Design, Manufacture, Transportation, and Erection of Systems Bridges

summary

Thomas A. Hanson

DESIGN

In addition to utility, safety, and appearance, systems bridges must incorporate standardization of details and sections. Thus the economies of repetitive forms, jigs, tooling, and design can be achieved. Timber railroad bridges, for example, have been standardized with 16-ft spans.

There is some question regarding the permanence of present design standards. There is a tendency toward larger trucks and smaller automobiles. If European trends are adopted here, the use of bicycles will grow. Two paths are open to us: We can assume that present regulations are permanent and perhaps design structures for particular uses, or we can design structures with flexibility of usage such as converting three 12-ft lanes to six 6-ft lanes.

An attempt should be made to stabilize design concepts. In-depth studies should yield the best solutions, and then designers should use these solutions. For example, the concepts of continuity and reduction in the number of expansion joints could be studied in this way.

The relative merits of American versus European systems should be examined. Legal, political, and practical problems may exist, but trials may be instructive. The European system is generally as follows:

1. An engineer establishes design parameters and sometimes prepares designs;
2. His specification allows submission of alternate designs;
3. The specification also points out that the lowest cost solution may not be selected, but, on occasion, 4 or 5 qualified bidders are selected, and the decision is based on cost alone;
4. A jury is selected to judge the entries;
5. The engineer checks submissions to see that design parameters and specifications are met (if the engineer requires more steel, for example, this must be paid for by the contractor out of pocket); and

6. The owner requires the contractor to carry insurance, and the insurance company's engineers check the design (the policy rates will vary according to the risks involved with the particular design).

Work is needed on load factors. For instance, concrete suffers from a 1.5 factor on dead load. If a concrete bridge is designed for a 1.5 dead load factor and the actual dead load is 1.0, the resulting live load factor would be 10 or more.

To stimulate innovation requires that there be an incentive of future jobs to amortize the investment in special equipment. This can be accomplished by market aggregation, such as awarding 50 or 100 bridges at a time. The Munich-based firm of Dyckerhoff and Widmann utilized market aggregation when it built 800 railroad bridges during a 7-year period. Some ideas relating to bridge design philosophy may be garnered from other industries. The Steel Joist Institute, for example, has set out a range of joist designations, each having certain moment and shear ratings. The manufacturers, then, prepare unique designs that meet the established ratings. The designs are approved in advance by the Institute so that further approvals are not needed for each project. In a similar manner, prior approval could be given to designs prepared by any industry. These designs could then be bid as alternates in competition with the base bid. This method encourages innovation by each industry, whereas the establishment of so-called "standard" designs could stifle future developments and improvements.

MANUFACTURING

Some of the major advantages of systems bridges will appear in the manufacturing phase. Tooling, materials, labor, special equipment, and handling of products and assemblies all provide opportunities for cost-saving innovations. Some of these are as follows:

1. Substructure—With precast, prestressed piles, the pay item increments in most specifications require too many stock lengths. Larger increments should be used. Pressure treating of wood piles is no limitation, but lengths should be kept under 100 ft. At the top of steel piles the need for a bearing plate is questioned.
2. Pier Caps—Prefabricated pier caps should be designed for the moments that occur during handling, not just for the in-place condition. If the member weight is excessive, segmental construction should be considered. Consideration should be given to permanent steel forms, filled with concrete. The cap and pier could be one piece. Laminated construction should be used for large wood piers.
3. Bearings—Elastomeric bearing pads are suggested for steel, concrete, or timber bridges. Selective inspection of bearing pads should be adopted, rather than complete inspection of all pads, which is time-consuming and expensive.
4. Girders—With precast, prestressed girders, spaced box beams should be considered, formed shear keys for composite construction should be eliminated, diaphragms in box and I-beams should be omitted, ½-in. diameter 270-k strand should be used, and bond should be broken at the ends to reduce cracks. With timber girders, laminations should be used for longer beams in lieu of sawed timber, and wood beams with a composite concrete deck should be tried. On steel bridges, weathering steel or aluminum should be used in lieu of painting. Only critical welds should be tested, and secondary welds should be spot-checked. In all materials, short spans should be standardized to permit stockpiling of members.
5. Deck—Transverse segmental slabs may be used, monolithic with the guardrails. Conversely, longitudinal precast slabs more easily allow the development of composite action.
6. Expansion Joints—Sliding plates and finger plates are time-consuming and hard to make. Mechanical attached joints such as Transflex or extruded joints are recommended.
7. Drains—If drains are located along the center of the bridge, half as many can be used.
8. Automation—The ultimate development of systems bridges must involve labor-saving and time-saving devices. Plants are already in operation that are controlled by

a man seated at a single console and assisted by computers. Improved efficiency of materials, equipment, and labor has made it possible for some plants to produce, for example, precast concrete products on a 12-hour cycle rather than a 24-hour cycle.

TRANSPORTATION

The advantages of factory production are offset somewhat by the need to transport large and heavy units. However, it is not unusual to see huge laminated wood arches being shipped from one coast to the other. The modes of transportation considered include truck, rail, truck on rail (piggyback), barge, and helicopter. With minor modifications, existing methods of transporting are adequate.

Road regulations are generally not a limitation for systems bridges. We should strive for uniformity among the various states because many shipments cross state lines.

When designing a bridge structure, the designer should consider the transportation limitations. If necessary, long or heavy members can be produced in segments to be joined at the site.

FIELD WORK

On urban bridges, where traffic interruptions are difficult and hazardous, the erection of systems bridges must proceed quickly. Field work must be kept to a minimum. Ways to accomplish this include the following: Use the largest pieces that can conveniently be shipped and erected; put as many operations as possible in the shop; consider precast footings; eliminate test piles, use piles that can be easily spliced, and drive until needed capacity is reached; consider pier shafts that are an extension of the piles; prefabricate pier shafts and caps; prefabricate medians and parapet walls; award contracts with performance specifications (including time); conduct contests with awards for optimum designs; consider design-and-build contracts; have regular conferences among designers and contractors to exchange ideas; and provide contractor with bonus for early finish.

design

Arthur L. Elliott

We took for granted the usual basic tenets of good design philosophy: that any design should perform with good utility; that it should provide the greatest possible safety; and that it should present a good appearance. Our main purpose was to find design applications that would minimize field work (because labor costs in the field are higher than those in the shop) and traffic disruption during construction. We wanted to find ways to fabricate more of the bridge under shop conditions, to bring it to the job in larger pieces, and to put it together in the field in less time.

The first thought that occurs to everyone is, To what extent can we standardize our units? The term "standardization" does not mean the same thing to all people. We concluded that we did not mean "standard" bridges—carbon copies turned out like lead soldiers from a mold. Neither for the most part did we mean standard stock girders as on-the-shelf items. Although in some special cases the stocking of girders is possible, it does not really fulfill the intended purpose.

We did mean, however, the sort of standardization that permits many duplications. Multiple uses of forms and jigs are the factors that make a repeating process economical. Details also can be made similar. Expansion joints, bearings, drains, railings, beam sizes, and column shapes and diameters—those are the things, used and reused, that permit a contractor or a fabricating plant to work economically. Yet, these items may be frequently duplicated without stereotyping the structures or creating a monotony of design.

Although we recognized the undesirability of extreme standardization of span and member, we remembered that the timber industry actually did standardize in this manner for trestle bridges. Railroads were standardized on 16-ft spans and highways on 19-ft spans. For these, standard lengths of timbers were available.

Moreover, we were not certain that current lane or shoulder widths will remain the standard. What would happen if many very small cars were developed and used? Is it possible that the ecology enthusiasm will result in greater bicycle use and a demand for bicycle lanes on structures and along freeways? These foretell very possible changes, but such changes come slowly. The standards we now have will remain with us long enough for fabricators and contractors to recover their tooling costs. Therefore, we regarded the geometrics as relatively permanent.

Load factor design is generally regarded as a more accurate method of assigning loads to a structure. However, concern was expressed that the design methods are becoming so exact that we are not leaving any reserve strength in structures. We also recognized that, if all structures were designed by the same load factor relationship, the concrete structures on a route would generally have greater reserve strength than the steel ones. The load factor approach has more effect on the longer spans. It seems wise to include some allowance for reserve strength, higher loadings on highways in the future, or multiple overloads even though to some extent these allowances negate the advantage of the load factor approach.

The American contractual system was examined in contrast with the European system where design and construction are often combined. This combination enables the designer to utilize the best capabilities of the contractor, and in turn the contractor can see that the design fits his best abilities. We agreed that there would have to be rather extensive changes in the American system of administration before a complete design-and-build philosophy could be adopted.

The European system embodies several refinements that we do not yet have. The codes and specifications must be very specific so that the designs are acceptable and comparable. The system uses referee consultants with broad powers to control the work and insurance or guarantee of the work during a period of years or either of these. As a result, the European contractor's overhead runs about 6 to 8 percent. In contrast, an American contractor may operate on about 2 percent overhead.

Some steps in the design-and-build direction are being made in this country, and we felt it might be very instructive if a few contracts of this sort were arranged on an experimental basis. The problem of selecting the winning bidder is a tough one. European contractors are not always happy with their selection process. The American requirement that the work go to the low bidder does much to eliminate conflict, argument, and pressure.

Value engineering or cost incentives are being used to try to realize some of the benefits of contractor participation in the design process. This has not been overwhelmingly successful. Contractors do not usually have time within the contract limits to go through the procedures of redesigning and securing approval. Consulting engineers make their money by getting the job done in the minimum time and do not like to take time to develop a number of innovations or to explore a variety of novel ideas.

The possibility of allowing alternate designs apparently has pitfalls too. After one designer has turned out a design, another designer can take the plans and almost certainly develop savings through skimping here and there. Thus, they are really not competing on an equal basis, and it is doubtful whether the designs are entirely equal in capabilities.

Any system has its shortcomings, and any system in wide use must have benefits that people consider worthwhile. It is beneficial, therefore, to continue to try to adapt the best parts of the various systems to achieve greater perfection.

There is an evident need, in our system, to stimulate innovation. A contractor must have some assurance of future use so that he can amortize his investment in a new idea or expensive adjustable forms. The designer's and the owner's philosophies must be progressive. Ways must be found to reward innovation or else it will never appear. Many old practices are becoming obsolete, and we must seek to change them for the better.

manufacturing

Jacob O. Whitlock

Because the soil-supported spread footing and drilled caissons were not in our general domain, loads to soils were considered with piles only. In general the piling types in common use do not present a problem in either manufacture or supply. There are, however, some revisions in specifications and design policy that would contribute to an overall economy and saving of time. Among these are pay increments in 5 ft on concrete piling to minimize inventory and ensure continuous driving from test pile to specified length placement, elimination of capping plates on steel H-piles where a concrete distributor cap is used, and awareness of maximum lengths of timber piles available in a given area to preclude delivery delays.

Completion of the substructure by use of a distribution cap to provide the superstructure bearing surface was considered in 3 materials. Concrete can be precast in the plant in basically any configuration and fastened to the piles or pier stems by grouting or post-tensioning. The main concern is to keep the size of the piece within highway transportation limitations. Timber caps in long lengths and large cross-sectional sizes should be specified to be laminated rather than to be sawed from a single piece. Single stem piers with hammerhead caps might well be fabricated of steel-skin plate properly reinforced internally and filled with concrete after erection. The fabricated steel serves as a stay-in-place form.

We agreed that bearings should be elastomeric in every condition where they can be utilized. No one likes the effort required to fabricate for or design around rollers, rockers, sliding plates, or other combinations of a similar nature. The forgiving nature of elastomeric bearings under conditions of workmanship or load conditions beyond the original intended limits of the design can be a most worthwhile asset.

The prestressed concrete box beam placed in intimate contact across the roadway and, thus, providing an immediate structural deck is the greatest single time-saver. The box-beam deck can be used immediately to carry traffic even though a mat is placed at a future date.

Timber girders in the longer spans can best be supplied as laminated in lieu of sawed timber. Decking of laminated panels covered with an asphalt wearing surface has proved itself a time-saver on many jobs.

Two avenues seeming to hold the most promise in utilization of construction on bridges with steel girders are the use of weathering steel and revisionary testing procedures for welding. The problem in weld-testing procedures seems to be the failure of some highway agencies to recognize that all welds are not of equal importance, and 100 percent perfection is not necessary throughout the girder. General acceptance of modular span lengths in maximum increments of length would be most beneficial in all materials.

The deck in most bridge construction is one of the largest consumers of construction time, and most of this time is expended in forming and placing reinforcing steel. A most logical approach then to the concrete deck is the use of stay-in-place concrete forms. An additional benefit can be derived by using prestressed concrete plank forms that not only provide the forming surface but also replace a portion of the positive moment steel. The precast, prestressed segmental deck for use on steel beams is rapidly coming to be recognized as a construction time-saver. Segments consist of a prestressed slab 6 in. thick and 8 ft wide with a curb parapet cast on each end. The length of the slab then becomes the out-to-out dimension of the roadway. Slabs are set on the girders with their long axis at right angles to the girder lines and fastened to the girders with bolted flange clips. The slabs then are post-tensioned parallel to the centerline of the roadway through preformed holes in the slabs. Closure at expansion joints and abutments is cast in place and encloses the post-tensioned fittings. This procedure provides the structural deck, wearing surface, and parapet or curb in one operation.

The wearing surface should be considered as an expendable item and isolated from the structural integrity of the deck. Field construction time is an inverse function of the degree of prefabrication in the structure, but all the basic materials manufacturers agree that the cosmetic touch necessary for good ridability is difficult to obtain in total prefabrication.

Expansion joints of the sliding, finger, or open types are difficult to fabricate and install and are a never-ending source of trouble. Plant-manufacturing and field-fitting problems are minimized when a compression or mechanical rubber joint is utilized.

Conservation of field construction time is within the immediate horizons of present knowledge and techniques. Maximum cooperation among all facets of the industry, wherein the state of the art is allowed to function and express itself without the encumbrance of obsolete specifications, is an important parameter.

transportation

James C. Holesapple

Transportation modes for use in systems bridge construction include truck, rail, truck-rail combination, barge, and helicopter. We agreed that in most cases truck or a truck-rail combination would be used, that is, short hauls by truck and long hauls by a truck-rail combination. Helicopters are useful only as erection equipment because of the danger in transporting over occupied areas. We generally agreed that, with minor modifications existing, transportation equipment is adequate and there is no pressing need for new or special equipment.

The present limitations placed by regulatory agencies on length, width, height, and weight of transportation equipment and load do not make it impossible to design and transport a systems bridge. Limitations in Virginia are as follows:

Roadway	Overall Length (ft)
2-lane	90
4-lane, undivided	100
4-lane, divided	110

In addition, the overall length can be increased to 125 ft when the over-the-road haul is 25 miles or less. These limitations are similar to those of most other agencies. The maximum weight in Virginia is 115,000 lb, and the width is limited to 10 ft. Some group should be established to work with and through AASHO to secure more uniformity among various regulatory agencies especially where shipments pass through the jurisdictions of more than one agency. Also this or some other group should determine what length, width, and tonnage will satisfy most of the present and future needs. In general, the length and weight limits are at or near the safe maximum limits that will not cause undue harm to existing roadways and structures.

The systems bridge criteria considered were length of 100 to 110 ft, width of 6 to 8 ft, and depth of 8 to 10 ft. A 2-lane structure having 2 girder members and a field insert between the girders could be erected in a minimum time. By addition of standard systems components, the structure could be expanded to any width required. A systems girder longer than 110 ft may have some limited usage in urban areas, but the transportation problems created by physical limitations imposed by existing structure would outweigh its usefulness. This type of structure would be keyed, bolted, or welded with a minimum of field labor. With large components and a full-length longitudinal splice, precise shop quality control is very necessary. To compensate for any misalignment between adjacent components requires that the surface be field-coated with a wearing surface.

Under previously mentioned limitations, systems structures of steel, concrete, wood, or aluminum could be constructed to support present highway loading. The systems bridge should be designed to support the AASHO HS20 loading with military modifications, complying with the Interstate System standards. Prime considerations in design should be usage, initial construction cost, time of construction, aesthetics, and maintenance cost. Any design adopted should accommodate grade-level, elevated, and depressed roadways; the most probable usage would be over depressed roadways.

There must be coordination among those responsible for transportation and for cover design, shop quality control, and erection because these latter areas dictate the size and shape of the pieces for shipment. Who is responsible for the shipping of the structure? The responsibility for fabricating an item for shipment is at present that of the fabricator and should remain so because he alone knows the route, equipment, and final requirement. The designer must also consider the limitation placed on transporting the structure by both legal and physical conditions. At the present time there are some older structures in the existing system that will place weight limits on the size of any component that may be transported, and this problem will exist for several years because the existing system was designed by using several criteria.

We do not think a systems approach to bridge design will create any major problems in transportation even with existing equipment and over existing structures.

erection

H. B. Elsasser

The subject of erection has the most direct and obvious application to the purpose of the workshop and that was to develop means for reducing the on-site construction time for short-span highway bridges in urban areas. The speed of performing on-site construction work will be increased by achieving duplication in the various parts, by minimizing the requirements for on-site labor, by using construction techniques that are relatively independent of weather conditions, and by developing connections that provide adequate adjustment to accommodate normal tolerances.

The primary advantage of having duplication in parts is to justify the development and use of mechanized production techniques and to enable the repeated use of temporary devices such as forms. These developments should also reduce the unit cost of the various components. Up to some point, the gains are proportional to the quantity. However, beyond some minimum quantity at which the optimum technical methods are used, there will be no further benefit. This minimum quantity will vary with the component being considered. For some items the quantity on one project may be sufficient; for other items it may be necessary to have duplication covering many projects. This may require standardization throughout a state or region in order to obtain quantities sufficient to justify the establishment of industrialized manufacturing techniques and the maintenance of an inventory of component parts. Even with standardization throughout a state, the quantity necessary to justify industrialized manufacture might constitute the total number of items used in a complete year or more. Therefore, it would be necessary for the manufacturer to produce the total supply for one year and to carry these items in inventory until they were sold.

In regard to duplication, the most important, but not the only, factor is size. Duplication requires that the dimensions of various parts be either identical or modular so that finished components of different size can be readily manufactured or assembled by using different numbers of identical parts or forms. The dimensions chosen should take into account the standard dimensions of materials normally used in manufacture. For example, cast-in-place concrete should be dimensioned in some integer multiple or fraction of the 4-ft by 8-ft plywood sheet, which is normally used to make forms.

For any items that are to be manufactured and stored in advance of and in anticipation of an order, duplication also requires that the material type, strength, and finish be identical. This may require some apparent structural inefficiency in order to obtain the economic advantage of duplication. For example, it may become desirable to specify a single size of bridge bearing throughout a project; that size would be determined by the most severe loading condition and would be more than that required structurally for all other locations. For other items, such as cast-in-place concrete, the variation in material type or strength may not be a deterrent to rapid on-site work.

An additional incidental benefit of this dimensional modularity or duplication will be to increase the efficiency of both the shop and site workmen by reducing the amount of training and skill required. Learning curves will be steeper, and normal production should be faster. New personnel will not have to learn as many variations; experienced production personnel will not have to be as alert to detect variations. Presumably, the multitude of small variations that currently exist will be eliminated.

On-site labor requirements can be minimized, obviously, by transferring as many operations as possible into the manufacturing plant. This can be accomplished by designing and allowing for the maximum use of precast and prefabricated components made in the manufacturer's plant either in the largest pieces that can be shipped and handled or in modular pieces that increase duplication. This maximum prefabrication is already being done normally in the case of structural steel and precast concrete. The problem is to increase the use and application of these materials in place of monolithic construction requiring a high input of on-site labor. In addition, many operations that are normally performed at the construction site could be performed in the manufacturing plant. For example, in multiple-coat painting systems, all coats except the last could be shop-applied instead of simply the first (primer) coat as is now done. The shop paints should be chosen so that coats can be applied every 16 to 24 hours under shop conditions in order not to inhibit excessively the flow of material through the shop. Significant touch-up of the shop-applied coats might still be necessary at the site, but the total time and labor required would be less than that now required for an application of complete intermediate coats. The final coat may still be applied at the site with the structure in place in order to achieve a uniform appearance in the finished structure. Undoubtedly, there are many other construction operations that could be performed prior to delivery.

The transfer of work to the manufacturing plant from the construction site should yield other additional benefits. The quality of materials and workmanship should improve because of the superior working conditions and controls available in the shelter and permanent installation of the plant. The superior working conditions for labor should help to stabilize the working force and attract more capable personnel.

In many places, the occurrence of adverse weather is responsible for major prolongations in the construction time. The complete sheltering or enclosure of even small bridge sites will be practical only under extreme conditions. Short of this, there is probably no way to prevent the interruption of work during periods of actual precipitation. However, it is practical to develop and use construction techniques that do not require optimum weather conditions so that work can continue during marginal weather such as damp, foggy, cold, hot, or windy conditions. In short, the materials and techniques should not require any better weather conditions than the personnel so that the work can be performed whenever the personnel are willing. The maximum use of prefabrication will facilitate this goal. In addition, it is necessary to design on-site connections between prefabricated units, connections that can be properly made in a wide range of weather conditions with the level of skill and equipment normally available at the site. The need for highly trained experts or highly specialized equipment, which may not be readily available to meet the construction schedule, is not desirable. For these reasons, bolting is preferred to welding or cast-in-place materials for on-site connections.

Another major requirement for rapid erection is the ability to accommodate variations from the detailed dimensions of both the shop and the field construction. On-site connections must provide adequate adjustment without sacrificing structural integrity. The economy of systems building will be lost if an excessive accuracy is required in prefabricated components in order to obtain proper on-site assembly. Tolerances must be allowed that are obtainable by using regular and economical manufacturing methods. In some cases, it may be less expensive totally to use a relatively small amount of relatively expensive cast-in-place material at a joint rather than to require the greater accuracy necessary to allow the use of a prefabricated joint. The small areas and volumes involved in joints could be formed with relative ease.

The susceptibility of the various parts of bridges to significant improvement in on-site construction time varies widely in approximate proportion to the irregularity and requirement for on-site labor involved in present practice. Those parts that are already highly prefabricated will show the least improvement. Other parts that are least susceptible to prefabrication will also show only a slight improvement. Significant increase in speed can only be achieved for those items that can be made modular and prefabricated but that are not under present practice.

Spread footings could be precast to modular dimension but would present some difficulties. The variety of soil conditions will require modular components that can be connected into assemblies of various sizes and strength. Provision will have to be incorporated for adjustment to achieve correct alignment and grade on rough or inaccurate excavations. This might be accomplished by casting a grout underneath prefabricated units. The prefabricated units could be supported on piles to accept the loads during construction of the upper part of the substructure until the grout cured sufficiently to accept the additional construction loads and the permanent loading.

The construction of foundations on piles could be expedited by eliminating the time-consuming practice of making and loading a test pile. This can be done by using steel piles with an easy splice and simply continuing to add lengths and to drive until adequate resistance is encountered. This could also be done with timber piles if construction personnel are trained in adequate and easy splicing methods. In the case of large concrete piles, additional time can be saved by making the concrete pier shafts an integral extension of the concrete pile.

The upper portions of the substructure, including the pier shafts and caps, which are not in contact with the ground, can all be made of precast units. The main superstructure beams do not present much opportunity for significant savings because they are already prefabricated and erected with relative rapidity. Standardization would increase the rate of prefabrication and the feasibility of maintaining an inventory of readily available members. The various deck elements, including parapets and median barriers, as well as the roadway deck itself could all be precast or prefabricated.

The major change necessary to achieve these improvements is better and more imaginative coordination between the requirements of design and those of construction. This will be brought about effectively only by providing an economic incentive. Engineers should write performance specifications that include time as a parameter and that allow the contractor as much freedom as possible in the choice of design, materials, and methods. Owners might award "design and construct" contracts that enable the contractor to optimize the design to suit his particular construction skills and equipment. Major owners might conduct contests offering awards for the design of optimum systems. The awards would have to be sufficient to attract the interest of experienced and skilled industrial organizations. Within states or regions, there should be regular conferences among designers and contractors to exchange ideas and develop compromises between any conflicting requirements of design and construction. Under the present system, contracts should provide a bonus for early completion as an incentive to the contractor to reduce construction time.