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Steel Bridges

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New materials, new design concepts, and a better understanding of the trade-off between structural reliability and life-cycle costs make the next millennium an exciting time for steel technology. In evaluating the trade-off between structural reliability and life-cycle costs, engineers need to keep in mind the potential advantages steel structures can offer. These include but are not limited to the following:

- *Lighter weight* than concrete for superstructures of comparable spans, reducing foundation requirements and, more significantly, reducing the inertia effects induced by seismic events;
- *Reduced depth* of structure for comparable spans, thereby reducing the significant approach-roadway costs for the large number of overpasses used throughout the United States;
- *Ability to repair* the component to full strength whether the need for repair is generated by collision forces from over-height vehicles or environmental causes, such as the effect of roadway deicing chemicals; these repairs can generally be made without affecting traffic flow on or below the structure;
- *Corrosion-resistant* materials that lower first and life-cycle costs for virtually all bridge environments with proper detailing (*1*);
- *Flexibility* for complex geometries, including horizontally curved and skewed alignments, longer spans, odd span arrangements, and bifurcated structures; and
- *Ductility and toughness* of material to allow absorption of loading well above design values without catastrophic failures.

RESEARCH

As the new millennium approaches, development and implementation of new high-performance steel (HPS) currently dominate steel bridge research efforts. This technology will continue to reduce significantly the initial and life-cycle costs of steel bridges. Research centering on HPS falls into three categories: production of new steels, new design concepts for HPS, and traditional design with HPS.

Production of New Steels

HPS was first developed in 1994 with the beginning of a long-term research effort sponsored by the American Iron and Steel Institute, Federal Highway Administration, and the U.S. Navy. HPS is defined as a steel with significantly greater toughness than other existing grades and with slightly enhanced weathering characteristics (using ASTM G 101 procedures for determining such characteristics). In addition, certain fabrication processes are less restrictive because of some relief from current preheat and interpass temperature requirements. With significant input from the steel industry, academia, and bridge owners, HPS with 70- and 100-ksi yield strengths has already been developed, providing greatly enhanced toughness over the existing grades of these steels. Future efforts will result in new and higher HPS strength levels. More than 10 bridges (as of early 1999) have been constructed using ASTM A 709-97^{el} Grade HPS70W steel. Grade HPS100W steel has been developed, but additional research on welding issues must be completed to ensure safety and cost-effectiveness before implementation of this grade, which has more than three times the strength of the steel used at the beginning of the 20th century.

Both HPS70W and HPS100W grades are currently manufactured using a quenched and tempered (Q&T) heat treatment process. This process adds a significant premium to the unit price of the material and limits the maximum available plate lengths to 50 feet. To offset this, non-Q&T steels are under development for Grade HPS70W without lowered material requirements, which will allow even more cost-effective steel bridges to be designed. In addition, since many bridge components do not require strength levels of this magnitude, lower-strength HPS grades are being considered. HPS50W, the lowest strength one can economically obtain and still maintain the weathering characteristics, is being developed for use in areas where 70- and 100-ksi strength levels are not needed (e.g., hybrid girder webs). The use of HPS is resulting in cost reductions of 10 percent and greater, and this is just the beginning.

New Design Concepts for HPS

In order to make effective use of HPS, especially the higher-strength grades that may be available in the near future, some changes to the standard I and box cross sections need to be considered. Some potential concepts for the application of HPS are shown in Figure 1. The corrugated web has already received some application in Europe and Japan, and at least one bridge utilizing a corrugated web is to be built in the United States in the near future. There are at least two examples of tubular flange bridges in Europe, and this design is also under active consideration in the United States. This concept could be used with either flat or corrugated webs and with or without either internal or external prestressing strands. A proof-of-concept test for a double sheet steel web has indicated that this concept has the potential to greatly reduce the weight of web plates and eliminate stiffeners. However, adequate core materials and welding processes to connect thin steel sheets to flanges are necessary to bring this concept into the marketplace.

Combining these steels with high-performance concrete (HPC) substructures and HPC or fiber-reinforced polymer (FRP) decks will provide, for the first time, high-performance bridges rather than high-performance steel bridges. The new bridges will take full advantage of the inherent benefits of each of these construction materials.

Traditional Design with HPS

The introduction of HPS for bridge applications has raised several issues with regard to traditional bridge design.

Load and resistance factor design (LRFD) specifications allow the flexural resistance of I-shaped girders of 36- and 50-ksi yield strengths to exceed the yield moment M_y using the Q-formula, with a maximum resistance equal to the plastic-moment resistance M_p. Recently completed research suggests that the current limitations of M_y in the LRFD specifications application of the Q-formula to 70- and 100-ksi steels can be relaxed.

There is the potential for eliminating or softening fracture critical requirements when these steels are used, which may in turn increase the viability of single boxes, two-girder bridges, and other economical structures. These structures are often discounted on the basis of code requirements, concerns over redundancy, and other factors.

In addition to materials, long-overdue research is under way to develop integral connections between steel superstructures and concrete substructures in emulation of successful concrete bridge designs. Though these connections have been used several times in the past, rarely, if ever, were they evaluated for the potential loads from seismic events and other lateral loads, such as ship impact, not to mention resistance to vertical loads through frame action. The idea is that more economical designs can be utilized to reduce the mass that would normally be associated with a drop or hammer-head bent cap.

Another category of ongoing research involves trying to better understand steel superstructures, in particular the fundamental behavior of horizontally curved I-girder superstructures. An exciting analytical and experimental research project is under way to better understand the effect of curvature not only on the design and analysis of steel I-girder bridges, but also on the construction of these bridges.

FABRICATION

The team of researchers working on the new steels has developed the American Association for State Highway and Transportation Officials (AASHTO) *Guide for Highway Bridge Fabrication with HPS70W Steel*. This guide supplements the AWS D1.5 Bridge Welding Code and includes specific guidance and requirements for fabrication of HPS70W steel to ensure cost-effective, safe, and reliable structures.

The fabrication shop has changed significantly over the last 100 years. More and more automation is utilized in the fabrication of welded steel bridge members. The most advanced shops are becoming more computer based, from computer-drafted shop drawings through computer-aided fabrication, all from one set of data and in three dimensions. The latest development is the use of lasers for measurement and alignment. Instead of preassembly of spans to ensure proper fit, computer simulations of the fit based on actual measurements of individual components will produce a satisfactory product for increasingly complicated shapes. Ultrasonic peening for weld fatigue-resistance enhancement, a technology imported from the former Soviet Union, shows promise for retrofitting as well as for enhancing the fatigue resistance of unavoidable low-fatigue-resistant details on new bridges.

Robotics already plays an important part in steel fabrication and will continue to develop.

DESIGN PHILOSOPHY

Behavior and Economy

An efficient bridge design balances the two fundamental rules of structural behavior and economy.

At the close of the second millennium, bridge engineers have at their disposal the tools to thoroughly understand the distribution of loads and corresponding structural responses in three-dimensional space. Simple three-dimensional models of steel structures or steel composite structures can be developed by experienced engineers to reflect the basic load paths and responses of relatively complex structures.

Steel bridge concepts should maximize structural efficiency by reducing the amount of material and the number of components without compromising safety, serviceability, or constructibility of the structure. Simplicity and ease of fabrication and erection are still paramount to cost-effective steel structure design.

One of the benefits of a properly conceived and executed bridge design is aesthetics. When structures have a clearly defined load path and members are correctly proportioned, they will be both cost-effective and aesthetically pleasing.

Flexibility and Constructibility

Industrialization of steel bridges can take different forms. The advent of digitally controlled cutting, welding, bolting, and forming technology, for example, will radically redefine the scope for steel bridges. Robotics has added another dimension to the production of steel members by providing the potential for expedited production without sacrificing quality control.

Designers are taking advantage of a more integrated approach to design and construction through the concept of design-build. This concept will become more prevalent in the next century. The configuration of the bridge should always be developed to optimize the construction methodology, which is a primary component of the cost. This further emphasizes the need for designers to look at both the superstructure and substructure in their optimization process.

Composite steel bridges lend themselves to a wide variety of structural forms and construction methods, which can be customized to meet the specific needs of clients and site conditions.

The steel industry has a vision for expanding the scope of the current specifications for composite structures beyond simple I-girder and box-girder bridges to include a variety of steel bridge configurations, to encourage the use of other forms where feasible, and to provide the necessary guidance to designers.

Examples of such structures, including unique shapes and methods of fabrication, are as follows:

- Single-rib arches;
- Laterally unsupported arches;
- Tubular and corrugated sections;
- Hot induction bending;
- Long-span, single-cell steel boxes;
- Segmental and composite trusses;

- Composite through-box girder bridges; and
- Full-depth precast composite deck panels.

The profession must challenge traditional design practices and restrictions placed on design, but that challenge should be based on the proper respect for past failures, successful practice, data and facts, and the incorporation of research results.

Durability and Adaptability

Steel bridges can be designed to complement many other materials, notably HPC and advanced composite materials, and to provide structures with enhanced durability, extended life span, and reduced life-cycle costs.

Many steel structures in service today were designed and constructed over a century ago and are still safe and serviceable. Steel bridges that can be designed as a basic load-carrying frame with replaceable components, such as a deck or a wearing surface to absorb the wear and tear of daily use and deleterious environmental effects, can essentially remain in service indefinitely with proper maintenance.

Life-cycle cost analysis is essential to the responsible management of funds used for public transportation infrastructure. High initial cost is still used as an argument to discriminate against more imaginative bridge designs in favor of the least-cost solution. The result has been a preponderance of bridges that are utilitarian in appearance and that may have earned the bridge engineering community a reputation for limited creativity.

Bridge engineers need to reconsider their perceptions of the least-cost solution. Utilization of labor and material resources and life-cycle cost analysis have an impact on the least-cost solution. The prospect of increasing unemployment in the industrialized countries may soon shift the current balance between costly labor and less costly resources, especially as nonrenewable resources are consumed and become more expensive.

In addition to providing durability, steel bridges are also adaptable in that they can be designed to act compositely with many complementary materials, including HPC, advanced composite materials, and other metals and high-tech coatings for additional durability, increasing the efficiency of all materials, and improving aesthetics. The use of these materials can be focused on the specific component needs and function of the structural system.

As some of these principles are carried forward, the goal must be the continued evolution of cost-effective designs that reflect the response of the structure to a life-cycle environment and result in structures that are safe, buildable, maintainable, serviceable, inspectable, and decommissionable. Engineers must start to plan ahead for maintenance, expansion, and decommissioning. Steel is rapidly becoming a completely recyclable product, which benefits the environment when decommissioning must take place.

CHALLENGES

Very often steel structures are not selected in the type selection phase because of the concern over life-cycle costs. However, many people fail to keep in mind that the goal of design and management of highway bridges is to determine and implement the best possible strategy that ensures an adequate level of reliability at the lowest possible life-cycle cost. Unfortunately, the integration of life-cycle cost analysis with structural reliability analysis has been limited. Currently, there is no accepted methodology or criteria for life-cycle cost design and reliability analysis of bridges. Issues such as target reliability level, whole-life performance assessment, and optimum inspection-repair-replacement strategies should be analyzed and resolved on the basis of life-cycle cost. In addition, there is no adequate information on the maintenance costs of "modern" steel bridges.

The recent NCHRP Report 406 introduced "system factors that can be used to assess the member capacities of a bridge system as a function of its level of redundancy." However, further effort is needed to calibrate and refine these factors. With time, improved quantification of bridge system reliability and redundancy is expected. This will result in a better evaluation and design of highway bridges by capturing the system behavior effects, which will in turn allow a better and fairer evaluation of life-cycle costs associated with a desired level of structural reliability.

Long-span bridges represent a very exciting and evolving product. Though there is not as much demand for these structures, these are often the bridges that capture both the engineer's and the public's imagination. As we move into the 21st century, we have seen the Warren truss, designed without verticals to give a cleaner open look, and there is continued interest in the different varieties of arch bridges, such as tied and multi- and continuous arches. Even in the more common plate-girder and box-girder bridge designs, we are seeing economical designs at spans up to 650 feet. Box girders in particular have become very popular, and are used as efficient and aesthetic solutions for curved ramps in certain regions of the country. As this century closes, we see a few modern cable-supported bridges either under design or in construction. The key to the efficient cable-stayed and modern suspension bridge is the utilization of hybrid designs consisting of steel and concrete. The economics of the situation seem to indicate that in the United States, the hybrid bridge is one of the most economically advantageous ways to use steel in the large-span bridge market in the future.

CONCLUSIONS

Bridges are the monuments of our profession. Bridges generally outlive their designers and provide a visual testimonial to the skill and ingenuity of their engineers and builders.

Several areas of endeavor are identified in this paper in which the efforts of the bridge engineering community will continue to be focused in order to optimize the design and delivery of steel bridges and to ensure a growing share of the bridge market. These areas include, but are not limited to, the following:

- Continued development of HPS;
- Advancement of technology for fabrication, forming, and welding for speed, economy, and quality of bridge systems and bridge components;
- Expanded scope of research and development to capitalize on current technology for analysis and design and to provide an incentive for creativity and the evolution of new bridge forms;
- Encouragement of designers through the continuing development of more rational design specifications and analysis tools;
- Development of complementary high-performance materials in conjunction with new forms of composite steel bridges to enhance the efficiency of all materials; and
- Integrated design and delivery during design and concept development of steel bridges.

Steel structures are poised for a dramatic resurgence, given the opportunities available with recent research and the development of HPS for innovative, cost-effective, and pleasing steel structures. It will not be long before much of today's bridge infrastructure will have to be replaced, and properly designed steel, concrete, or other bridges will all have their place. Finally, composite applications or hybrid structures will continue to evolve, and may in turn redefine the typical steel bridges that are designed in the next century.

ACKNOWLEDGMENT

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REFERENCE

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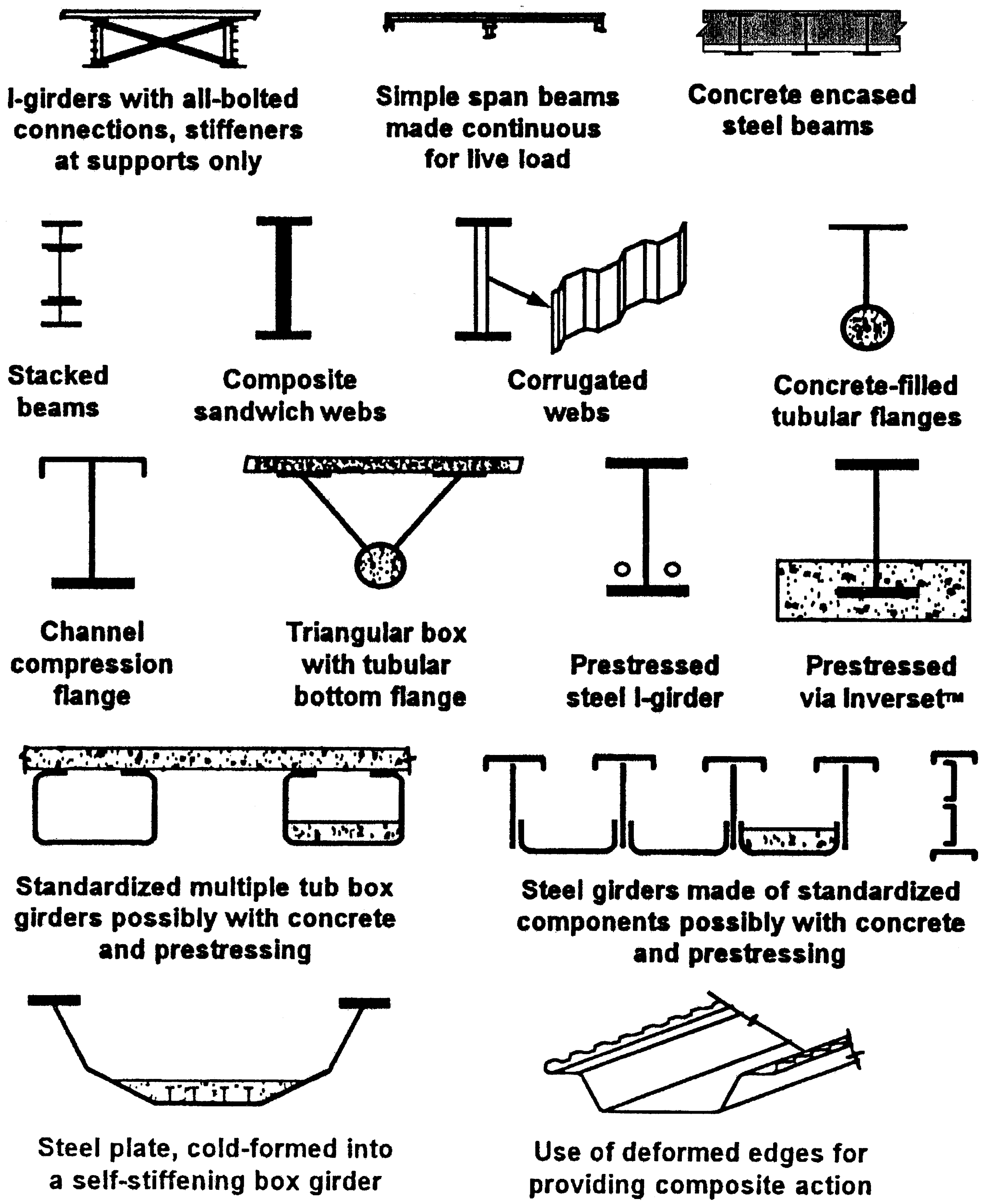

FIGURE 1 Possible concepts for use of HPS.