specification doesn't address a lot of the considerations for larger bridges. We establish additional criteria that we decide are appropriate for a particular design. For example, creep is the deformation over time of a material under a constant stress. The formula for creep is not universal, so we specify the formula that we'll use for a particular project. Another factor of increasing importance with larger bridges is natural phenomena: If a bridge is in an area where hurricanes can occur, or where there is considerable seismic activity, we have to establish appropriate design loadings to account for these phenomena. The goal is to establish acceptable bounds in terms of the relevant probability of risk and the cost and importance of the project.

***AS* What do you do after you establish all your specifications?**
GF The next step is to establish a mathematical model of the bridge. We have to specify where joints, pins, and other connections are to be placed—we would consider, for instance, how the bridge should be connected to the piers. We try to get a general outline of the various components of the bridge.

Once we have a model for the bridge, we integrate it with the specifications—analyze the structure in terms of the various loads we had previously established. There's the dead load of the structure itself, as well as the live load of vehicles on the bridge. We have to determine how many situations to account for. Do we combine the live load with a full hurricane wind? The answer is "no" because there wouldn't be vehicles on the bridge during a hurricane. So there are certain combinations we need to check. We also have various safety factors for each combination. For a major earthquake, we might have a very low safety factor, because major earthquakes are very rare; whereas for vehicles only we would need a high safety factor, since that's a usual mode of operation. This level of analysis gives us the forces acting on all the components and brings us to the next level: designing the components. The final

The four traveling forms at the corners of the deck allow a concrete structure to be extended out over the open water. Sections are supported by cables attached to the tower. Prestressed concrete and traveling forms initiated a whole spate of new techniques that now make it possible to build concrete spans of up to 1400 feet—long enough for an East River span in New York.

FIGURE 3. Innovation in Concrete

step is to connect the components. This is probably the most important part of the design process, since experience shows that it's the place where a lot of things can go wrong.

During the whole process, we pay attention to "fatigue." Usually, if there's going to be a problem in a steel bridge, it will be with fatigue. Fatigue failures occur when alternating stress on a member causes small cracks/flaws to grow. Most steel bridges today are welded, and it's very difficult to have a welded bridge without cracks and flaws; fatigue is going to increase the size of these cracks. If safe limits for fatigue stress on cracks are exceeded, they will grow until an entire element is fractured.

AS **We'd be curious to know if you try to divide your design personnel into teams that can work in parallel. This is often a major way to reduce completion time for a computer project.**
GF After the model is complete and the interconnections are determined, we may have teams working on different parts of a large structure. We could have a substructure team working on piers and foundations, and another team working on the superstructure. We actually divide the substructure into the pier element and the foundation element, which is usually underground or underwater. The first thing the superstructure people do is to define the interface with the substructure team by estimating the loads that will be acting on the substructure.

DG **So the interaction between these two teams is just in terms of the load that the superstructure puts on the substructure?**
GF For the most part, although there may be other interactions from time to time. For example, if the superstructure is rigidly clamped to the substructure, a rise in temperature will bring forces that act on the superstructure and the substructure into play. These forces depend on the relative stiffness of both elements.

AS **Are there subgroups within these teams that work in parallel as well?**
GF Yes, but now we're really getting to the level of individual responsibility. For example, there might be one person designing the slabs for the roadway deck, another designing the stringers supporting the slabs, etc. There aren't an enormous number of people involved in the design; when there are too many, they get in each other's way, and it becomes more difficult to keep everyone up-to-date with changes. However, there might be more engineers involved for bridges with multiple spans or complex approaches. In that case, different groups can work on different sections of the bridge in parallel.

AS **How hard would it then be to link the work of these separate groups?**
GF It wouldn't be hard because there would be one engineer in charge who would ensure that all the groups were designing compatible structures.

AS **Componentwise, is there a trade-off between innovation and convenience? Would a designer be inclined to use components that are available or can be easily manufactured even when customized components might be more appropriate?**
GF There's very little standardization, except for small-span bridges. Most elements are built up out of steel plates. An I beam or plate girder, for example, consists of a top plate, a bottom plate, and a plate between them. (The top and bottom plates are called flanges; the connecting plate is called a web.) In addition to steel plates, you can buy angles and I beams in some standard sizes. However, the number of standardized parts available is really quite small, and many elements have to be welded together to form larger components. So I would say the standardization is not very great in terms of components for steel bridges.

DG **What about in concrete?**
GF One of our biggest industries in prestressed concrete is the making of concrete I beams. These are trucked or barged to the site, lifted, and placed in position. So, the sizes of some of these I-sections are standardized.

AS **It must be more economical to use standardized components?**
GF Sure. For example, it's more expensive to use nonstandard concrete sections because special steel forms have to be built for pouring the concrete. We actually have six standard sizes of concrete prestressed beams. On the other hand, the economies of scale with a large bridge may make it more logical to use nonstandard components.

DG **So, while you're very specific about standardizing loads and allowable stresses, and possibly even basic designs, you're not all that standardized when it comes to components.**
GF Yes, I think that's correct. It's rare that you can obtain complete plans for even a small span—75 feet or so. There's almost always some customization to be done.

AS Does it concern you that there isn't more integration of the design and the construction processes?
GF Yes, it does. In this country, there's a tendency for the consulting engineering firm not to be involved in the construction process. We check the shop drawings, but we often aren't involved in the actual construction. This can cause problems, since the contractor can't read the designer's mind. There is a certain aspect of the bridge that's best understood by the person who designed it. In my judgment, the designers of bridges, especially of long-span bridges, should be involved in the construction process.

Contractors actually design and prepare their own plans for such things as erection schemes and traveling forms. They also check the stresses in the structure for each phase of the construction, and if the stresses are too high, they may add extra material to the structure to reduce the stresses to within the allowable limits.

AS So the designer's specification and drawings don't really capture everything?
GF It's difficult to get every nuance of the design into the drawings.

AS Are there ever problems with the initial design that are noticed only in the construction phase?
GF It's rare, but it happens. Sometimes the designer will fail to anticipate the tolerances required by certain materials. Also, suppliers of different prestressing systems use different techniques. Designers can't always come up with a design that suits all prestressing techniques. These problems arise because the design cannot take all possible construction materials and techniques into account.

DG What happens if there's a flaw in the design?
GF The contractor checks with the designer: Usually, the designer can come up with a solution. Designers are required to be available for consultation during the construction phase, even when they're not responsible for inspecting the construction.

INNOVATION

AS Is there some particular point in the design process where you consider new options? How exactly does innovation occur?
GF Innovation is an important part of the preliminary design, once we know the broad requirements of the client. Most new ideas come out of the preliminary roundtable discussion I mentioned earlier. We'll discuss new types of bridges as well as improvements that can be made to existing types. For example, truss bridges have traditionally been designed with transverse joints in the roadway deck to prevent the deck from participating as a main load-carrying member of the bridge. We spent a lot of time thinking of ways to eliminate these joints the last time we designed a truss bridge, since they're both expensive and corrosion prone. By letting the deck more or less float, we were able to control the longitudinal participating stresses and thus were able to eliminate the joints.

AS What kinds of things can motivate innovation in bridge design?
GF A major stimulus right now is the competition between concrete and steel. Until recently, concrete was never used in long-span bridges. When prestressed concrete came into use after World War II, though, things began to change (see photo on page 272). One important technique eliminated the need for scaffolding to support the forms into which the concrete is poured. This technique was developed by a man in Germany named Ulrich Finsterwalder and was particularly important for bridges over bodies of water. Finsterwalder's idea was to construct the pier and then to start 15-foot traveling forms out from each side. These forms are cantilevered out, which means they are just extended out over the open water. He would pour 15 feet of concrete, prestress it back to the previously poured portion of the bridge, then go another 15 feet, and so on. His longest span was 680 feet, which was about 20 years ago.

Then we asked, Why pour the 15-foot sections up in the air? Why not make 15-foot sections on the ground, and then lift them up and prestress them back into the previously erected segments? So we now have what we call "precast segmental construction." And then the idea of the cable-stayed bridge came along, and that was even better. These bridges have linear steel cables from the towers to each of the segments, making even longer spans possible.

So the maximum length of a concrete span increased from maybe 200 feet prior to World War II to 1400 feet today. There were some longer arch spans before the war, where concrete was completely in compression all the time, but I would say that there has been consistent progress in making concrete feasible for longer and longer spans since World War II.

AS What about steel?
GF There's also been progress with steel bridges, although not on the same scale as with concrete. For instance, after World War II, most of the bridges in

Germany had been destroyed, although the piers were intact. But these piers had supported very narrow bridges, and the engineers in charge of rebuilding them had to come up with weight-saving devices, such as the orthotropic steel-plate riding surface, to utilize them.

DG **Could you identify some bridges that were thought to be particularly difficult when the design was begun?**
GF Some of the early suspension bridges were particularly difficult, and there were many failures. An example is the Wheeling Bridge over the Ohio River, built in 1849. This was the first span in the world over 1000 feet. The bridge actually collapsed after five years, but was rebuilt, and is still in use. I have to admire the courage of those pioneer engineers, trying to build long flexible bridges without the benefit of much analysis or knowledge of the dynamic effects of the wind.

AS **That preceded the Brooklyn Bridge?**
GF Yes. The Wheeling Bridge was about 30 years earlier. The Brooklyn Bridge illustrates the problems of constructing deep foundations under water. In the case of the Brooklyn Bridge, a lot of the workers building the foundation developed caisson disease from the high air pressure they were forced to work under. At the same time, a bridge was being built in St. Louis called the Eads Bridge, which is also still in existence. The workers there were experiencing the same sickness.

DG **What problems were overcome from a design perspective?**
GF The early bridges were built without much knowledge of exact analysis: They were built on intuition and experience. We've since learned how to actually calculate most of the stresses and deflections from all types of loads.

TOOLS

DG **What are the tools that a bridge designer would use?**
GF Well, to put things in a historical perspective, up until the 1950s we were using slide rules and desk calculators to help determine the forces on components. On reasonably large, indeterminate structures, we used approximation techniques to reduce the number of simultaneous equations that needed solving. This would leave us with a maximum of 25 simultaneous equations to solve. On a little hand-operated machine, that took a lot of time. The towers on the George Washington and Golden Gate bridges were indeterminate, and were analyzed in this fashion. The Hardy Cross approximation method was also widely used to analyze frame structures of all types.

With the advent of computers, we returned to classical analysis techniques with matrix methods. This allowed us to routinely solve hundreds of simultaneous equations. I think the aeronautical industry really led the way in this area. Classical matrix methods to obtain forces acting on components were predominant in the 1960s and 1970s; today we're also using finite-element methods, which allow us to combine linear components with plate elements, and even to compute stresses in solids. With these methods, we're able to calculate the response of just about any type of structure to any conceivable load, static or dynamic.[1]

AS **What other kinds of calculations do you do besides determining forces?**
GF Once we get the forces, we have programs that take them and determine the stresses in and deflections of elements. For certain situations, we have separate programs that can actually design components. But overall we haven't come too far with interactive design, since we rely mostly on what we call "canned" programs. The reasons for that are probably historical, in that the original tools solved for forces and deflections in isolation from the design process. I think things are finally beginning to change, though. Interactive design is now becoming more popular, especially on the ubiquitous PCs.

AS **Can you tell us a little bit about the actual program that you use?**
GF The most often used structural analysis program is STRUDL, which, for an input of external loads acting on the structure, obtains the deflections of the structure and the forces acting on each of the components. STRUDL was developed by Steven Fenves many years ago at MIT and was originally called STRESS. MCAUTO and Georgia Tech have brought it up-to-date and commercialized it. When nonlinear effects come into play, we use a nonlinear program, and we also have finite-element programs. There are also analysis and design programs for specific components: beams, piers, columns, etc.

AS **Do you run any optimizations?**
GF We do some optimization with the computer, but mostly we rely on experience and trial and error: Trying a design and then changing the elements if it is understressed or could be designed less ex-

[1] See Karen Frenkel's "Computers and Liberty," in this issue, for a more detailed treatment of finite-element analysis.

pensively. But we don't have a major program that will do optimizations.

DG **Do you foresee any such program?**
GF Absolutely. This is an important area where a lot of work is being done right now. It's also a very complex area, though.

DG **What computers do you use today?**
GF We have two VAX 11/780s in this office, one dedicated to engineering calculations and the other to CAD. We've got another VAX 11/780 in Kansas City, and VAX 11/750s in Milwaukee and Orlando. These are all linked by DECNet. We're now purchasing MicroVAX IIs; at present, we have two MicroVAX IIs and one MicroVAX I. This is all DEC equipment because we value compatibility. We have 38 CAD stations with Tektronix screens throughout the firm, 5 in this office. We also have a plotter and some hard-copy units, digitizers, etc.

DG **What is the extent of your CAD applications?**
GF We mostly use CAD to make detail drawings, although it's also useful for such things as perspective drawings and maps.

DG **Is there any interconnection between the engineering system and the CAD workstations?**
GF Not in bridge design. This is one area where very little has been done in structural engineering. Mechanical engineers are a lot further along with this kind of integration. We would like a more integrated, interactive program for determining forces, designing members, and producing drawings. Right now, a designer receives computer outputs and produces rough sketches, which are then entered into the CAD system.

DG **How much would more interactive programs change the design process or reduce its costs?**
GF They would allow engineers to make revisions to designs immediately, rather than after running a canned program. Engineers would also be able to try various alternatives and thus to arrive at optimal solutions more quickly. It would be possible to design and make drawings simultaneously. This would save a lot of money.

DG **Is there any mechanical verification or validation of outputs on the CAD system?**
GF There isn't any automatic checking in bridge design. The CAD output is completely hand checked by an engineer. If there are changes, the drawings are changed on the CAD system. In our building area, though, there is some validation in terms of interference. For example, a program will automatically determine if two pipes are touching or intersecting.

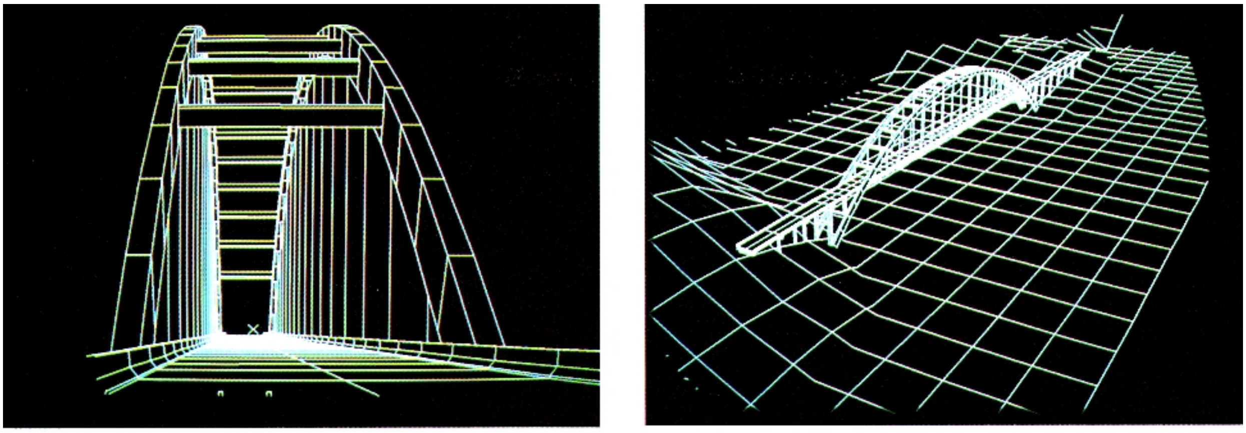
DG **Do you use any planning or scheduling tools during the design process?**
GF We have tried to use the PERT or CPM packages for design scheduling, but we have never generated much enthusiasm by doing so. Most people complain that it's difficult to keep the schedules up-to-date. It may be that our design process is not complex enough, or that the number of people involved is not large enough to make these techniques practical. However, PERT and CPM are used in construction management. We also use them on very complex projects when we serve as general consultant: that is, when we run a very large project of perhaps one-half billion to a billion dollars and are the lead firm of five or six consulting engineering firms.

DG **How have computing tools been useful in the design process?**
GF We're able to analyze a lot more alternative bridge types than we were before. We're also able to do a lot of simulations, where before we could hardly do any, as well as dynamic analyses, which are becoming crucial for the more slender structures of today. We live in a nonlinear world, and the computer is making it feasible to perform nonlinear analyses instead of the less-useful elastic analyses we relied on before. All of these factors contribute to making bridge design more cost-effective than it ever was before.

DG **Is there a possibility that mistakes in a computer program could cause a bridge to fail?**
GF Yes. A mistake in a computer program could certainly have dire results.

DG **Are the bridges you design today with computers as safe as the ones you were building 30 years ago?**
GF I would say so. Before computers, we needed high safety factors to take into account things that we couldn't analyze. Now that we can be more precise, we don't need to be so conservative. We're able to achieve a more uniform factor of safety throughout the structure, where before the factor of safety would be high in some areas and low in others.

DG **Have your design tools failed you in any way?**
GF I wouldn't say the tools have failed us: Failures usually occur when we extrapolate beyond our



Shown are two perspectives for a steel arch bridge. Designers have two media for expressing a design to a contractor: textual specifications and drawings. Many drawings are now done on CAD workstations.

FIGURE 4. CAD Drawings

experience and models. From each failure, there's a lesson to be learned.

***DG* Many of your tools model the behavior of bridge components. How nearly do these tools correspond to the actual structures you eventually build?**

GF From my experience, and from studying the experimental results, I would say that the models are within 10 to 20 percent of the actual structures.

***DG* What about the expected inputs to the models—the loads?**

GF The loads are more variable because you can't predict traffic or wind very exactly. But I would say we're conservative with our loading. Our understanding of materials is also quite good. You must remember that, even with such inputs as dead-load forces, which we are relatively sure of, we apply a safety factor; in general, 1.8 is the safety factor that is used. This takes into account any variability in the loads or materials, as well as possible mistakes in the model.

***DG* Do you supplement your analytical modeling with empirical testing?**

GF We test most cable-stayed and suspension bridges in a wind tunnel because our analytical models for wind are very poor. For cable-stayed bridges, we have to determine the critical wind speed that would cause instability in the structure. On the other hand, wind-tunnel tests aren't usually necessary for truss bridges because they're not nearly as slender as cable-stayed bridges. We've actually revised cross sections as a result of wind-tunnel tests. The supercomputer might be able to help us develop a model for wind effects; we now spend between $30,000 and $50,000 for a wind-tunnel test, including the cost of the model.

We've also done some vertical load tests. When segmental bridges were first introduced into the United States, a 1/10 scale model of a 750-foot-span bridge was built. It was a very good model, although, at $750,000, it was very expensive. This model did help sell the government on the design concept, however.

There's also some modeling of connections, since there have been some problems with connecting the segments on some of these segmental bridges. There is also a lot of empirical testing of components to establish rules for their design.

RELIABILITY

***AS* How do you ensure the correctness of a design?**

GF Good engineers check everything. The design is usually checked before the drawings are made, and then the drawings are checked as well. This checking is always done by an engineer who did not work on the original design. After the drawings are completed and checked, they are reviewed by a senior engineer for completeness.

AS **Do you have any special administrative procedures to ensure that the checking is done?**
GF On top of each of the calculation sheets for the design phase, we have a "made by" and a "checked by" line, both of which must be signed. When we use a computer program, we print both the input and the output, and an engineer must always check these to see that the proper inputs were used and that the outputs are sensible. The checking engineer certifies that the proper inputs were used. We don't verify the computer program each time, but rather the use of the program.

AS **What sorts of structures do you put into bridges to make them reliable?**
GF People do not expect to be taking any risks when they cross a bridge. Since such risks as do exist are therefore involuntary, it is essential that they be kept to a minimum. If a bridge incorporates redundancy, the collapse of an element will not cause the failure of the entire structure. We strive for redundancy, but in a lot of bridge types, we don't have redundancy at the present time, mainly because of the costs involved. We try to increase the safety factor to compensate for a lack of redundancy.

AS **That means that the failure of a nonredundant element could cause such a bridge to fail?**
GF Yes: On some long-span bridges, for example, if there are two trusses holding up a bridge, a failure of one member in one of those trusses might cause the bridge to fail. It costs a lot of money to make that type of structure redundant. Most small bridges are redundant. As you drive under one of the multiple stringer bridges that you find on highway overpasses, you can see a large number of longitudinal beams. If one of those beams failed, that bridge would probably not collapse.

DG **Do you expect more bridge failures as nonredundant bridges age?**
GF No: I would say that inadequate inspections would be more to blame for such failures than lack of redundancy. If you can detect cracks in steel members, then you can repair them and prevent failures. What's difficult is finding the cracks—it's very difficult to detect cracks visually. A lot of time and money are now going into developing nondestructive testing for bridges. For example, acoustic methods might be able to pinpoint cracks before they would be apparent to the eye. X rays are also an option, except that it would take a long time to x-ray an entire bridge.

AS **So reliability requires an ongoing maintenance procedure?**
GF Yes: Failures in the past have led to a whole spate of rules and regulations—that every bridge should be inspected yearly, at least visually, and maybe in depth every five years or so. And, with the increased gas tax, a lot more money is now being spent on rehabilitation, so a lot of old bridges are being repaired.

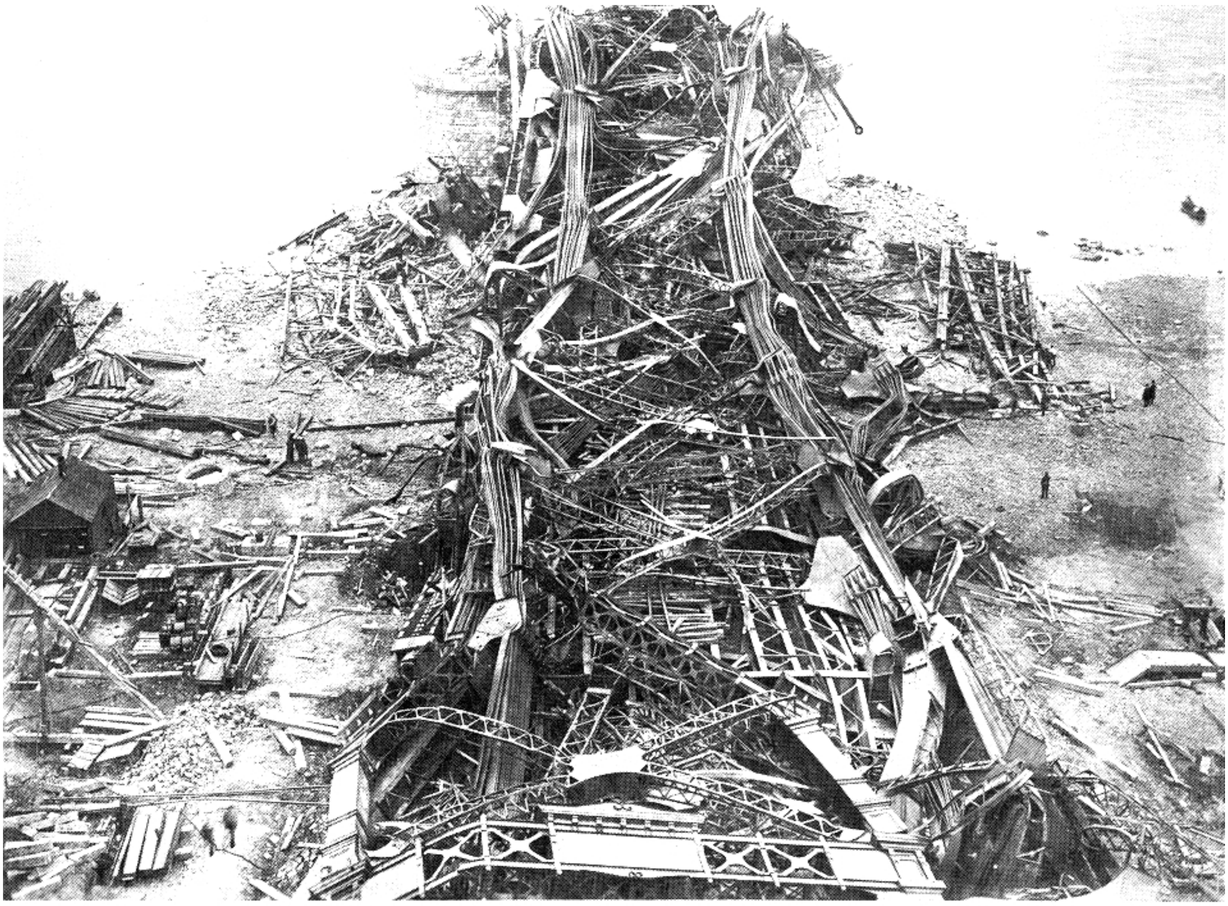
AS **How does metal fatigue contribute to bridge failure?**
GF The typical chain of events is that a crack or flaw occurs in the bridge, usually either from welding or fabrication. Fatigue generated by alternating stress then acts on this crack—there is what we call a fatigue crack growth rate. We have a lot of statistics now, giving the slope of that curve. If the crack achieves a critical length, it will propagate through the structure. A crack will continue to grow until it reaches a tougher material. So what can happen is that we'll have a crack that starts in the top or the bottom plate of an I-section and then goes right through to the opposite plate. Such cracks usually stop in the middle section, which is generally thinner and therefore more resistant to cracks.

In a redundant structure, cracks can usually be detected when they reach this middle section, and they can be repaired before they go right through the beam. In a nonredundant structure, however, there have been several collapses from fatigue. The great majority of cracks, however, are detected and corrected.

FAILURES

AS **You said before that problems arise when bridge designers extrapolate beyond their models and experience. Could you point to some specific instances of that phenomenon?**
GF The Tacoma Narrows Bridge failure in 1940 is a good example. Designers had been extrapolating beyond their experience to create more flexible stiffening girders for suspension bridges. They never thought about a wind-induced dynamic failure. After that, a lot of money was put into research, and we learned about aerodynamics and bridge response. As a result of that experience, we were very conservative in the design of our suspension bridges until about 15 years ago, when an aerodynamic shape was developed to resist the dynamic excitations that wind causes.

The Quebec Bridge, which failed during construction in 1907, is another dramatic example. Seventy-five people died. This 1800-foot-span bridge was to have been the longest in the world at that time. It failed because the designers underestimated the dead load and didn't understand how large members



This bridge, which failed during construction in 1907, was to have been the longest bridge in the world at that time. Most problems in bridge design occur when designers extrapolate beyond their models and experience.

FIGURE 5. The Quebec Bridge

could buckle on such a large bridge. It was beyond their experience.

AS **So Tacoma Narrows was a failure mode that no one had even considered before, and the Quebec Bridge was a failure mode that was known, but not sufficiently understood?**
GF That's correct. Although buckling goes back to Euler's time, the experience with large enclosed members just wasn't sufficient. The factor of safety was not large enough to take into account the state of knowledge.

AS **How can you be certain that you've considered all possible failure modes for a large bridge?**
GF We have a vast store of experience to draw from, which includes practically every possible failure mode for these bridges. When we extrapolate beyond this experience database, however, we are in unknown territory and must resort to empirical testing to identify some of the failure modes. For example, the proposed bridge across the Messina Straits, to connect Sicily to the Italian mainland, will have a main span of two miles. This is twice as long as anything that's ever been built. Probably most of the unknown failure modes will result from dynamic actions of some kind or other. Extensive model tests are now being performed to identify these failure modes.

DG **What is known about the failure of the Mianus Bridge in Connecticut?**
GF That was a nonredundant skew bridge that collapsed when a pin in a hanger that connected one main member to another failed. We've now reexamined such hanger connections, which were very common during the 1960s and 1970s. They're not used as much in today's designs because they're

nonredundant members, with a single point of failure, and because they're very susceptible to corrosion. The Mianus failure has not really been set to rest yet, since the final reason for the failure has not been officially established. The controversy has to do with whether the failure was due to corrosion, to unanticipated movements, or to a combination of both factors.

There have been some fatigue failures, usually in combination with brittle steel—the 1964 Kings Bridge failure in Australia, for example. All four parallel 100-foot girders failed after a crack, which had started at a weld, reached a flange cover plate on each girder.

The Silver Bridge in West Virginia was a suspension bridge that collapsed in 1967 when a pin failed and the suspension portion pulled apart. A railroad bridge over the Tey estuary in Scotland collapsed in a windstorm in 1879 with a train on the main spans. The train went into the river, and 75 people were killed. That bridge was not designed or constructed as well as it should have been. The wind loads were grossly underestimated, and numerous defects in the construction went undetected. Other wind failures include the first Wheeling suspension bridge that we spoke of before, and a bridge at Niagara Falls, which failed in 1889.

DG **What about small bridges?**
GF There are perhaps 100 failures of old small bridges in any given year. These bridges are usually overstressed because of increased loads. Fatigue and corrosion are usually the key factors. Earthquakes and scour (the erosion of the foundation because of flowing water) affect some as well. Fortunately, there aren't usually any fatalities when a small bridge fails.

DG **Were there any bridges that were designed and then abandoned during construction because of faults in the design process?**
GF I can't think of any that were abandoned during construction because of design considerations. A change in planning or environmental considerations are the only things that I can think of that can stop a bridge during construction.

DG **Are there any bridges in the world that you wouldn't drive your car over?**
GF Not that I know of.

THE PENANG BRIDGE

DG **Could you describe the history of a particular project so that we can see how a bridge actually comes to be built?**

This cable-stayed bridge, designed by HNTB, has a main span of 738 feet. It was opened in September 1985.

FIGURE 6. The Penang Bridge

GF The Penang Bridge in Malaysia is HNTB's most recently completed large bridge. The Malaysian government wanted a bridge over the Straits of Malacca to connect Penang Island with the mainland. A group of Danish and Malaysian consultants started a feasibility study in 1971 and eventually recommended a four-lane low-level connection, partially on fill and partially on structure. The bridge travels 5.2 miles over water and is 8.4 miles long in its entirety. It's the longest bridge in Asia.

The Malaysian government hired HNTB and a Malaysian consultant in 1976 to develop preliminary plans for a high-level bridge that would permit some ships to go below the main spans. After working for about nine months, we made a preliminary report in August 1977. We studied five different designs and proposed that final plans be prepared and bids be let for both a tied arch steel bridge and a concrete cable-stayed bridge. The Malaysian government accepted our recommendation, and we then prepared final detailed designs of both bridge types. The approach spans were done by our Seattle office and by the Malaysian consultant; the main cable-stayed spans were done in our New York office. In the case of the cable-stayed bridge, the center spans were to be 738 feet long, at the center, and the side spans 353 feet each. The design was submitted in 1981 and let out for bid.

There wasn't much difference in price between the two designs, but the Malaysian government decided on the cable-stayed bridge for a few reasons:

A concrete bridge could make more use of local labor and materials, and could be constructed more quickly. Also, the cable-stayed design was more distinctive. The client had asked us to come up with something unique for the towers that would identify this bridge with Malaysia. In the photograph of the bridge, you can see the unique little pinnacles on top of the tower. This was one of the four or five different options that we designed. The contract was let in 1982 to a Korean firm, Hyundai, which is a very large company involved in shipbuilding, automobiles, and many other things. They were given three years to complete the bridge, which was opened to traffic in September 1985.

DG **What were the design considerations for the main span?**
GF One of the most important things we had to establish initially was the design standard: Malaysia has historical ties to England, so we were asked to use the English specification for design instead of the AASHTO standard. England had just established a new design specification at the time, and we found a lot of bugs in it.

Other considerations were seismic activity, wind, and materials. Seismic activity is more of a concern in a concrete bridge than in a steel bridge since concrete has so much more mass. There's not much wind in the Straits of Malacca, and it's not a very active area seismically, but we did have a seismic analysis done to be sure. The critical materials issue was corrosion protection of the cables. There was one other major consideration: ship impact. To prevent this, we decided to build islands around the piers. Many older bridges do not have adequate protection against ship impact.

Next we had to consider how the bridge should be constructed. We decided to have edge beams at the outside of the roadways that would be cantilevered out and constructed with traveling forms. This is rather easy for the contractor. We worked out from both sides of the main pier for balance. We also had a traveling form behind that first traveling form for installing the deck. In construction, the cantilever was built out to the center of the span; the travelers were then dismounted and brought over to the other side, which was built out to meet the first at the center.

We used STRUDL to do the calculations, along with a nonlinear program, which is a modified linear elastic program. We also used some finite-element programs on the deck, to determine the distribution of the transverse stresses. We also used element design programs to design the columns of the towers, as well as the beams, taking the forces from the analysis program. The drawings were all made by hand: Remember, this was several years ago.

DG **How many drawings did this bridge require?**
GF About 65 for the cable-stayed spans.

AS **What did it cost to design and build the bridge?**
GF Hyundai said that construction costs came to 400 million American dollars for the whole project.

An interesting point about construction costs: When Hyundai was chosen as the contractor for this project, they came up with a design change that would save some money. They made a proposal to the client, which was accepted, and then the two of them, the client and the contractor, split the savings. This is a common practice with big contracts. It's called "value engineering." The design firm must accept the change, however. In this case, Hyundai proposed a change from ¼-inch wire cables to 1⅜-inch bars. Of course, that changed the stiffness of the structure somewhat, which meant reanalyzing some things on the computer, but it saved some money.

DG **Was HNTB involved in supervising the construction process?**
GF Yes. In fact, the people who supervised the Penang Bridge are now supervising the construction of another large cable-stayed bridge in Jacksonville, Florida.

FINAL COMMENTS

DG **How do you think the design process can be improved?**
GF I think we should be moving toward more interactive design on computers. I think we should be developing databases, or knowledge bases, as well. Unit costs, technical data, historical costs, and failures could be put into these databases. Right now, designers aren't able to get to the information that's out there. They rely on what they've seen recently. I don't think many of them use bibliographic services, such as Dialog, which could be a big advantage. Of course, the disadvantage with Dialog is that it can come up with so many citations that the user begins to lose interest. If you narrow the query down to something specific, there's still the problem of obtaining the referenced papers in a reasonable amount of time.

DG **What don't you like about the design process today?**
GF I don't think our checking is as rigorous as it could be. We check everything, but someone check-

ing a design can fall into the trap of checking what the initial designer did, instead of looking for things that should have been in the design, but weren't. I feel that an automatic or mechanical device would be useful in this respect. The cost of liability insurance is also becoming a problem: There are many lawsuits being filed for worker injuries, car accidents on bridges, etc. Finally, I think it's inefficient to separate design and construction the way we do. Just from the designer's point of view, we're not getting the benefits of contractors' construction skills, and we're not able to target our designs to the skills of specific contractors. I don't know how this can be done under the present system, where contractors are selected after the design work is more or less finished.

DG **And what do you like best about the current design process?**
GF I think it's good that we produce a number of alternative designs at the outset, and that we don't immediately focus on one alternative. It's also good that we present these alternatives to the client. Clients often provide very useful feedback. And, because most large bridges in this country are financed at least in part by the federal government, the Federal Highway Administration often has useful suggestions and comments to make on our preliminary designs. I also think the AASHTO specification document is a noteworthy accomplishment. It's evolved over a 50-year period into a valuable record of the collective understanding of bridge requirements and materials.

EDITORS' CONCLUSIONS

The use of common problem-solving skills, problem decompositions, and special representations underlies both the design of bridges and the design of computer systems (including hardware design, software design, and programming). The major differences are in the scope of the design problems and in the type of knowledge that is applied. Herbert Simon writes about design in general in *The Sciences of the Artificial* (2nd ed.):[2]

> Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state.

[2] MIT Press, Cambridge, Mass., 1981, p. 129.

Much about the process of bridge design described in this case study should seem familiar to computer-systems designers. Structural engineers decompose a bridge into a hierarchy of subcomponents, all of which are ultimately constructed from relatively simple objects like beams and plates. Programs and VLSI designs, for example, are also hierarchically decomposed, but the primitives are instructions and transistors. Dynamically, the bridge-design process is arranged so that separate groups can address separate aspects of the design, much as occurs in computer systems design. A bridge designer's concerns for functionality, reliability, serviceability, and even aesthetics are familiar to computer systems designers. Failure-mode analysis also plays an important role in both fields. Increasing interest in long-term maintainability and in using redundancy to achieve reliability is also common to both professions.

The most noticeable difference is that the bridge-design process is much more structured than computer systems design. Similar design decompositions and project organizations are used for each bridge. Standardized specifications like the AASHTO specification in the United States further constrain designs, by mandating standardized requirements and constraints on materials. These standards tend to make bridges more like each other. While there has been innovation in materials, construction techniques, and analysis, innovation has proceeded more slowly in the realm of bridges than in the realm of computers, and this too has contributed to greater standardization of designs and of the design process. Finally, bridge designs are just not as complex as computer systems designs, at least as measured by the number of person-years required. Project-management issues in the design phase are much simpler, though this may not be so in construction management, where many individuals work in parallel.

Some other specific differences in the disciplines emerged in the interview:

Attention to Reliability. Structural engineers take reliability seriously, and the percentage of bridges that fail is small. Although the interview highlighted notable disasters to elucidate failure modes, long experience with designs and materials has benefited reliability. In addition, structural engineers check each other's work as a matter of course. They check each stage of the design including the calculations, design drawings, and construction drawings. Finally, they perform on-site inspections. This checking process seems more formalized than that of many software-design groups. There would seem to be many fewer failure modes for bridges than for computer systems, and this also makes reliability easier to achieve.

The Use of Tools. Structural engineers use analytic models comparable to those of hardware designers and more advanced than those used by software designers. The structural-engineering models and CAD tools are not as integrated as in VLSI design, but a similar degree of integration seems likely in the near future. In fact, there are efforts under way to develop expert systems to aid in the bridge-design process.

Standardized Bridge Requirements. The standardized specifications that mandate usage requirements simplify the requirements-analysis phase for bridges and ensure that collective experience is fed back into future design requirements. Increasing standardization of this sort for computer systems to simplify use, interoperability, and maintenance seems likely.

Standardized Material Specifications. Standardized specifications mandate the allowable uses for structural components in bridges. Such standards contribute to reliability and design standardization. These specifications, however, are conservative and may slow the use of innovative techniques. In computer software, generic packages are available, and even more packages may soon exist, for example, in Ada® and Common Lisp. We might expect to see an increasing number of specifications requiring and governing the use of packages.

Formal Design Documents. The preliminary and main design processes result in explicit, comprehensible design documents for bridges. They are held up to the scrutiny of the client, the Federal Highway Administration, and others. For complex bridges, the client is permitted to choose among different preliminary designs. The plans and specifications that result from the main design process are comprehensive, permitting a complete separation of the design and construction processes. Such complete plans and specifications are expensive and represent about 70 percent of the design cost at HNTB. Specification of most software systems is more difficult and rarely done so far in advance.

Separation of Design from Implementation. The bridge-design process is separated from the construction process by very complete design drawings and specifications. Fox believes there would be benefits from increased interaction between the designer and contractor, since there are some things that cannot be communicated through the specifications. Additionally, designers could change designs in some instances to better fit the skills of a particular contractor.

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Bridge design is a mature engineering discipline, and as such, it might provide a glimpse of the future of computer systems design. As computer science matures, there may be more standard specifications and designs. When the design space for certain application areas becomes more constrained, it may be possible to produce clearer specifications earlier in the design phase. Reliability guarantees may assume increasing importance, and the use of tools may become more prevalent. On the other hand, innovative application domains, increasing computer speeds, memory sizes, and increased use of parallelism will continue to lead to more diversity than exists in the bridge-design process.

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CR Categories and Subject Descriptors: D.2.9 **[Software Engineering]**: Management; J.2 **[Computer Applications]**: Physical Sciences and Engineering—*engineering*; J.6 **[Computer Applications]**: Computer-Aided Engineering—*computer-aided design (CAD)*; K.6.1 **[Management of Computing and Information Systems]**: Project and People Management; K.6.3 **[Management of Computing and Information Systems]**: Software Management

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