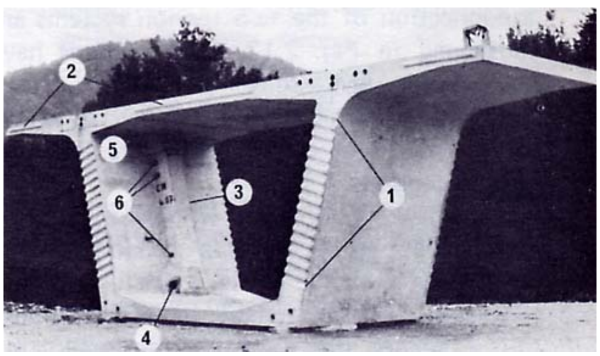
My primary reseach objective is to develop new structural systems that will enable bridges to make efficient use of the mechanical properties of high-performance materials. These systems will be significantly less expensive to build than currently used systems, will be more durable and easier to maintain, and will create exciting new aesthetic possibilities for bridge designers.

In this document, I wish to outline the need for this research and to map out the primary elements of my long-term research program.

1 CURRENT BRIDGE TECHNOLOGY

The practice of bridge design is currently locked in time. The bridges we build in 2003 closely resemble those built a quarter century ago. Even newly constructed precast segmental bridges, generally regarded as the most technically advanced type of bridge, are practically indistinguishable from segmental bridges built in the 1970s. The photos below show two segmental bridges, the one on the left from before 1975 and the one on the right from 2000. It is apparent that there are very strong similarities in all primary structural characteristics, including arrangement of slabs and webs, layout of tendons, and details of shear keys.



The static state of bridge technology has caused several significant problems. Because technology has not evolved, the practice of bridge design has become increasingly commoditized. When the materials, systems, and details used in bridge design do not change, then bridge design is transformed from a creative activity to a mere exercise in sizing up reinforcement or steel plate sizes. Advances in computer technology have allowed many of the calculations required for this task to be done automatically. In addition, the availability of design charts, tables, and catalogues allows designers to pick suitable components without having to expend much effort actually designing them. One could certainly argue that this type of work could be reasonably handled by technologists rather than engineers.

The consequences of this lack of progress in bridge technology extend outside of the profession. The US Federal Highway Administration compiles an annual highway construction cost index.[1] These data, when adjusted for inflation, show that the unit cost of highway construction has remained practically constant from 1970 to 2000. It is reasonable to assume that this trend also applies to bridge construction. So even though the current prac-

1. FHWA. 2003. U. S. Federal Highway Administration. Highway Construction Price Trends and the Consumer Price Index. <http://www.fhwa.dot.gov///////ohim/onh00/line15.htm>.

trice of competitive bidding for construction contracts ensures that each individual bridge is the "lowest cost" structure, this minimum is obtained within the constraint of an underlying technology that is constant. We can contrast this situation to the one that prevails in microelectronics, where the cost of silicon chips per transistor has decreased exponentially from 1970 to 2000. This trend is the result of constant advances in technology, which has seen the density of transistors on a chip grow exponentially over the same period of time.[1]

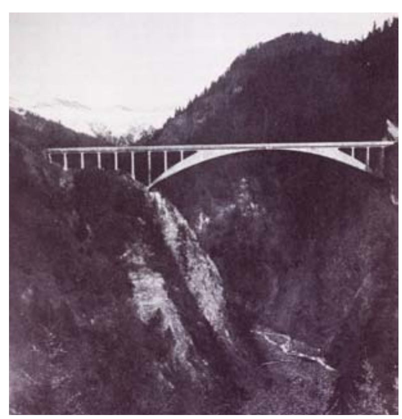
The static state of bridge technology has deprived designers of the means to create real economic value for society. Although it is probably too optimistic to expect bridge construction costs to decrease at the same frantic rate as the cost of transistors, even a fraction of this pace would result in lasting economic benefits, creating new opportunities to build more bridges and build better bridges.

The absence of technological progress also compromises the ability of bridge designers to respond to new challenges. Society is beginning to insist, for example, on the use of environmentally sustainable technologies in a wide range of industries. Because bridge designers have grown accustomed to working with technologies that do not change, it will be difficult for them to develop innovative new solutions that give an acceptable balance between cost and sustainability.

Finally, if we consider the visual expression of the flow of forces to be a valid and powerful means of aesthetic expression, then the lack of technological progress implies a loss of opportunity to move this form of artistic expression forward. This situation has led owners and communities to look increasingly to architects or community focus groups for primary design input on important bridges, and to relegate engineers to a mere supporting role (i.e., ensuring compliance with code) in the design process.

2 OPPORTUNITIES

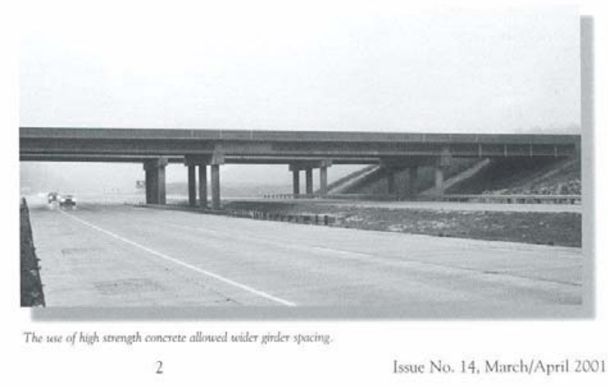
Ever since the industrial revolution, significant periods of rapid development in bridge technology have been made possible by important advances in materials technology. The industrial production of iron and steel in the mid-nineteenth century led to long-span truss and suspension bridges. The development of reinforced concrete in the late 1800s enabled long-span arches and rigid frames, culminating in the masterpieces of Robert Maillart. The invention of prestressed concrete, and its propagation after World War II allowed concrete bridges to reach spans that were previously considered to be the exclusive territory of steel.



In each case, the challenge for structural designers was to create new structural systems that took advantage of the unique properties of the new materials. This creative step is not self-evident. In the early twentieth century, for example, engineers designed concrete arch bridges as if they were made of masonry. There was a certain logic to this, since both concrete and masonry have no significant tensile strength. The resulting structures were heavy and limited in span length. The designers of that day knew that reinforced concrete could resist tension, yet they persisted in using the material in systems that did not take advantage of this property. Robert Maillart was the first designer to develop structural sys-

1. Intel. 2003. Intel Research. Silicon. Moore's Law. <http://www.intel.com/research/silicon/mooreslaw.htm>.

tems for arches that took full advantage of the mechanical properties of reinforced concrete. His bridges, such as the Salginatobel bridge shown on the preceding page, were significantly more economical than the masonry-inspired bridges of his contemporaries. His developments also opened up exciting new possibilities for artistic expression.



We are currently in a similar situation with regard to our own new materials. Recent developments in other areas of engineering have given us high-performance concrete, high-performance steel, and advanced composite materials, all of which offer greatly enhanced properties relative to conventional materials. Generally speaking, designers have used these new materials in conventional systems. The figure on the right gives an example of this situation for high-performance (high-strength) concrete. The figure was taken from a recent issue of *HPC Bridge Views*, an industry newsletter showcasing the applications of high-performance concrete in bridges. In spite of the fact that it is made of a modern material, this bridge looks like bridges built forty years ago. Although it is probably more durable than bridges built in the 1960s, it is not significantly different from earlier bridges with regard to cost, function, and aesthetic impact.

3 OUTLINE OF RESEARCH PROGRAM

The aim of my long-term research program is to address the need to move bridge technology forward by taking advantage of the opportunities presented by recent developments in materials technology. The primary theme of the program is to develop new structural systems for bridges that make efficient use of the mechanical properties of new materials.

3.1 *Approach*

This research will be strongly design-oriented. All of the scientific investigations to be performed within the research program will support an overall effort to develop innovative structural systems using new materials. The following steps describe the approach that will be taken:

1. Define target areas for development. These will initially be chosen to correspond to classes of new materials, such as high-performance concrete or carbon fibres.
2. Within a target area, identify important material properties and develop initial design concepts that take advantage of these properties.
3. Define areas of concern arising from the design concepts that require scientific investigation. These areas will relate primarily to issues of reliability (safety, serviceability) or quality (cost, ease of construction, sustainability)
4. Perform the scientific investigations defined in Step 3. If necessary, revise design concepts to reflect the new knowledge generated by these investigations. It is anticipated that the focus in this step will be primarily on analytical and small-scale experimental studies.
5. Validate the design concepts through construction, testing, and monitoring of full-scale structures in service.

6. Assess the behaviour of the demonstration projects in service to identify new areas of concern regarding reliability and quality. Where applicable, modify the design concepts and return to Step 4 for further scientific investigation.

The process is thus driven by the overall objective of putting new ideas into service. The process represents a cyclic flow of knowledge from design, through research, application in practice, assessment of behaviour, and then back to design.

An important aspect of this approach is to perform Step 2 with creativity and rigour. It is of little value to perform a large number of in-depth scientific studies on design concepts that are unsuitable to begin with. This is where the insights of a designer can truly be valuable. A designer has a sense, often difficult to articulate, of what is “right”, that has been acquired through many years of generating design concepts and then seeing them built and in service. This sense can and should be used to define concepts that are sensible and have good potential for success. We will therefore spend a considerable amount of time and effort in developing good concepts up front, to ensure that the time and effort spent on subsequent scientific studies are well spent.

3.2 *High-Performance Systems for High-Performance Concrete Bridges*

The first area that has been targeted for development is high-performance concrete. This material has been selected for the initial thrust of the research program since it is commonly available at reasonable cost everywhere in Canada, and many of the models of structural behaviour and capacity used for bridges in conventional concrete have been or can be extended to cover high-performance concrete. The primary mechanical property of high-performance concrete that will be used in this study is its high compressive strength.

The systems that will be developed and validated have the potential to provide greater structural efficiency and economy than currently used systems, due to a rational and intensive use of the high compressive strength of high-performance concrete. This will be accomplished by selecting the dimensions of primary cross-section components (top slab, bottom slab, and webs) as closely as possible to the values required to achieve maximum efficiency in longitudinal bending under service conditions and at ultimate limit state. The anticipated benefits of these new structural systems include lower construction cost, reduced greenhouse gases through lower consumption of cement, and greater possibilities for aesthetic expression.

Conventional structural systems for short and medium span concrete bridges generally make inefficient use of the compressive strength of concrete, since the dimensions of primary cross-section components are selected on the basis of thickness requirements given by code, detailing requirements, or rules of thumb, none of which consider the requirements of strength and serviceability in longitudinal flexure. This results in structures in which compressive stress at serviceability limit state is significantly less than allowable stress and the compressive stress block at ultimate limit state is significantly less than the thickness of the top or bottom slab, even for the relatively low compressive strength of conventional concrete. This practice is not only inefficient, it also inhibits the use of high-strength concrete, since cross-sections that use conventional concrete inefficiently will be even less efficient when high-strength concrete is used. An important opportunity both to improve the economy of concrete in bridges and to advance bridge technology through the appropriate use of high-strength concrete is thus currently lost.

The structural concepts that will be used as the basis for the scientific studies will be single-cell box girders. This cross-section is efficient in bending and in torsion, and is thus suitable for a wide range of spans and geometries. Box girders can be built using a wide range of methods of construction, ranging from traditional casting in place on falsework to highly mechanized methods of segmental construction. For a representative range of compressive strengths of concrete, we will begin by determining the minimum thickness of slabs and webs that can provide adequate longitudinal strength and stiffness. This will be the starting point for the more detailed scientific investigations.

If we wish to use thin cross-section components, then we must adequately address the following issues:

1. Local behaviour of the deck slab under heavy wheel loads, including dynamic effects
2. Stability of thin sections
3. Because we will achieve thin cross-section components in part through the use of external, unbonded tendons, we must also address the effects of this type of prestressing on structural behaviour of very thin-walled sections
4. Robustness of the section, especially with regard to the handling and transportation of precast concrete segments with thin cross-section components
5. Details of prestressing anchors, which often control the thickness of cross-section components. Currently used technology was developed forty years ago to allow stressing at concrete compressive strengths two to three times less than strengths that can now be easily obtained in precast, high-performance concrete.

I have already secured a reasonable level of funding for this work, including an NSERC Discovery Grant ($22,000 per year for four years), and major funding from the Portland Cement Association through the Cement Association of Canada ($280,000 over four years). (The latter grant is in collaboration with colleague Professor Frank Vecchio.) The funding from the Cement Association is eligible for matching from NSERC at a ratio of one to one through their Collaborative Research and Development program. An application for this funding will be submitted in January 2004.

The application of these new ideas to real projects is an important component of the approach of the overall research program. We have an agreement in principle with the Ministry of Transportation of Ontario covering demonstration projects for the validation of these new technologies. The agreement is now undergoing final review by Ministry legal staff and we expect a signature early in 2004. This agreement will be of vital importance to the program, since it will allow us to "close the loop", ensuring an unbroken flow of knowledge from design, through research and application, and then back to design.

The testing and monitoring of the prototype bridges built as demonstration projects will be made possible with modern equipment that will be purchased through a recently obtained grand from the Canada Foundation for Innovation. (This grant was in collaboration with colleague Professor Constantin Christopoulos.) The total amount of this grand, including contributions from the Ontario Innovation Trust and industry partners, is $1,000,000.

3.3 *Future Prospects*

The project described above is intended to the the first of many projects, each focusing on a specific material or application. Additional projects that will be pursued include the development and validation of new structural systems using reactive powder concretes, advanced composite materials, and new steel/concrete composite systems.

Another long-term interest that I intend to pursue is related to applications of material technology, information technology, and modern surveying technology to improve geometrical tolerances in the manufacture of precast concrete components. In new bridge construction, we have come very close to the ideal of 100 percent prefabrication thanks to the segmental method of construction. In bridge rehabilitation, the advantages of prefabrication are evident: prefabrication allows bridge components to be replaced quickly, thus minimizing lane closures and significantly reducing traffic delays associated with major rehabilitations such as deck replacement projects.

One of the major impediments to the use of large prefabricated components on rehabilitation projects, however, is the challenge of connecting these components to each other and to this portions of the existing structure that remain in place. Until now, extensive cast-in-place concrete closure pours have been required to achieve these connections. These require time to cure and have lower intrinsic durability than factory produced precast concrete. The use of new materials, advanced survey techniques, and information technology holds promise to integrate new methods of connecting components, precise surveys of existing conditions, and modern manufacturing techniques, to ensure that prefabricated components can be made to measure and then installed with perfect fit. This will allow us to get much closer to the objective of one hundred percent prefabrication in bridge rehabilitation.