Steel, Concrete, Aluminum, and Timber in Systems Bridges

summary

Charles F. Scholer

Each of the four materials considered—steel, aluminum, concrete, and timber—has established and proven performance for many bridge applications. Some of the material capabilities are not fully utilized by bridge engineers, however; and education and demonstrations of these capabilities are necessary. In some instances, a combination of these materials may best utilize the materials in systems building.

Two major requirements of tomorrow's bridges are economy and aesthetics. Each material is economically competitive in some situations and is not competitive in others. For example, wood can compete with any other material in both function and economy in a large number of short-span bridges, yet it cannot do so for long-span bridges. Aluminum has many economical applications for bridge appurtenances, but at present it is only competitive for major components in structures such as military bridges and pedestrian bridges.

Aesthetically, each of the 4 materials has enhanced the appearance of a structure in its particular location. The current and future concern for aesthetics will not limit the overall use of any material, but it may be a greater factor in materials selection at any given location as designers fit the bridge into the surroundings.

Quality control, inspections, and tolerances are problems that concern all materials. Quality control to the required level can be ensured for all these materials with present technology. Concrete is possibly most sensitive, yet good quality control can be obtained in concrete production so that the designer can have confidence in strengths and other properties of his materials. Inspection is a requirement whether it is done by a representative of the producer or the owner. Tolerances on many current specifications are not well suited to systems building of bridges. In such systems, as much tolerance as may be allowed is of great help in speeding the erection as well as the fabrication, regardless of the material. However, in some bridge systems some present tolerances are not close enough. It is apparent that tolerances, regardless of the material, must be explicitly stated, set to meet the requirement of that portion of the structure, and not generalized for an entire structure or organization.

Future developments in bridge-building materials promise to aid systems building for bridges. Future concrete use includes adjustable, numerically controlled forms both in precast and in slip-form application. Higher strength concrete, up to 10,000 psi, should become commonplace especially in precast applications using low or no-slump concretes. Better quality control, admixture, and consolidation procedures are now allowing this to occur. Better economy will result from reduced turnaround time in precast operations brought about by several new cements and by improved methods of accelerating the curing of concrete. Use of self-stressing cements seems to be more promising than at any time in the past. Lightweight aggregate will also gain in acceptance as its benefical performance is recognized by engineers.

Steel already has a number of high-strength products available, but further improvements not only in strength but in ease of fabrication are in the future. Numerically controlled fabrication promises to improve not only the speed but also the economy and precision of steel fabrication. It will be beneficial to complex configurations as well as to repetitive standard units.

The great advantage of aluminum is its lightweight and flexibility of fabrication, especially the use of extruded slopes. The relatively higher first cost however eliminates aluminum from many applications. The first cost is expected to be reduced in the future, and aluminum should become competitive for more application in system bridges.

Probably the greatest future development in wood will be in educating engineers regarding the capability of glued and laminated structural timbers for bridge construction. The properties of these structural timbers allow them to be engineered and to form durable structures.

steel

Andrew Lally

Versatility in aesthetically adapting to any geometric structural configuration with economy of construction is an advantage of structural steel for both long- and short-span bridges. In urban areas where speed of erection is important, steel bridges can be erected in the least amount of time and with a minimum amount of interference to traffic. However, the full potential of structural steel in these areas has not been realized, and we explored avenues of prospective changes in construction methods for improved utilization of these inherent advantages.

One of two basic approaches to the problem is to provide a stock of constituent elements of a pre-engineered bridge system that would accommodate a range of span lengths for rapid construction in urban areas. This would include also a system of orthotropic plate deck components prefabricated and shipped in large sections to the job site for rapid erection with the least interference to traffic.

The other approach is to utilize the steel in its currently available standard shapes by recognizing that new numerically controlled systems of drilling and welding and, perhaps, future automated control of other fabricating operations will afford the same advantages as standard repetitive sizes. The numerically controlled equipment can produce the varying sizes for a complex structural configuration as easily as standard repetitive sizes and, perhaps, with greater accuracy because of the elimination of much of the present human error.

The arguments for the first approach, standardized components, have the supporting evidence of success in European applications and especially in Germany where urban bridges have been erected in a surprisingly short period of time with minimum interference to traffic. The standard components, fabricated and shipped in large sections, can accommodate varying span lengths. The steel pier bents and girders are rapidly assembled during periods of the least traffic.

The arguments for the second approach are that although the standard system may be acceptable in Europe the trends and demands here are the opposite in that planners are not going to accommodate to simpler straight alignments even where this may be possible. The cost of additional property in urban areas is one factor, and the demand for aesthetic bridge construction is another. The forest of columns employed in the earlier days of railroad bridges in urban areas is gone, and curved girders replace straight cords, box girders replace stringers, and cable-stayed bridges will probably replace the truss with economies following as they become more standard. The most realistic approach is to recognize this trend and not concentrate on standardized components at the expense of exploring better ways of building the more complex structure, because history and current trends show that the demand will continue to require these curved, spiralled, superelevated, and warped alignments.

Greater tolerances than those currently imposed should be allowed to speed erection wherever this will not affect the structural integrity. An example could be acceptance of oversized or slotted bolt holes for HS friction connections.

Recent investigation at the University of Illinois indicates that current depth-to-span ratio and LL deflection limitations in AASHO specifications are not justified, and perhaps more flexible bridge structures can be built without sacrificing the condition of concrete decks because of increased cracking or without introducing disturbing vibrations that can be uncomfortable to bridge users. The potential use of high-strength steel is greater with this knowledge.

It was agreed that redundant inspection is not the answer for achieving quality, but quality control programs as established in steel-fabricating shops of the American Institute of Steel Construction provide the confidence expected from the product and are effective in achieving results. Unfortunately, inspection requirements are not geared to the qualified fabricators. Unwarranted inspection calling for the same degree of perfection for secondary minimum stress-carrying members as for butt splices of main members is time-consuming and unnecessarily costly.

We agreed that we should concentrate on accommodating the complex geometry of the future urban bridge by use of automated fabricating equipment such as numerical drilling, investigate new decking systems that can be easily adapted to the resulting varying beam spacing, provide greater erection tolerances where practicable to reduce erection time, and provide incentives to the contractor for completing the field work ahead of schedule.

concrete

Donald W. Pfeifer

MATERIALS

The use of portland cement concrete in bridge construction is traditional, and the search for industrialized building procedures to accelerate the efficiency and economy of bridge construction is a natural development. Concrete with compressive strengths of 2,000 psi were common in site-cast bridge construction 50 years ago. With the subsequent development of the precast-prestressed concrete industry and the concurrent development of higher strength portland cements, the industrialized approach to concrete bridge construction appeared in the early 1950's.

This industrialized approach was made by the precast concrete industry using plant-produced pretensioned prestressed concrete bridge elements. These industrialized processes already being used for some 20 years allow for the production of unusually high-quality, high-strength concretes. The technology to produce concrete strengths at 28 days of 7,000 to 10,000 psi is now well known and, in fact, is being practiced on a day-to-day basis at many precast factories in the United States.

Correct mix proportioning procedures, proper mixing and placing procedures, consolidation by external or internal vibration or both, and an appropriate method of accelerating the cure of the high-quality concrete now makes it possible for numerous plants to obtain strengths of 5,000 to 6,000 psi after overnight high-temperature curing. The more recent development of structural lightweight aggregates for use in structural concrete has also been taken advantage of by the precast concrete industry. Such concretes weigh approximately 100 to 120 lb/ft^3 and strengths of 4,000 to 8,000 psi are easily attainable. These lightweight concretes are now being used as an engineered material in bridge construction, and more economical longer span bridges are being plant-produced.

While the precast concrete industry develops more industrialized manufacturing processes that result in higher and higher quality products, the owner-specifier still specifies to the lowest common denominator. This results in artificial restraints on the development of systems building techniques for bridge construction. It is a proven fact that economy can be gained by allowing design compressive strengths to be raised 1,000, 2,000, or 3,000 psi above the present levels. There have been cases where design strength change from 5,000 to 6,000 psi allowed for a greater girder spacing and the elimination of one girder. This example illustrates how excellence in design and production of precast concrete bridges can occur if an incentive for higher quality products is provided by the owner-specifier.

The steel industry provides numerous steel strengths that result in built-in economy that the designer recognizes and utilizes. Such economy can also be gained from the precast industry by providing alternate designs with concretes of 5,000, 6,000, 7,000, and possibly 8,000 psi.

Such alternate designs will accelerate the development of industrialized manufactured precast concrete bridges. There are no disadvantages associated with plant-produced high-strength concretes. On the other hand, numerous technical and economic advantages result. An associated advantage is the general up-grading of machinery, production techniques, and materials in the precast plants that today do not attempt to use highly industrialized processes and available knowledge to produce higher strength concretes. This up-grading will occur when incentives for excellence are provided and higher strength concretes begin to compete with the lowest type of concretes.

Even though the strength spectrum within the precast concrete industry is broad, the technology to raise strengths to higher and higher levels is available. This technology is not complex and is certainly available to the owner-specifier if he wants it.

Once the owner-specifier decides that the industrialized approach is desirable, he must work with the precaster. Inspectors must be educated and trained to handle low- and zero-slump concretes during their quality control program. Aggregate gradings should be controlled and nominal aggregates rejected. The owner-specifier should also recognize that a nondestructive test method is needed for strength observations. Research should be undertaken to validate reasons why such nondestructive methods are either satisfactory or unsatisfactory for use in an industrialized process such as production of plant-produced bridges.

If nominal sands and coarse aggregates are used, concrete quality and strength will suffer. Such materials should not be used, and the owner-specifier should work with the precast concrete producer to eliminate or minimize the effects caused by borderline materials.

SPECIFICATIONS

There are definite specification modifications and changes that will help to accelerate the industrialized process of bridge building. The most important is the use of alternate bid procedures for concrete strength classes of 4,000, 5,000, 6,000, 7,000, and 8,000 psi. Such a procedure will provide the entire precast industry an incentive to industrialized bridge construction.

As strengths increase because of the use of low slump, low water-cement ratio concretes, permeability of the concrete will cease, and cover over the steel reinforcing may be reduced. Concrete cover of ½-in. may prove to be very serviceable when concrete strength is more than 7,000 psi. Additional economy is then attained when this unnecessary deadweight is eliminated.

Several artificial restraints are placed on the curing of precast concrete even though published research and years of experience have shown that the present specifications are extremely conservative. When accelerated-cured concrete reaches strengths of 4,000 to 6,000 psi after overnight curing, there is little justification in specifying that the concrete should have additional curing. Such high-strength concrete is very impermeable, and the water remaining in the concrete is sufficient to hydrate the remaining portland cement not already hydrated during the accelerated curing. Research studies have shown that compressive strengths will increase by 1,000 to 2,000 psi even when no additional curing is provided.

Another restraint on curing is the specification that allows only live steam-curing to accelerate the strength of the precast concrete. The owner-specifier should allow alternate methods for providing accelerated high-temperature curing.

All methods such as radiant heat from oil or water lines and electrical radiant heat as well as live steam should be allowed. These curing-procedure specifications would, of course, apply only to concrete bridge elements produced in steel forms or their impervious forms, which will contain all the water within the concrete during the curing cycle. The top or exposed surface must also be covered with an acceptable impervious cover or membrane.

The third restraint on curing is the specification stating that the concrete shall not be exposed to temperatures below freezing for 6 days after casting. High-strength concretes used in precast bridge and building elements have been stored at below freezing temperatures immediately after accelerated curing in numerous plants in the United States and Canada, and no problems have occurred from the so-called "thermal shock" or possible freezing. Even the published research on the damage to accelerated-cured high-strength concrete shows that high-strength concretes do not suffer from exposure to freezing temperatures immediately after high-temperature curing.

The precast industry believes that cast-in-place field concrete has its place in the industrialized process. Field connections of precast concrete and continuity advantages are definite assets. However, the use of low-strength, 2,000- to 3,000-psi, field-placed concrete places a restraint on the total industrialized process. The owner-specifier can obtain from properly designed and maintained equipment field-placed concrete that could have 28-day strengths of 4,000 to 7,000 psi. Use of judiciously placed high-strength field concrete would be an additional advantage to the whole industrialized process.

The 1971 Interim AASHO Specifications for Prestressed Concrete introduced increased allowable tensile stresses (from 3 to $6\sqrt{f'c}$). In the future, when sufficient experience has been gained, additional increases of more than $6\sqrt{f'c}$ for allowable tensile stresses can provide for more serviceable structures with less long-term camber problems. In Germay bridge designs are based on zero allowable tensile stress under 50 percent of the live load.

ECONOMICS

Economy will result from industrialization. Complete economic studies should be made by the owner-specifier comparing the effects of using 4,000- to 8,000-psi concretes. Such studies should include the effect on the substructure, piers, caps, and superstructure when high-strength concrete is used. Once the economic advantages of industrialization are studied and uncovered, a massive educational effort must be made within the precast industry as well as the owner-specifier agencies. Additional economic benefits are sure to follow this educational process.

FUTURE USES AND RESEARCH

The precast industry is constantly watching the research and development activities within the concrete and steel industries. Because drying shrinkage and creep are major problems, an admixture that when added to concrete would prevent the internal water from escaping would be well received. This admixture would eliminate drying shrinkage and significantly reduce creep.

The use of chopped steel wires as web reinforcement to achieve minimum web thickness along with reduced total weight would also be an advancement.

The age-old problem of painting or coating concrete, if solved, would provide new architectural possibilities from industrialized urban bridges.

The precast industry is closely watching the developments taking place in the fields of polymer-cement-concretes, self-stressing expansive cements, and regulated-set (fast-setting) high-strength cements. All three of these new types of concretes and cements will have applications that would benefit the industrialized process of building precast-prestressed concrete bridges.

aluminum

John W. Clark

USE IN HIGHWAY BRIDGES

Aluminum is used extensively in bridge railings and lighting standards mainly because of its appearance, low maintenance, and competitive cost. Easy transportation and erection resulting from aluminum's light weight also help in these applications. The same characteristics of aluminum have dictated its use in pedestrian bridges and in military. Light weight is also the prime factor that has caused aluminum to be used in bridge-decking of old bridges such as the Smithfield Street Bridge in Pittsburgh.

Aluminum has been used as the primary structural material in a number of bridges where the main reason for its use was to gain experience with the material. Some examples of bridges of this kind are as follows:

Use	Length (ft)	Location	Year
Railway girder	100	Massena, New York	1946
Arch span	290	Arvida, Canada	1950
Bascule bridges	100	England	1948, 1953
4-span welded bridge	220	Iowa	1958
Reynolds bridge	97	Petersburg, Virginia	1960
4-span Fairchild bridge	212	New York	1960
Riveted girder bridges	80	New York	1960

LIMITATIONS ON USE IN BRIDGE STRUCTURES

Aluminum is not used more extensively for the main structure in highway bridges because its first cost is higher than that of steel and concrete. The question of cost must be continually reevaluated, however, as new methods of fabrication and erection are introduced. Historically, the price of aluminum has not risen so fast as that of competitive materials and, therefore, cost should not be so great a deterrent to the use of aluminum in the future. Of course, the development of a large market should help to reduce prices.

Limitation on availability of aluminum in needed shapes and sizes—especially large structural shapes—is another factor tending to restrict use of aluminum in bridges. Presumably large structural shapes in standard sizes could be stocked if the demand were sufficient. Although extruded shapes are generally limited to a 24-in. circular size, extrusions can be designed with edges prepared for easy shop welding into larger shapes.

Because the modulus of elasticity of aluminum is about one-third that of steel, aluminum structures will generally deflect farther than their steel counterparts. This factor can be a deterrent to the use of aluminum for structures where deflection limitations are significant. This limitation can be partially overcome in many cases by using aluminum sections of greater depth. Because aluminum weighs about one-third as much as steel, it is possible to use, say, a 40 percent greater volume of aluminum and still have one-half the weight of a steel structure. Other methods of reducing deflection are to spread the load by means of a torsionally stiff design, as in the Fairchild bridge, or even to introduce post-tensioned steel cables.

The coefficient of thermal expansion for aluminum is higher than that for either steel or concrete. However, existing structures demonstrate that the problems thus created can be handled satisfactorily by proper design that either allows for expansion and contraction or resists the forces developed if expansion is restricted.

Another factor that the designer must be aware of is that galvanic corrosion of aluminum can occur where it is electrically coupled to steel. This problem can be taken care of by separating the materials with paint or joint compound. Experience has shown the effectiveness of the protection procedures called for in current specifications.

The heat-treated or strain-hardened aluminum alloys generally used in structures lose some of their strength because of the annealing effect of the heat of welding. This factor is taken into account in current structural specifications (such as those published by the Aluminum Association and adopted by AASHO) in which the allowable stresses are reduced in the vicinity of welds, with the result that the metal that is not affected by welding is not used so efficiently as it might otherwise be. However, the effect of the heat of welding is minimized in new alloys such as 7005-T53, which is now being used in military bridges and in other applications.

The reduction in deadweight that accompanies the use of aluminum may cause a higher ratio of live to dead load stresses and even result in stress reversal. Therefore, the possibility of fatigue failure must be closely checked. However, fatigue tests made on the Fairchild and Smithfield Street designs, as well as field experience to date on all aluminum bridges, indicate satisfactory resistance to repeated load.

POTENTIAL FOR USE IN BRIDGE SYSTEMATIZATION

Aluminum structures generally weigh about one-half as much as corresponding steel structures. Thus, use of aluminum reduces restrictions on size of parts that can be transported to the site and erected in one piece and minimizes on-site time and labor. The size of the part that can be lifted by a given piece of equipment can be effectively doubled, for example. This advantage of light weight is perhaps the most important contribution that aluminum can make to bridge systematization.

Aluminum offers advantages in flexibility of fabrication. The extrusion process produces integrally stiffened panels, parts that snap together to eliminate welding jigs, and parts with bolting or welding flanges at any location to reduce fabrication time and cost. Its excellent resistance to corrosion permits thin-gauge construction that results in savings in weight and material cost. Most aluminum bridges are unpainted. Freedom from painting will reduce traffic stoppage during erection and later maintenance.

Where aluminum is used, it may be advantageous to consider forms of construction different from those normally employed. For example, consideration might be given to orthotropic or sandwich decks to reduce weight, integrally stiffened or corrugated panels to increase stiffness, and tubular truss construction rather than plate girders.

When thinking of advantages of lightweight material, one generally thinks of bridge superstructures. However, it is believed that aluminum should also be considered for piers or columns, bearings and expansion joints, GM guardrails, and temporary structures such as crossover bridges.

CONCLUSION

Aluminum has not been widely used as a primary structural material in highway bridges mainly because its first cost is higher than that of competitive materials. However, it is believed that this cost gap will continue to narrow, and the advantages of aluminum from the standpoint of light weight, ease of transportation, speed of erection, and reduction of maintenance will merit its serious consideration in systems building for bridges.

timber

Thomas G. Williamson

Probably the first use of timber in bridge construction was when a Stone Age man rolled a log across a ravine, chasm, or river and used it as a footbridge. Since then timber bridge construction has evolved through a series of forms, including the famous covered bridges, which are now historically preserved in numerous states throughout the country, the timber trestle railway bridges of which there are thousands in the United States, and eventually the modern-day structural timber construction such as the Keystone Wye Bridge in the Black Hills area of South Dakota.

In order to discuss the subject of structural timber as it applies to the construction of highway or other bridge structures, it is first important to define the materials that are actually involved in modern heavy timber construction. The first of these is solid sawed timber such as that often used for smaller framing members. These are controlled by the regional associations that establish allowable stresses and are included in Section 10 (which contains a table providing all the basic stress data for this type of member) of the AASHO Standard Specifications for Highway Bridges.

A second type of timber used in heavy timber construction is the round timbers, such as timber foundation piles or poles used in highway pier construction. In the past few decades, technological advancements in the areas of gluing and basic lumber strength evaluation have led to the widespread use of glued and laminated structural timber that now forms the basic material for heavy timber construction with respect to large framing members in the superstructure of a highway bridge. Other applications of glued and laminated structural timber in bridge construction are in deck systems.

Because the architectural and engineering profession is relatively unaware of this product, it is important to state what glued and laminated structural timber means. According to the U. S. Commercial Standard 253-63, which covers the fabrication and design of those timbers, the product is defined as follows: "Structural glued laminated timber refers to an engineered, stress-rated product of a timber laminating plant, comprising assemblies of suitably selected and prepared wood laminations securely bonded together with adhesives. The grain of all laminations is approximately parallel longitudinally and the separate laminations shall not exceed 2 in. in net thickness." Because of the modern methods available for fabricating these members, it is possible to achieve almost any shape or size of structural member by using glued and laminated timber.

The results of research indicate that approximately a one-third savings in size can be gained over conventional glued and laminated structural timber by prestressing with high-strength steel tension wires, much in the same manner as prestressed concrete is produced. At the present time, technology for producing these members under routine plant production has not advanced to the stage where this is a common practice. However, the use of this material in the future should be considered.

If timber is to be used in exposed conditions, such as in highway bridges, it is assumed that the members will be pressure-treated or pressure-impregnated with an approved preservative to ensure a long life for this material comparable to the anticipated life of other common structural materials. Those treatments should be in accordance with the American Wood Preservers Association's standards and the AITC Standard 109-69.

STRUCTURAL TIMBER IN SYSTEMS CONSTRUCTION

Timber has a long history of use in systems construction of bridges and other buildings. A systems approach has long been used in the construction of railroad timber bridges in which there are fixed spans and member sizes for both substructure and superstructure elements. For example, in trestle construction, an 8 by 16 solid sawed timber stringer spanning 14 ft is normally used. Another example is the use of a standard sized pier cap of solid sawed or glued and laminated timber in railroad bridge construction. As the source of large solid sawed structural timber members becomes more and more limited, the railroad companies are looking to the use of glued and laminated structural timber as a potential replacement and feel that this material will eventually replace solid sawed timbers. Thus engineers will continue to be provided with structural timber for bridge structures.

In building construction, glued and laminated structural timbers almost invariably form a part of some type of systems approach to reduce erection cost and time. Because of the nature of the fabrication of these members, they are always prefabricated in the laminating plant to exact job-site specifications such that when they reach the erection site they are ready for immediate installation with little, if any, on-site preparation necessary. Because they arrive on the job site cut to exact size and precisely drilled for all connection hardware, assembly and erection of these members is remarkably simple and requires minimum labor to be maintained in the field. This prefabrication procedure also applies, of course, to bridge construction and was used in the construction of the Keystone Wye Bridge that is a twin structure consisting of a curved girder-span lower level structure with 3 prefabricated glued and laminated structural arches spanning the lower structure. In the construction of this bridge, all timber superstructure elements and timber pier elements were prefabricated at the laminating plant, and all hardware was prefit such that when it reached the field the piers were merely placed into their respective positions on the concrete abutments, and the arches were then lowered into position on the pier members. The deck was reinforced concrete; however, it could have been any type of compatible deck surface.

The superstructure is probably the area where timber will find its greatest potential. As previously stated, it is possible to produce both straight or curved systems for simple spans up to 120 ft in length, this being limited primarily by transportation, and glued and laminated arches for spans of 300 ft or more. Thus, timber lends itself to use either in a straight girder type of construction or in an arch type of structure for highway bridges.

The second area where timber can be used in the construction of highway bridges is in the deck system. Several systems are available, including prefabricated nail panels or glued and laminated panels in 4-ft widths and variable lengths that are placed either transversely over girders or longitudinally between piers. The latter configuration forms a major load-carrying element of the superstructure itself. Various surfaces such as asphaltic concrete can be placed over these timber deck panels. Composite action using a cast-in-place concrete deck over timber superstructures is also a proven system as illustrated by the Keystone Wye Bridge and other installations. Plank decks have also achieved widespread acceptance in secondary bridge structures, such as state and county highway bridges.

Timber in pier construction is primarily limited to pile bents or glued and laminated bents prefabricated and shipped to the job site as a unit. These might be used in short-span structures or to be attached to foundation structures, in the case of water crossings where piers can be used with minimal interference.

Timber can be used in the construction of abutments, in pile abutments with timber or concrete caps, in crib construction to prevent scouring and erosion around piers and stream crossings, or in crib walls or wing walls adjacent to main abutment structures. These cribs can be prefabricated and shipped to the job site ready for installation.

Another primary use of timber, particularly round timber piles, is in foundations, particularly in relatively shallow depths where other materials are not economically competitive. In these instances, it is possible to use lighter and less complicated pile-driving equipment and reduce on-site labor and equipment costs.

There are certain advantages and disadvantages related to the use of a certain structural material in lieu of another material, and this applies, of course, to structural timber. The following are some of the advantages of timber construction particularly as it relates to the systems concept.

1. Timber lends itself to a systems approach because of prefabrication of all components that are ready for rapid on-site assembly, thereby minimizing on-site labor costs and time. This is particularly important in urban areas where it is difficult to close other facilities during construction of a structure such as a bridge.

2. Timber is a very lightweight construction material and thus allows for the transportation of larger, more complete structural units such as girders with timber panel decking preassembled at the manufacturing site. This also minimizes on-site construction costs and shipping costs based on a weight basis.

3. Almost any configuration of members can be readily prefabricated including complicated curved girders and arch members so that the bridge designer has complete freedom in his structural component design.

4. The lightweight feature previously mentioned also permits use of smaller on-site construction equipment. That plus the low cost of timber per pound leads to a lower total cost for the initial structure itself.

5. Construction of modular timber units can be accomplished on the site by unskilled labor, and field modifications are possible in instances where tolerances are not satisfied by the plant production, although the necessity of an on-site modification is unlikely.

6. Timber fits into existing environments, particularly in urban and suburban areas where a natural appearance is desired.

7. Timber, as a material, is not affected by chemicals or corrosive materials, and thus possible corrosion such as that caused by de-icing salts is not a concern in a system using a laminated deck with a thin overlay wearing surface.

8. Timber exhibits excellent strength characteristics in dynamic loading situations that occur in highway bridge construction and that might occur in areas of high earthquake possibilities.

9. Timber is one of the few renewable natural resources, and this should be a consideration in any design whether it be highway bridge, a pedestrian footbridge, a school, or a large warehouse.

There are, of course, potential limitations associated with the use of timber in highway bridge construction, and following are examples of these.

1. In pile foundations, it is often necessary to use a splice as soil conditions vary and affect driving length. However, this is primarily a design problem and can be overcome through sound research and design efforts.

2. In general timber members must be deeper than members of other materials, such as steel, to carry a given load and, in locations where roadway clearance is critical, this could be a deterrent to the use of timber. One solution to this problem is to use prestressed timber girders as previously described that reduce the required depth significantly.

3. Fire is always a consideration in timber construction. In general, large timber members burn very slowly, and as they burn they form a char that acts as an insulating surface. This charred surface tends to inhibit further burning of the member, and often in severe fires structural timbers still carry their design loads long after other structural materials have failed. In many instances, it is possible to go into a structure that has been damaged by fire in which heavy timber is the primary structural material and salvage these structures by merely removing the charred material and reanalyzing the structure to ascertain that the remaining section, which is completely structurally sound, is adequate to carry the imposed loads. Of course, it is always possible that vandalism by fire can occur, but this should not represent a primary deterrent to the use of structural timber.

4. The engineering profession is not educated in the use of structural timber in design and construction. College curricula generally do not provide students with opportunities to learn about the designs of structural timber members. Therefore, most graduate engineers are unfamiliar with this material as a major structural element. Also practicing engineers lack experience in the use of timber and are not familiar with the simplicity associated with the design, connection details, and erection of structural timber units.

5. The potential damage to structural members from vehicular accidents and possible resulting fire should be a secondary consideration in material selection and should not be considered a liability for structural timber because of the relative ease of repairing timber members and heavy timbers that might be damaged under such circum-

stances. Related to this is the concept of maintenance of the structural elements in service. Maintenance of timber bridge systems should be minimal; the only maintenance recommended is the application of a periodic (approximately every 10 years) water-repellent stain used to provide a pleasing aesthetic appearance. Paintings and coatings are not recommended because they add unnecessary cost to the project and serve no primary function.

POTENTIAL FOR TIMBER BRIDGES

It is not proposed that structural timber bridges be used in areas where tremendously long spans are involved or in certain urban settings where timber would not lend itself to this type of construction. However, as previously noted, timber is a part of a systems approach to construction and has a long history of use in systems construction because of its prefabricated nature and compatibility with other materials.

One area in which timber bridges should be considered is in the construction of either pedestrian overpass bridges or vehicular bridges in parks or park-like settings where the use of timber would be aesthetically compatible with the natural environment. Such a condition would be found in downtown urban areas or in suburban areas where major highways go from an urban to a rural setting. Timber construction can also be used in temporary structures that are needed when an existing facility is replaced and that have to be erected and removed in very short periods of time. In designing such a temporary timber structure, the engineer may determine that it could actually serve as the final structure with certain additional design considerations, and this should be a consideration during his initial design of this type of structure.

A relatively new approach to the use of timber in systems construction is in the area of completely glued and laminated superstructure elements shipped to the job site with all connecting hardware prefabricated and in place on the members when they arrive at the construction site. These are then spanned by a glued and laminated deck panel fabricated in modular units according to the superstructure design.

It is also possible to preassemble entire bridge superstructures adjacent to bridge crossings and place these as complete units by using cranes or helicopters. An example of this is the construction of a 100-ft span pedestrian and light vehicular bridge in the San Diego area. That bridge was lifted into position in less than 20 minutes by prefabricating the entire unit adjacent to the final crossing and lifting it into place as a single unit.

Another approach to systems construction with timber is a girder-laminated deck bridge system shipped as a preassembled unit in, say, 12-ft widths and spans up to 100 ft in length, depending primarily on transportation limitations. The use of new surface materials, in lieu of conventional asphaltic or reinforced concrete, which can be applied to the laminated deck panels at the fabricating plant and thus eliminate need for on-site paving of roadway wearing surfaces, will undoubtedly be evaluated in the future installations. These epoxy coatings should provide a long-lasting durable wearing surface and add to the reduction in on-site labor and material costs.

CONCLUSION

Timber as a material lends itself to the solution of the current problem of highway bridge construction in either urban or rural areas by its use in systems construction. A systems approach reduces field labor costs and reduces site construction time, both key factors in reducing total cost of construction of highway bridge structures. The use of standardized components such as girders and panel deck systems eliminates excessive design considerations, provides simplified details and cross sections, and lends itself to potential stockpiling of small bridges.

Although each bridge is a unique design, its potential construction using basic modules or units that might consist of structural timber girders and deck systems or other similar types of units should be a consideration. The lightweight characteristic of timber as a structural material and its high strength-to-weight ratio make it ideally suited for reducing on-site labor and equipment costs and in-transit shipping costs. Although the use of timber will not replace prestressed concrete or structural steel for large urban highway bridge facility construction, it should be considered for smaller crossings in areas where aesthetics is of prime concern or in areas where time of construction is limited.

A material should not be considered alone but in combination with other materials for true systems design. Examples of this are timber superstructures placed on concrete substructures with asphaltic concrete decks and timber piling used as substructures for prestressed reinforced concrete piers and steel superstructures. Designers should keep all potential materials in mind when developing bridge systems and determine which material best suits the specific needs regardless of whether it be wood, steel, concrete, aluminum, or some other material. Only by making optimum use of all structural materials can we efficiently build the highway bridges needed at a reasonable cost.