Modular Timber T-Beam Bridges for Low-Volume Roads

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Wood has a long and successful history as a bridge-building material. Recently, a new wood construction technique known as stress laminating has been developed sufficiently so that wood bridges may become cost-competitive with concrete and steel, particularly for short span ranges and on low-volume roads. At the Constructed Facilities Center of West Virginia University (WVU), a variation of the stress-laminated deck has been developed that shows excellent structural performance and reasonable costs. The modular timber T-beam bridge is the result of many years of effort on the part of engineers from WVU, West Virginia Division of Highways, the USDA Forest Service, and the USDA Forest Products Laboratory. Ten modular timber T-beam bridges are currently in service throughout West Virginia, and one is in service in the Ozark National Forest in Arkansas. Modular timber T-beam bridges consist of glued-laminated wood beams and wood deck planks stress-laminated together to form 4-ft-wide modules, each as long as the bridge span. To illustrate the advantages and problems of the modular system, two case studies are presented. The Camp Arrowhead bridge is one of the first modular T-beams built and is an example of a moderately priced structure showing excellent performance. The Nebo bridge, a short modular T-beam bridge, offers some insight into the construction problems resolved during the development process.

Timber has a long tradition as a bridge-building material for low-volume roads. From the earliest log structures to modern engineered timber bridges, wood was often selected by bridge builders for its strength and availability and because it could be easily worked and handled. In recent years, steel and concrete have replaced timber for much of our bridge construction because these materials are considered by most of today's engineers to be stiffer, stronger, and more durable than timber. New timber technology has created better timber products, however, and timber could once again compete with steel and concrete, particularly for short spans on low- and medium-volume roads.

Timber technology has evolved from dependence on solid sawed components to fabrication of components formed from many smaller pieces. Plywood, laminated veneer lumber, and oriented strand board are typical engineered timber components that combine smaller pieces of wood to form a strong, high-quality timber component. These new products are often less expensive and more readily available and have more reliable engineering properties.

A less recognized innovation in timber engineering emerged in Canada in the late 1970s: stress laminating. Used principally for bridge decks, stress laminating is a technique of pressing boards (usually 2 or 3 in. thick and 10 to 16 in. wide) together to form a bridge deck. The traditional fastening method for laminating adjacent planks—nailing—has a relatively short practical life and limited load-sharing capabilities. Stress laminating, which requires more expensive hardware and equipment, has been shown to dramatically improve the load-carrying capacity and durability of timber deck bridges (*1*).

Since 1988, a federally funded project has been promoting the use of timber for bridges in the United States. The Timber Bridge Initiative (TBI), administered by the USDA Forest Service, State and Private Forestry, provided funding for demonstration bridges in all 50 states and for research to improve timber bridge technology. In West Virginia, the West Virginia Department of Highways (WVDOH) and the Constructed Facilities Center (CFC) at West Virginia University joined forces to design and construct 60 modern timber bridges between 1988 and 1994, most of which were partially funded by the TBI. Several types of stress-laminated and glued-laminated bridges have been built, but perhaps the most innovative and efficient is the stress-laminated modular T-beam.

Early Stress-Laminated Timber Bridges in West Virginia

Stress-laminated timber decks (Figure 1) are a significant improvement over nail- or dowel-laminated decks, but span lengths are limited by the availability of large-dimension lumber. Butt-joined laminations are acceptable in stress-laminated decks, so long lengths are not required. To resist the bending stresses, however, depths up to 16 in. are often necessary. The practical upper limit for stress-laminated decks is 30 to 35 ft using the local hardwoods available in West Virginia. The first stress-laminated timber bridge planned for West Virginia had a span of 73 ft, far greater than any stress-laminated timber bridge previously built. To construct a stress-laminated timber bridge to cross that span, modifications to the existing designs were necessary to create added stiffness. The T-beam system, which originated at the CFC, combines glued-laminated beams with a stressed deck to create a substantially stiffer structure than the stressed deck alone (Figure 2).

West Virginia's first stress-laminated timber bridge, the Barlow Drive T-beam bridge, was constructed in May 1988 and has been serving the local community well since then. Approximately 500 vehicles, many of them heavily loaded trucks, use the bridge daily. A nearby concrete plant and an oil depot have been able to reduce the length of many trips that previously required a detour around the old steel truss bridge. However, at $79/ft^2, the new timber bridge was not competitive with those built with precast concrete.

Between 1988 and 1991, 30 more stress-laminated timber bridges were built in West Virginia. The success of the first T-beam bridge played a large role in the rapid expansion of the TBI but none of the next 30 bridges built was a T-beam. Rather than design each bridge individually, most of the 30 bridges were designed from standard plans prepared at the CFC and WVDOH. The first standard plans included stress-laminated decks and a modification of the T-beam, the stress-laminated box beam, but not stress-laminated T-beams. It was not until 1992 that stress-laminated T-beam standard plans were prepared and incorporated into the WVDOH standard plans.

After the first 2-year period of stressed timber bridge construction, it became apparent that all of the new timber bridge types cost more than expected. The least expensive system, the stress-laminated deck, cost an average of $42/ft^2 and the box-beam structures cost, on average, $60/ft^2 (*2*). Unfortunately, the least expensive timber bridges performed poorly (*3*) and would require either deeper (and more expensive) timber or added stiffeners to meet AASHTO performance requirements. Clearly, changes were necessary if timber bridges were to be competitive in an open market.

Modular Stress-Laminated Timber T-Beam Bridges

An "optimization" project was conducted at the CFC to determine what changes could be made to improve performance and decrease costs. With the cooperation of engineers from the USDA Forest Products Laboratory, WVDOH, and Burke-Parsons-Bowlby Corp. (the largest timber bridge fabricator in West Virginia), a critical review of the bridge systems already built was performed. A modular concept was proposed to reduce costs and improve performance. The modular T-beam system—which should be less expensive than a box beam (because it uses less material) and should perform better than the stress-laminated decks (because it is stiffer and stronger)—was selected as the system with the most potential to compete with precast concrete.

Advantages of Modular Systems

Numerous improvements were expected by changing to a modular bridge construction. Primarily, constructing the bridge in modules shifts most of the assembly operations to a fabrication shop where costs were expected to be less than at the bridge site and the quality of workmanship more consistent. Second, the cost of installing the modules was expected to be lower due to

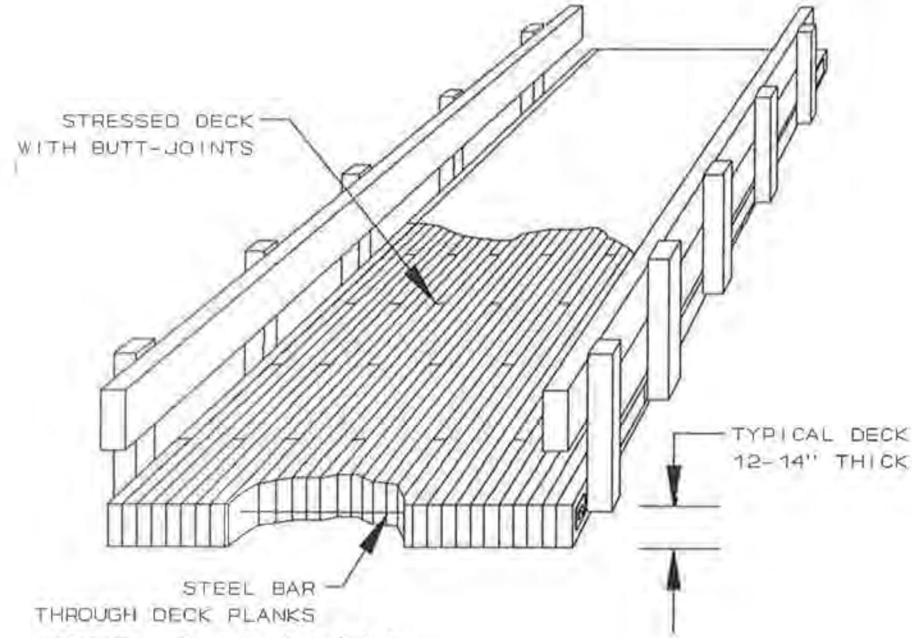

FIGURE 1 Stress-laminated deck.

the smaller-sized crane required and shorter installation time.

Design of Modular T-Beam

Although the current AASHTO specifications (*4*) do not yet contain design guides for stress-laminated T-beam structures, the similarity of stress-laminated decks and stress-laminated T-beams allows many of the provisions to apply (Figure 3). In many important phases of the design, however, the differences between the two types of bridges are substantial. For these areas of the design, the CFC has developed its own standards. These standards, which have been submitted to AASHTO for possible incorporation into the Standard Specifications, are based on laboratory and field testing, as well as on theoretical studies.

The design process used by the CFC is a relatively simple one. Each of the beams of the bridge is assumed to consist of a single-width web with a fully composite flange. The flange width is determined to have an "effective" width that is used in the calculation of the moment of inertia of the T-beam unit. Generally, the effective width of the flange is less than the spacing of the beams (Figure 4).

Each T-beam unit is designed to support a portion of the expected live load plus a share of the dead load. For highway bridges in West Virginia, an AASHTO HS-25 truck loading is required. Because each T-beam unit shares the loading with the other T-beam units, a load distribution factor can be applied. Depending upon the number of beams, the spacing of beams, and the stiffness of deck members joining the beams, the load distribution factor can reduce the applied load to one-half of the HS-25 wheel load.

After the effective flange width is determined, the dimension of the T-beam can be established. The stresses and deflection of the T-beam can then be found using the load distribution factor to calculate the live load that must be supported by the beam. The beam is modeled as being simply supported with a span equal to the bridge center-of-bearing to center-of-bearing spacing. Stress-bar spacing and size, bearing plate size, and stress-bar force level are then chosen in the manner prescribed in the Standard Specifications. The full design process can be found elsewhere (*5*).

The designs prepared at the CFC became the basis for a new set of standard plans for the WVDOH. The new stress-laminated modular T-beams have a span range of 24 to 63 ft using glued-laminated beams from 19.25 in. to 49.5 in. deep. Some of the shorter spans use a 7-in. deck, but most of the standard plans require a 9-in. deep northern red oak deck.

Fabrication of Modular T-Beam

Each module of the stress-laminated modular T-beam bridge consists of two glued-laminated beams and 30 deck planks (the number of deck planks can vary slightly to create wider or narrower modules). To fabricate an exterior module, one 10-in.-wide glued-laminated beam, one 5-in.-wide glued-laminated beam,

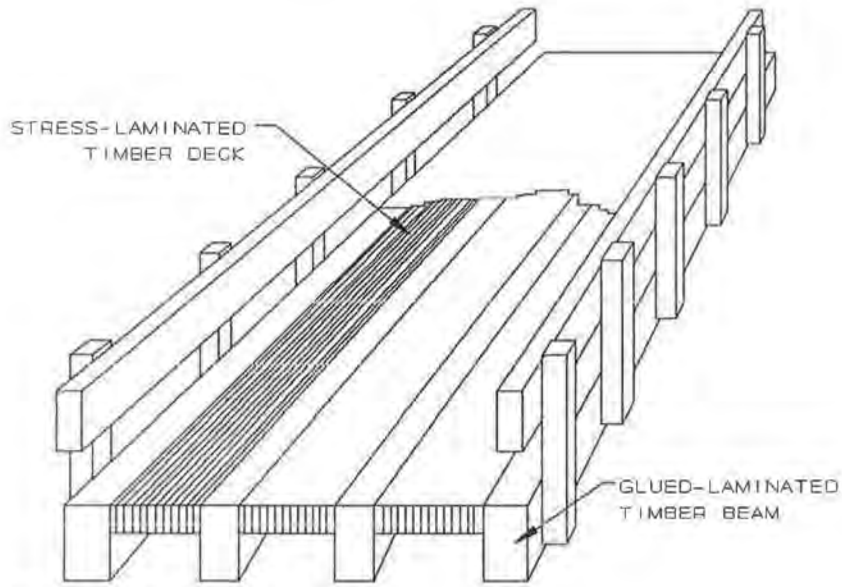

FIGURE 2 Stress-laminated T-beam.

and thirty 1.5-in.-wide boards are joined by high-strength steel stressing bars. One set of high-strength steel bars passes through holes drilled in the planks and the beams on 2-ft centers (temporary bars), and another set of bars passes through holes on 6-ft centers (fabrication bars). Interior modules are constructed similarly except both beams of the interior modules are 5 in. wide.

Both interior and exterior modules are stressed three or more times at the fabrication shop using both the temporary bars and the fabrication bars. Guide rail posts, curbs, and guide rails are fastened to the exterior modules. After approximately 6 weeks in the fabrication shop, the modules are ready to be shipped to the bridge site.

Erection of Modular T-Beam

Generally, one or two modules are shipped to the bridge site on each truck. Just before the modules are craned onto the abutments, all the 2-ft center bars are removed leaving only the fabrication bars to maintain the compressive force on the modules. Once all the modules are positioned on the abutments, full-length steel bars are inserted through the vacant holes on 2-ft centers and the entire bridge is stressed one final time. The steel bars on 6-ft centers in the exterior modules can then be removed for reuse on another bridge; the fabrication bars in the interior modules remain in the bridge.

Because the guide rail and curb have already been fastened to the exterior beams, all that remains to com-

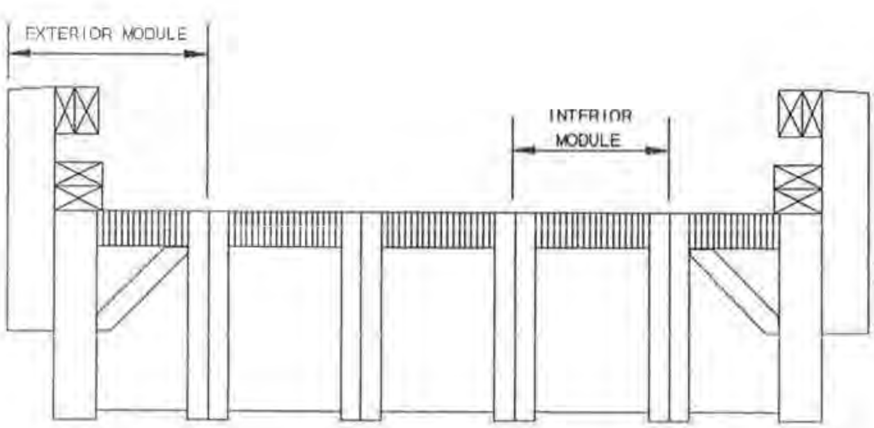

FIGURE 3 Cross section of typical modular T-beam bridge.

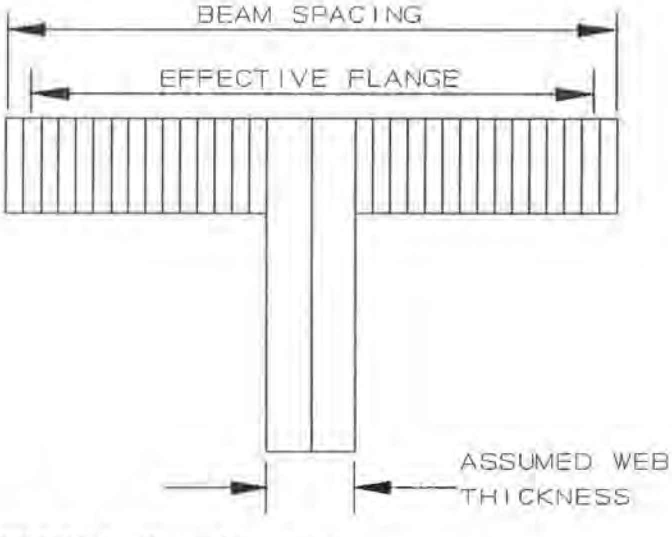

FIGURE 4 Design T-beam unit.

plete the bridge is to cast the concrete back walls, erect the approach rails, complete the approach subgrade, and then pave. The erection of the modules—if all steps go as planned—should take less than 1 day.

Case Studies

Ten modular T-beam bridges were built in West Virginia in 1992 and 1993. Twelve more were in various stages of construction in 1994. Although these bridges have not been without problems, the general consensus has been that structures perform better and are slightly less expensive than their predecessors. Two bridges have been selected as case studies for this report; the Camp Arrowhead bridge in Cabell County, West Virginia (Case A), and the Nebo bridge in Clay County, West Virginia (Case B). Technical data for these bridges are shown in Tables 1 and 2. These two bridges are representative of all the modular T-beam bridges already built. The Camp Arrowhead project proceeded as planned, with only a few delays. The Nebo bridge project was not as smooth and was delayed several weeks, but the bridge is now in service and functioning well. By studying these cases and the other bridges built, specification and design revisions can be made as needed. But, as these cases show, the costs of stress-laminated timber bridges remain high.

Case Study A: Camp Arrowhead Bridge

The new timber bridge crossing Little Cabell Creek near the Camp Arrowhead Boy Scout Camp replaces a precast concrete bridge on timber pilings (Figure 5). The concrete bridge had a span of only 22 ft, almost 40 ft shorter than the new timber span. The extra span length is a result of the use of spill-through abutments. The spill-through abutments used in West Virginia are stub abutments generally set back 15 to 20 ft from the normal stream channel to prevent scour of the foundation. The low height of the spill-through abutments also reduces the volume of earth retained, thus increasing the longevity of the abutment.

The stress-laminated, modular T-beam bridge was fabricated by Burke-Parsons-Bowlby Corp. in Spencer, West Virginia, and erected on May 12, 1988, by WVDOH forces. Because this bridge was the first West Virginia bridge built using the new modular construction technique, a great deal of attention was given to the fabrication, erection, and performance.

The fabrication of this modular T-beam was significantly different from the procedures previously used. Five modules, each 63.5 ft long, were manufactured at Burke-Parsons-Bowlby Corp. The two exterior modules are each 60 in. wide, and the three interior modules are 55 in. wide. Following the WVDOH specifications (6), each of the modules was stressed two times over a period of 6 weeks. As the modules were stressed, it was discovered that some of the modules were becoming misshapen (Figure 6). Several attempts were made to remedy the problem. Temporary steel diaphragms were bolted to the beams before stressing to maintain squareness, but they were ineffectual because the lag bolts used to fasten the diaphragms to the beams would pull out as the stressing was applied. An additional set of steel bars was installed at the bottom of the beams to pull the bottoms together as the stress was applied.

TABLE 1 Technical Data for Camp Arrowhead Bridge

TECHNICAL INFORMATION	**Curb**
Bridge Type: Modular T-BEAM Abutment Type: Stub on piles Design Load: HS-25 Average Daily Traffic: 50	Size: 6"x12" Grade: 3 Species: NORTHERN RED OAK
Geometry	**Rail**
Number of Spans: 1 Out-to-Out Length: 63'-6" Center of Bearing-to-Center of Bearing: 62'-0" Number of Lanes: 2 Out-to-Out Width: 23'-9" Curb-to-Curb Width: 21'-9" Skew: NONE Beam Size: 10"x44", 5"x44" Deck Depth: 9"	Size: NONE Grade: Species: Quantities: Wood: Steel: **Preservative** Type: COAL-TAR CREOSOTE Quantity: 22,800 lbs.
MATERIALS INFORMATION	**Steel**
Deck Lumber Grade: 3 or better Species: NORTHERN RED OAK Quantity: 11,250 bf Sizes Used: 1 1/2"x9"	Bar Size: 5/8" No. of Bars: 32 full length 50 fabrication Plate Size: 7"x11" Quantity: 3500 lbs.
Beams Grade: 24FV3 Species: SOUTHERN PINE Quantity: 14,000 bf	**COSTS** Fabrication Cost: $79,512 Erection Cost: $10,500 Substructure Cost: n/a Total Project Cost: $90,012
Guiderail system Posts: NONE Size: Grade: Species:	

Again, the results were less than successful. After one beam cracked near midheight, this method was also abandoned. The solution chosen by the manufacturer was to remove the stressing bars, insert a tapered deck board, and restress the misshaped module. Although this method does not address the cause of the problem, it did result in a module with minimal deviation from the desired shape. Upon completion of the specified stressing sequence, the curb was installed to the two outside modules (because this bridge is on a very low-volume and low-speed road, no rail was needed).

Each module was loaded onto a "stretched" trailer and trucked from the fabrication plant in Spencer to the bridge site in Cabell County, a distance of about 50 mi. A single 60-ton crane lifted the modules from the truck with the aid of a lifting system designed specifically for the modular bridges (Figure 7). A second crane was used to help position the modules. The lifting system is composed of steel eyebolts through the deck connected to two lightweight steel angles under the beams. The angle steel is slightly shorter than module width so that the modules can be set on the bridge seats tightly against the neighboring module.

The WVDOH District 2 crew installed the bridge in less than 2 days. After the modules were craned onto the bridge seats, the full-length bars were inserted and stressed and the exterior modules' fabrication bars were removed. No problems were encountered with the installation or the stressing. To erect the bridge and stress the modules required 130 man-hours; the cranes were at the site for 30 hr but were used for approximately 15 hr. The back walls were cast before the installation of the timber modules, which left only approach work and paving to be done before the bridge could be

TABLE 2 Technical Data for Nebo Bridge

TECHNICAL INFORMATION

Bridge Type: Modular T-BEAM
Abutment Type:Stub on piles
Design Load: HS-25
Average Daily Traffic: 250

Geometry

Number of Spans: 1
Out-to-Out Length: 33'-6"
Center of Bearing-to-Center of Bearing: 32'-0"
Number of Lanes: 2
Out-to-Out Width: 21'-3"
Curb-to-Curb Width: 19'-5"
Skew: NONE
Beam Size: 10"x27", 5"x27"
Deck Depth: 9"

MATERIALS INFORMATION

Deck Lumber

Grade: 3 or better
Species: NORTHERN RED OAK
Quantity: 3,950 bf
Sizes Used: 1 1/2"x9"

Beams

Grade: 24FV3
Species: SOUTHERN PINE
Quantity: 4,550 bf

Guiderail system

Posts: 20
Size: 12"x8"
Grade: 3
Species: NORTHERN RED OAK

Curb

Size: 5"x10"
Grade: 24FV3
Species: SOUTHERN PINE

Rail

Size: 14"
Grade: A36
Species: STEEL
Quantities: 9500 lbs.

Preservative

Type: COAL-TAR CREOSOTE
Quantity: 8,275 lbs.

Steel

Bar Size: 5/8"
No. of Bars: 17 full length
25 fabrication
Plate Size: 8"x14"
Quantity: 1150 lbs.

COSTS

Fabrication Cost: $45,200
Erection Cost: $9,913
Substructure Cost: n/a
Total Project Cost: $55,113

opened for traffic. The bridge was not paved for several months after opening, but stress-laminated structures do not need to be paved to be driven on temporarily.

Testing of the Camp Arrowhead bridge began soon after completion of construction. A series of load tests, bar-force monitoring, moisture content measurements, and elevation measurements has been performed as part of a cooperative USDA Forest Products Laboratory and CFC project. Although the testing program is still in progress, the bridge has shown good performance in most categories. The stiffness of the structure, as measured by a live-load test, is slightly higher than anticipated. Moisture contents are near the specified levels and the bridge is maintaining camber. Bar forces are dropped more rapidly than expected, but they have stabilized at an acceptable level. The creosote retention of the bridge beams is vastly improved when compared with the 1989 funded bridges, but some bleeding still occurs during the hot summer months.

The cost of the Camp Arrowhead bridge delivered to the site was $79,512. Because WVDOH forces erected the bridge, the total costs of the completed structure are not known as precisely as they would be if a contractor had bid the project. Based on the time records of the state crew and using an estimated hourly rate of $20 for labor and $1,500 per day for crane time, the cost of the bridge installation was approximately $10,500. The cost per square foot of bridge surface area was $54.

Case Study B: Nebo Bridge

The Nebo bridge was the third stress-laminated modular T-beam bridge constructed in West Virginia (Figure

FIGURE 5 Camp Arrowhead bridge.

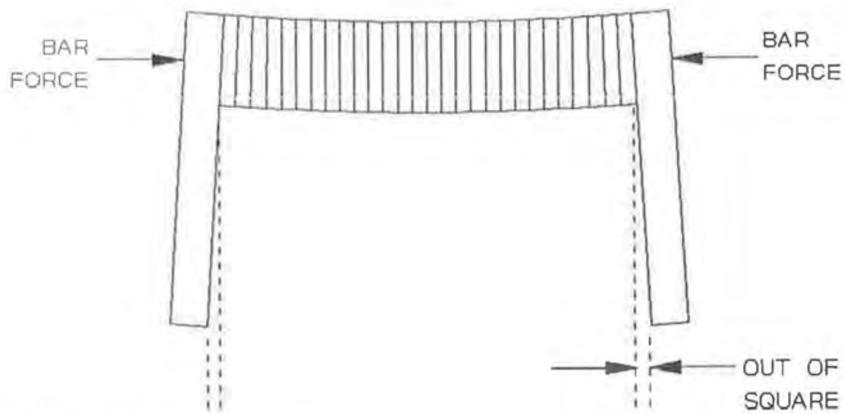

FIGURE 6 Misshapen module.

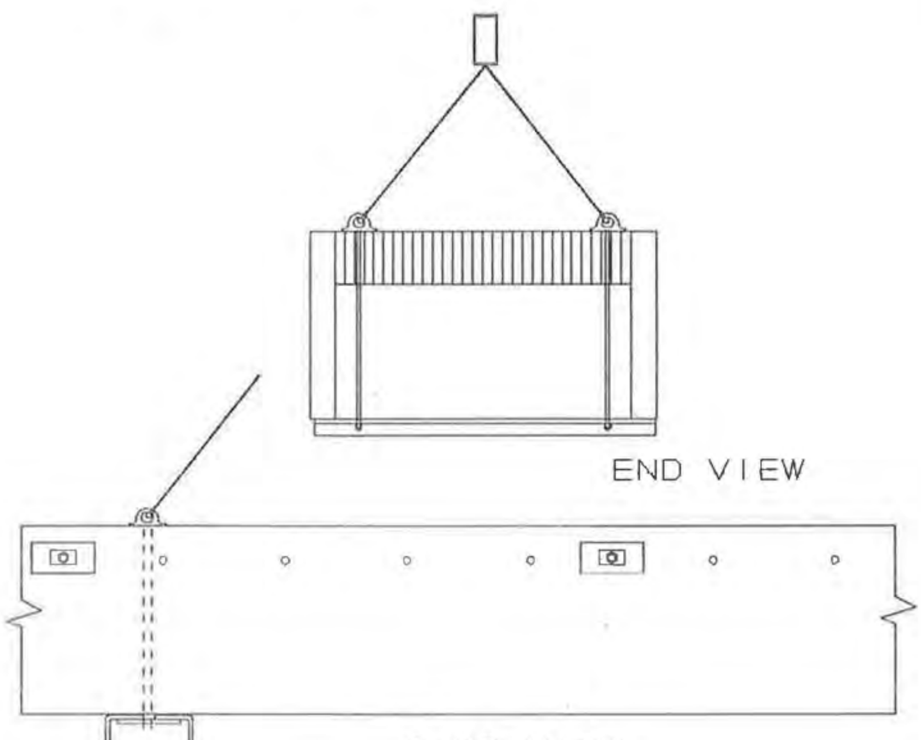

FIGURE 7 Module lifting system.

FIGURE 8 Nebo bridge.

8). The bridge is located in Clay County, West Virginia, and carries about 250 vehicles per day over the Stinson Creek. The 33-ft-long bridge rests on spill-through abutments on steel piles.

Fabrication of the Nebo bridge was done by Burke-Parsons-Bowlby at its Spencer plant. Like the other stress-laminated modular T-beam bridges, the fabrication sequence followed the procedure prescribed by the WVDOH specifications. And, like the first two modular T-beam structures, the stressing operations caused the modules to distort. On this bridge, however, no tapered boards were used to correct the problem based on the supposition that the modules would assume the expected rectangular shape after the final stressing at the bridge site.

Unfortunately for the contractor, the bridge did not take the expected shape after installation on the abutments and stressing. Rather, the error that appeared relatively minor on each module accumulated when the entire bridge was assembled. After stressing, the exterior beams lifted off the abutments and the structure took a noticeably distorted configuration.

Several potential solutions to this problem were considered. After a brief test run at the fabrication shop, engineers from WVDOH and CFC decided that the best option was to install a set of steel stressing bars through all the modules immediately beneath the deck. Located at this position, very little bending of the glued-laminated beam would result from the tensioned rods and maximum compressive force would be applied where it was needed.

The repair was successful and relatively inexpensive. Testing and inspection of the Nebo bridge have shown no adverse effects from the repair procedure. To prevent recurrence of this problem, WVDOH specifications have been modified to require that the modules be fabricated to within plus or minus 0.25 inch of the specified dimension. By applying a more uniform compressive force, the fabricators have been able to comply with the new specification. Only minor installation problems have been observed in the more recently built bridges.

Live-load testing and periodic monitoring of the bar force levels and moisture levels have shown the Nebo bridge to be performing well. The deflection of the bridge at the centerline was 0.375 inch when loaded with a 50,000-lb vehicle. Bar-force levels remain above 50 percent of the applied force and moisture levels are near 20 percent. Creosote retention of the beams and decks has been excellent.

The cost of the Nebo bridge, delivered to the site, was $45,200. The contractor charged the state $55,113 for the installed structure; thus the installation cost can be assumed to be the difference, $9,913. The cost per square foot of bridge surface area was $79.

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