

## Bridge Engineering

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The scope of the Transportation Research Board's (TRB) Committee on General Structures includes factors affecting the physical behavior, service life, economy, appearance, and safety of bridges and structures for transportation systems, and accounting for these factors and their interactions in design procedures and criteria. During the 20th century the United States has essentially created the safest, most efficient, and most effective highway and intermodal transportation network in the world. The challenge for the new millennium will be to further enhance this transportation network. In this paper the status of bridge engineering at the end of the 20th century in the area of general transportation structures is summarized. The focus is on bridge structure types, design aspects, new materials, aesthetic concerns, and key policy issues. An attempt is made to forecast the status of bridge engineering 20 to 30 years into the next millennium; the paper is written as though these forecasts will become a reality.

### BRIDGE STRUCTURE TYPES

Structure types have been evolving throughout history. The evolution will continue into the future, perhaps at an accelerated rate.

The driving forces behind continued advances in bridge engineering are traffic congestion and costs. In the future, just as now, the public will expect few traffic delays, if any. They will want transportation costs to be as low as possible. Computer technology will enhance traffic management so well that the public will become accustomed to flowing traffic and more aware of congestion locations. Disruptions from construction will be more obvious and even less tolerated. Given these conditions, structural types will be selected primarily on the basis of speed of construction to minimize traffic delays. Low maintenance will be a must, and the ability to widen a structure easily and quickly will be a priority in selecting a structure type.

Safety and aesthetics will continue to play major roles in the selection of structure types. Keeping substructures out of the roadway clear zone will dictate longer span lengths and will keep the engineering community striving for optimal spans. Input from the public will grow to such a level that interactive design programs will become a necessity. Computer programs that automatically prepare detailed plans incorporating changes at the touch of a button will allow the public to modify or add aesthetic details right up to the point that construction begins.

### **Long Span**

Posttensioning with high-strength materials will allow traditional concrete and steel bridges, especially box shapes, to reach continually longer spans that challenge steel truss bridges and even the shorter-span cable-stayed bridges. Cable-stayed bridges and suspension bridges will most likely continue to dominate the long-span bridge category. Long-span bridges will continue to be the most dramatic, capturing the public's awareness with highly visible and innovative structures. Shown in Figure 1 are two impressive structures, the Sunshine Skyway Bridge and the Houston Ship Channel Bridge, which is the longest concrete box to date.

### **Medium Span**

Medium spans include spans from 50 to 200 feet and traditionally have been prestressed concrete girders and steel girders. In the future, new materials with high-performance characteristics will be developed, and the strengths of concrete and steel materials will be enhanced. Stronger materials and innovative design concepts will come together to yield much longer spans. The result will be simpler structures with fewer substructures and a reduction in overall cost. Space frame structures using steel and concrete in combination may enter this market because of ease of construction and relatively low cost. Preengineered, "out-of-the-box," prefabricated component bridges will also become more common and will begin to challenge individualized designs. Innovations will cause greater change to the medium-span range than to the other two ranges. An innovative steel bridge that clear-spans an entire freeway is shown in Figure 2. Bridges that clear-span roadways will become popular in the future.

### **Short Span**

Concrete slabs, timber slabs, prestressed concrete shapes, and rolled steel shapes currently share the market for spans up to 50 feet. In the future, these types will be challenged by long-span culverts and preengineered, out-of-the-box, prefabricated component bridges. Shown in Figure 3 is a typical long-span culvert (44-foot span) that is starting to challenge more typical short-span structures.

## **DESIGN**

Designing bridges according to a standard specification became the norm in the 20th century. This will continue in the next century. However, the process of designing will be much different in the future because of changes in specifications, loads, testing, and computerization.

### **Specifications**

The specifications used for structural bridge design at the end of the 20th century are split between the American Association of State Highway and Transportation Officials (AASHTO) load factor design (LFD) specification and the load and resistance factor design (LRFD) specification, with LRFD recently being designated as the standard for the future. LFD will continue to be used for some time, but its usage will decline as LRFD becomes more widely accepted. Eventually LFD will be discontinued and LRFD will be fully adopted, which will prove to be the right course of action. The AASHTO LRFD specification will continue to evolve with new research, new design ideas, and new

materials. The LRFD method will prove to be effective and will be easily adapted to all construction materials including steel, concrete, timber, and the new high-strength plastic polymers.

Acceptance of the LRFD method by the design community will not be easy because of concerns in two areas: substructure design and computer software. One goal in establishing the LRFD specification was to provide a more uniform level of reliability in every component of the structure, from substructure to superstructure. The design of substructures using the LRFD philosophy will remain in an immature state for several years because of a lack of accepted methods for analyzing and designing foundations. Only after more research and specification enhancement will the situation for substructures change. Widespread usage of LRFD will be somewhat slowed by the lack of computer software. The detailed nature of LRFD code requires that designers develop spreadsheets and other computer worksheets to complete computations efficiently. Introduction of programs such as the AASHTO OPIS computer program will help, but the full benefit of the new design code will not be realized for several years.

### **Loads**

At the heart of the load specification is the design vehicle. The old HS-20 truck, which has been in use since 1944, is being questioned as a vehicle relevant to traffic needs of the 21st century. Early in the century, two specific questions will arise over the continued use of this vehicle. The first question is whether a different vehicle would better match the weigh-in-motion (WIM) data coming from the monitoring systems installed in roadways. Though the data are of questionable accuracy, they indicate definite trends—that truck lengths, weights, and traffic counts have increased dramatically since the arrival of the HS-20 truck.

The second question is whether another vehicle would simplify computations. Various factors and loading conditions were applied to the HS-20 truck to make it fit the LRFD specification. In consideration of these two questions, a new “millennium truck” live-load configuration will be proposed. After extensive data collection, the testing and monitoring will begin.

### **Field Testing**

To help determine an appropriate design vehicle, a more comprehensive system of WIM sites will be installed. Because of advances in accuracy and durability of the equipment, dynamic load data will begin to agree with static load data. An accurate picture will then develop of actual truck axle loads and axle spacings on highway bridges. Emerging technologies such as quartz sensors and fiber-optic enhancements, along with piezo cable, will make more accurate data collection possible. Smart bridges will be the order of the new millennium because of a dramatic increase in the number of instrumented bridges. Actual stresses will be measured and tracked in much the same way as the National Weather Service tracks daily temperatures. The WIM information will be correlated with the information from the instrumented bridges. Analysis of the massive amounts of data will be possible through the use of high-capacity computers. The LRFD design load factors will be updated on the basis of the new data.

Steel structures will especially benefit from instrumentation and field testing. In response to fatigue and associated problems, steel bridges will be instrumented to determine failure mechanisms, especially crack initiation at low stress ranges with large numbers of

loading cycles. Emerging technologies will lead to the discovery of relationships that will bring about a refinement of design methods. Cost-effective retrofit applications for fatigue-prone details will lead to a change in bridge management planning for bridges with fatigue problems. As this knowledge increases, steel bridges will be replaced mostly for functional rather than for structural reasons.

### **Analysis**

Computer programs capable of analyzing large amounts of data will be developed. Key design parameters such as distribution factors, multiple presence factors, and uniform loads will be verified. Trends in loadings and the way structures respond to those loadings will be made easier to predict. This may lead to a simplification of design factors and equations, which will allow a drastic improvement in the speed of completing design computations. The design of bridges in the 21st century will be much easier and more accurate than at the end of the 20th century.

### **Design Tools**

More and more states will cooperate in the use of standardized details, computer programs, and drafting details, making designs and plans more similar on a regional basis. Such standardization will tend to reduce construction costs for contractors and suppliers. Speed and accuracy will be increased.

After many years of working separately, computer-aided engineering and computer-aided drafting will be successfully integrated. Designs and plans will be iterative and interactive, and plan preparation will be extremely cost-effective. Design engineers will be alerted by automatic specification checkers and code verifiers, enabling them to minimize design errors. More important, optimization of a design will be a keystroke away. Artificial intelligence will supplement institutional memories and expand designers' options for obtaining real-time expert advice. The need to develop expert systems to check the accuracy and reliability of design software will be a challenge to bridge design professionals. Of course, associated with this challenge is the ever-present debate on professional liability.

### **Automation**

The Internet and e-mail will be standards for communication between designers, fabricators, and contractors. It will become more common for designers and drafters in different states to combine efforts. Correspondence will be handled electronically, eliminating the time necessary to print and mail correspondence back and forth. Contractors and fabricators will view the final plans electronically.

### **Materials**

Materials have always played a key role in the evolution of bridge structures. Enhancements of the traditional materials of concrete, steel, and timber will continue, but the most revolutionary changes will occur in the areas of fiber-reinforced plastics (FRPs), high-strength and high-performance steel, high-performance concrete (HPC), and the blending of FRP and timber.

### *FRPs*

Today, FRPs are in their infancy as bridge construction materials. However, further experimentation with various combinations of FRP materials will result in innovative and long-lasting solutions to simple and complex bridge construction issues. Experimental FRP bridge projects have shown that this material has inherent problems in deflection, material ductility, creep, reactivity with concrete and steel, and performance under long-term exposure to ultraviolet light and other environmental factors such as moisture, freeze-thaw, humidity, and external chemical attack. To help resolve these issues, material testing standards and design methodology will be developed to fit FRP material properties. A comprehensive research effort at the national level will be undertaken to make FRP a dependable, low-maintenance bridge material capable of delivering high performance over the life of a bridge structure.

Collaboration of practicing designers, construction engineers, and bridge owners will make FRP a feasible and competitive alternative to conventional bridge construction materials. Universities will most likely expand their curricula to include FRP and other composite materials in their structural and material courses to prepare future bridge professionals to accept and fully utilize FRP.

### *High-Strength and High-Performance Steel*

Unlike FRP, high-strength steel materials will be more readily accepted by bridge engineers. Initial acceptance will be gained because the new steel materials make it possible to reduce structural dead loads. Wider acceptance of high-strength steels will develop because of their enhanced material properties. Gains made in improving material toughness and weldability of high-strength steels will extend to all grades of steel. Design specifications will continue to be updated to deal with material performance issues such as welding, toughness, fabrication, and constructibility. The high-performance steel materials of today will become the standard for future construction.

Advances in construction and experimentation with bridge types, such as space frames and innovative composite structures, will lead to further optimization of steel materials. FRP combined with high-strength steel has high potential for future bridge structures.

High-performance reinforcing bars will become common in the new millennium. Composite bars with a steel core and a cladding of stainless steel or other noncorroding material will gain wide acceptance for use in concrete structures. Coupled with the use of HPC in bridge decks, the average life of such structures may approach twice the life span of similar structures built previously. Future national policies requiring life-cycle cost analysis will provide a large incentive to further develop and implement the use of innovative materials in bridge decks.

### *HPC*

HPC is well on its way to becoming a conventional bridge construction material as a result of Strategic Highway Research Program research and Federal Highway Administration implementation efforts. The debate as to whether strength or permeability is the primary indicator of long-term durability of HPC will continue among practicing engineers. However, past case studies clearly demonstrate the need for permeability tests as an indicator of long-term concrete durability. The future is bright for HPC because it has good durability and strength characteristics, making it a versatile material. Currently, assessment

of long-term durability is an after-the-fact determination, resulting in quality control/quality assurance problems, which hamper the use of performance-based specifications. Scientists and engineers will eventually develop a device that instantaneously predicts the long-term durability properties of hardened concrete by testing the concrete in an unhardened state.

### *Timber*

New processes of reinforcing wood will continue to be developed, including the combination of glued-laminated timber and FRP composites. The concept is similar to that of reinforced concrete; wood resists the compression load, while FRP composite resists tensile load. The concept will be commonly used in future timber structures. Advantages of this technology are in areas where bending strength controls the design (as with lower grades of wood). Reinforcing with FRP greatly increases the tensile capacity of the beams, which will allow lower grades of wood to be used economically in many structures. The new composite material will also be used where minimum clearance is a problem.

Breakthroughs in the area of wood preservatives will continue. They will result in the development and refinement of new alternative treatment processes and procedures that will be environmentally sound with respect to application, use, and disposal of treated timber.

### *Other Materials*

A significant future challenge for the construction industry will be the incorporation of recycled materials (including plastics), by-products, and waste materials into conventional and HPC construction materials. Future environmental regulations and lack of space to store waste products will bring this issue to a head. Significant time and financial resources will be spent in developing recycled materials into products suitable for use as construction materials.

## **AESTHETIC CONCERNS**

### **Public Involvement**

Public participation in the design process has increased in recent years because the public wants better aesthetic treatment of bridges, especially bridges considered neighborhood landmarks. Public participation will continue in the future and will likely increase. To facilitate the process, engineers will display plans using three-dimensional visualization technology. The public will be able to view and comment on the plans at hearings or on the Internet.

### **Interactive Design**

Incorporating public comment into the plans will require that last-minute changes be easily accommodated into the design and drafting process. Computer design and drafting programs that automatically adjust the designs and generate plans will allow for quick modifications. The latest engineering analytical skills will be needed to accommodate this technology. The emphasis on flexible design will undoubtedly require engineers to increase their aesthetic design skills and overall people skills.

### **Aesthetic Process**

Aesthetic treatment of structures will become so common that only the most remote sites will be unaffected. Nearly all bridges will have a detailed aesthetic treatment, or at least an aesthetic review. Extra planning time and design time will become an accepted part of the cost of a structure. The level of public attention will determine the extent of the aesthetic design process and the resources devoted to aesthetic considerations. Three levels of bridge aesthetic consideration and processes will tend to emerge: the highest level for landmark bridges with major cultural or aesthetic significance, a middle level for transportation corridors and urban structures, and a lower level for replacement bridges in rural and industrial settings.

### **POLICY ISSUES**

Several issues of a political nature will need to be addressed by the engineering community during the next decade. They need to be studied and discussed so that a consensus among engineers is reached. Only in this way can the voice of our profession be heard by the public, who will ultimately decide policy.

### **Design-Build**

The design-build method for project delivery will increase. Design-build specifications will become a major factor in acceptance and overall performance of the design-build method. The specifications need to require the contractor to consider both the life-cycle costs and the initial construction costs in the selection of materials and structure type. When the engineering community and the legal community work together to accomplish this, the bridge owners will become more comfortable with the design-build method and will begin to use it even more frequently. Successful design-build projects with improved speed of construction and reduced construction problems will continue to make this project delivery option attractive to owners.

### **Life-Cycle Costs**

During the 20th century, computation of accurate life-cycle costs was difficult because of a limited amount of historical data. But in the 21st century, data collection and analysis will improve because of significant improvements in bridge management systems. The sharing of information among states will lead to a much larger database. Because of better data and better ways of handling data, life-cycle costs will be much more accurate. Life-cycle costs will become the basis for selecting structure types and aesthetic treatments.

### **Truck Size and Weight**

Whether to allow larger and heavier trucks onto the roadways is a political issue that the engineering community will take very seriously. To predict as accurately as possible the consequences of such an action, extensive studies will be done to determine the relationship between the rate of deterioration and increased loadings. The resulting damage evaluation surveys, coupled with data from bridge management systems, will become the basis of a national debate on the financial effects on the transportation infrastructure.

**Intermodal Design Specifications**

The increase in funding for mass transit and the resulting proposals for light rail transit systems will bring to light the need for uniformity between the AASHTO and American Railway Engineering Association (AREA) bridge design specifications. Variations between the two codes and the lack of a definitive code for light rail transit lead to a great deal of confusion. Deciding which code applies in which circumstance will cause delays and add to the cost of design. The engineering community will sponsor studies leading to a blending of specifications and a more uniform code for the design and construction of intermodal structures.

**Public Involvement**

The public's desire to be involved in design will remain strong, especially in the area of aesthetics. At times engineers will be criticized for catering too much to aesthetic interests at the expense of completing the projects on a timely basis and at normal costs. Of course, at times they will be criticized for restricting input and being insensitive to the need for aesthetically pleasing structures. Obviously, interdisciplinary teams will be developed to better facilitate the process and resolve the issues. The engineering community will learn how to better incorporate public involvement into the overall design process.

**CONCLUSIONS**

During the past 100 years, bridge engineers have participated in major projects that have significantly affected society. In 1900, people and freight were transported primarily by horseback and railroad. Today, the public travels by automobile and airline, and freight is carried by truck and railroad. These are sweeping changes in transportation, and bridge engineers have played a major role in them. Will the 21st century have equally great changes? Whatever the future holds, it will be an exciting and challenging time for engineers. How well structural engineers address the needs and issues discussed in this paper will determine to a great extent how much society will rely on our expertise. People demand and have a right to expect safe and cost-effective structures that meet their transportation needs.





**FIGURE 1** Sunshine Skyway Bridge (*top*) and Houston Ship Channel Bridge (*bottom*).



**FIGURE 2 Steel bridge clear-spanning an entire freeway.**



**FIGURE 3 Typical long-span culvert (44-foot span).**