Performance of Stress-Laminated Bridges

Michael A. Ritter, Earl A. Geske, Lola Mason, William J. McCutcheon,
Russell C. Moody, and James Wacker

Abstract

Stress-laminating is a new concept for timber bridges that has received considerable interest during the past few years. A monitoring program is under way to evaluate the performance of these bridges. Preliminary data indicate that, in most instances, bridges presently in service are performing as expected.

Introduction

The concept of stress-laminating wood bridge decks originated in Ontario, Canada, in 1976 (Taylor et al., 1983; Taylor and Csagoly, 1979). In this system, vertical wood laminations are stressed together with high-strength steel rods (Fig. 1). The rods, which typically carry between 30,000 and 80,000 lb. each, squeeze the laminations together so that the stressed deck acts as a solid wood plate. Stress-laminating was originally developed as a means for rehabilitating existing nail-laminated lumber decks that had loosened as a result of cyclic loading and wood moisture-content variations. It has since been adapted for the construction of new bridges. Most stress-laminated (stress-lam) bridges have used solid lumber laminations for slab-type decks. This paper addresses only that type of structure. However, the concept is being extended to systems employing stress-laminated trusses, and T- and box sections (Dickson and GangaRao, 1989).

Design procedures for stress-laminated decks were included in the Ontario Highway Bridge Design Code in 1983 (Ministry of Transportation and Communications, 1983). Since then, many bridges have been built or rehabilitated in Ontario using this concept. In the United States, a design procedure has been approved by the American Association of State Highway and Transportation Officials (AASHTO), and will be published as a guide specification in the near future.

As of early 1990, ~30 stress-lam bridges have been constructed in the United States. These bridges were designed using the Ontario Highway Bridge Design Code procedure or one of various other design procedures developed in the United States. During 1990 and 1991, more than 100 stress-lam wood bridges are proposed for construction in the United States as part of the National Timber Bridge Initiative, established by the U.S. Congress in 1989.

Bridge Monitoring

To evaluate the performance of stress-lam bridge systems built in the United States, the USDA Forest Service, Forest Products Laboratory (FPL), initiated a nationwide bridge monitoring program in 1988. The purpose of the program is to monitor and evaluate bridge performance in order to develop, confirm, or improve methods of design, fabrication, and construction. This is being accomplished by obtaining representative information on the performance of different bridge systems and materials under various geographical and environmental conditions. Bridges included in the program are selected on the basis of location, structure type, wood species, and preservative treatment.

For stress-lam bridges, information on each bridge is normally collected over a minimum of two years and includes the following:

1. *Moisture content.* The moisture content of a bridge deck is measured at 6 to 12 locations using an electrical resistance-type moisture meter. Typically, readings are taken monthly for the first year and quarterly thereafter.

2. *Rod forces.* Typically, two load cells are installed to monitor the stressing-rod forces; one is located on the second or third rod from the bridge end, and the other is near mid-span. The force in the rod (transmitted through the load cell) is determined by reading the load cell strain with a strain indicator. Readings are taken weekly for the first 2 months, monthly for the next 10 months, and bimonthly thereafter.

3. *Vertical creep.* Long-term vertical creep deflection is measured on the underside of the deck at mid-span using either a survey rod and level, or a stringline attached to the bridge ends.

4. *Load test behavior.* Bridge behavior is determined by measuring the decks deflection pattern under vehicular loading. These are measured with a rod and level, or stringlines.

5. *Condition evaluation.* Overall bridge condition, including anchorage system and wearing surface performance, is determined through intensive visual inspections conducted annually.

The FPL bridge monitoring program currently includes 23 bridges located across the United States. By the end of 1990, the program will expand to a total of 55 bridges. At this time, most monitored bridges are newly constructed or are currently being built. Thus, data on the performance of many bridges are incomplete. The information presented in this paper is based on the data obtained from six stress-lam deck bridges that have been monitored continually for a year or more. Performance trends and conclusions are representative of the cumulative general behavior demonstrated by the bridges. More specific information on these and additional bridges will be available as data are collected and detailed reports are published.

Additional information on the performance of stress-lam bridges is available in reports on specific bridge performance (Dickson and GangaRao, 1989; Gutkowski and Lewis, 1989; Mozingo and DiCarlantino, 1988).

Field Performance of Stress-Laminated Decks

The stress-lam bridges constructed in the United States have generally provided good performance. The few problems that have arisen relate to serviceability and aesthetics, rather than structural (safety) features. The problems include local crushing of wood at the rod anchorages and loss of camber (vertical creep). These problems resulted from the evolutionary nature of the stress-lam system in the United States, and generally occurred on bridges that were constructed before national standards for design, fabrication, and construction were widely available. Proven design and construction criteria have been developed in Ontario, Canada for many of the design features. Using knowledge gained from bridges built with several alternative design features, standards in the United States have been developed to cover a variety of applications for stress-lam deck systems. These standards are currently available to bridge designers to provide direction for the design, fabrication, and construction of future bridges.

The following information was collected on the performance of stress-lam bridges built in the United States.

Moisture Content. The moisture contents of wood at installation and io service are considerations for the design of all exposed wood structures. Changes in moisture content can affect strength, stiffness, and dimensional stability. Changes in strength and stiffness are recognized in design by applying wet-use reductions, when applicable. Of primary concern in stress-lam systems is the dimensional stability of the wood under changes in moisture content. Below the fiber saturation point (~30%), wood expands as moisture is gained, and contracts when moisture is lost. In stress-lam bridges, these dimensional changes directly affect the force levels. Thus, rod forces will decrease when moisture is lost and increase when moisture is gained. Generally, moisture-content changes in stress-

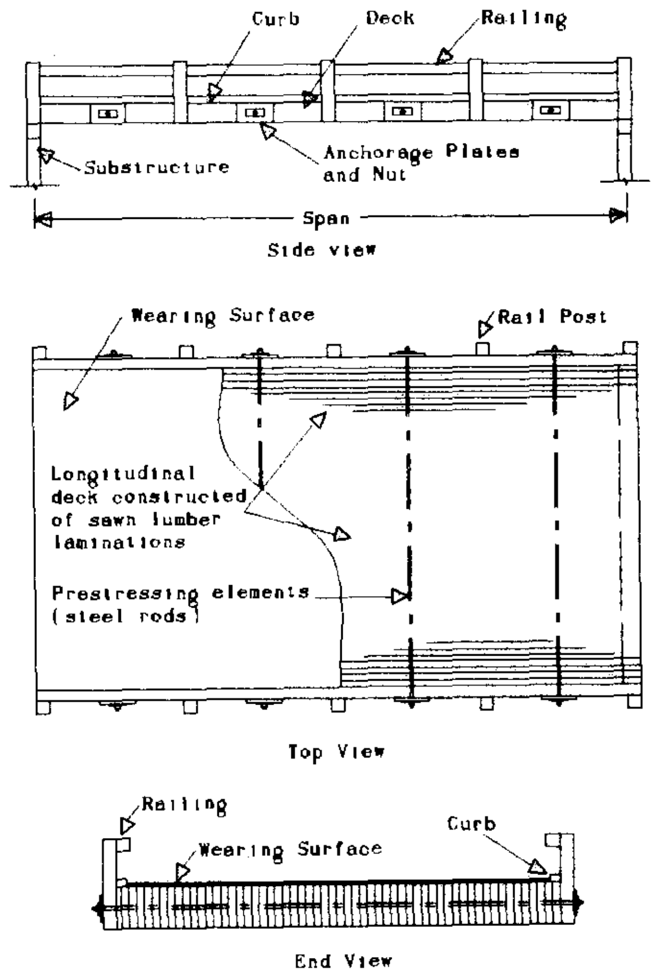

Figure 1. Typical configuration, for a longitudinal stress-laminated lumber deck bridge.

lam decks can be attributed to: (i) difference between the wood moisture content at the time of construction and the equilibrium moisture content at the site; (ii) seasonal changes in equilibrium moisture content; and (iii) short-term changes as a result of superficial surface wetting.

With few exceptions, bridges constructed in the United States to date have used lumber at a relatively high moisture-content level, typically 24 to 28% at the time of construction. Three of the bridges included in the FPL monitoring program were constructed with a wood moisture content >30%. At these levels, the wood moisture content is considerably higher than the expected equilibrium moisture content, which varies for different locations in the United Slates, but typically averages 18 to 20% (McCutcheon et al., 1986). Field measurements have shown that global moisture-content changes toward an equilibrium level are relatively slow in a stress-lam deck. Thus, the observed effects are minimal during the first several months after construction; however, the effects become much more pronounced as the decks eventually lose moisture. This moisture loss can lead to deck shrinkage and a substantial loss in stress. Based on field observations, the FPL currently recommends a maximum moisture content of 19% for stress-lam decks to minimize stress loss as the wood reaches equilibrium with the environment.

In addition to global moisture-content changes toward an equilibrium level, field data indicate that seasonal moisture-content changes and surface wetting also can affect the rod forces. The most pronounced effect appears when the top deck surface is totally exposed or covered only with a lumber-plank wearing surface. In such cases, the deck surface absorbs moisture more rapidly than the inner and lower deck. As a result, repeated wetting or standing water cause the upper portion of the deck volume to swell in relation to the lower portion. Preliminary observations indicate that two bridges are swelling in this manner. Although no adverse structural effects have resulted, evidence of differential moisture content is observed as a slight transverse crown in the deck, as wood crushing in the edge laminations along the top of the rod anchorages, or as an increase in stressing-rod force. Additional data are required to fully understand the long-term effects of this phenomenon; however, the comparative performance of several bridges indicates that the potential for these conditions can be greatly reduced or eliminated if the deck surface is paved with asphalt, preferably in conjunction with a waterproof geotextile membrane.

Rod Force Level. The structural integrity and serviceability of stress-lam decks depend on the compressive stress maintained between the lumber laminations (Oliva and Dimakis, 1988). For acceptable performance, this compression must be sufficient to prevent vertical slip, which is caused by shear, and openings between the laminations, which is caused by transverse bending. Current design procedures used in Ontario, Canada and the United States require a minimum interlaminar compression of 100 psi at the time of bridge construction. It is assumed that 50 to 60% of this stress will be lost over the life of the structure. Research in the United States has shown that slip between the laminations does not begin until the interlaminar compression has dropped below 25 psi. Since the long-term compressive stress should be approximately twice that required to prevent interlaminar slip, it is important to maintain a transverse stress of 40 to 50 psi.

Compressive stress between the laminations is monitored by measuring the forces in the stressing rods. Experience has shown that retention of these forces depends upon a complex interaction of several factors including wood creep, moisture-content changes, and rod anchorage-system performance. Given the variations in the data and the limited time in which the bridges have been monitored, it is difficult to formulate universal conclusions at this time. However, the following general trends have been observed:

1. *Moisture Content.* Moisture content at the time of construction is one of the most influential factors in maintaining rod force. The best performance has been observed when the lumber laminations were installed at a moisture content of 16 to 19%, or as close to the expected equilibrium moisture content as possible. When an asphalt wearing surface is applied, global increases in lamination moisture content tend to increase rod force, which offsets losses as a result of creep. When the lumber moisture content measures between 20 and 30% (approximate fiber saturation point) at installation, moisture content decreases have been gradual, but have resulted in a loss in rod force of as much as 80% over 2 years (Fig. 2). When the lumber has been saturated at the time of construction, drying has been slow. On one bridge constructed of lumber at an average moisture content of 39%, the moisture content decreased by only 5% over 18 months. At high moisture-content levels such as these, no loss in rod force will be evident until the wood reaches fiber saturation point and begins to shrink as it dries.

2. *Wearing Surface.* When the top of the bridge deck was not protected with an asphalt wearing surface, localized moisture-content increases in the deck top have caused swelling. followed by wood crushing at the stressing-rod anchorage plates. This leads to an increase in rod force as the deck swells, and then to a decrease in rod force as the wood crushes and/or dries.

3. *Wood Crushing.* Substantial decreases in rod force have been attributable to wood crushing at the anchorages for the stressing rods. Generally, this has resulted from undersizing of the bearing plates during design. Crushing has been most severe when the discrete-plate anchorage system is used in conjunction with softwood laminations at high moisture contents.

4. *Temperature.* Bridges included in the FPL monitoring program are situated at various locations in the United States. Several of the bridges are subjected to annual temperature variations of 100°F or more. Based on preliminary data, temperature changes, and the associated thermal expansion and contraction of bridge materials do not seem to significantly affect rod force levels. Work in this area is continuing and more definitive conclusions will be forthcoming.

The FPL is conducting laboratory tests on stress-lam deck specimens to augment field data. The purpose is to determine the relative effects of wood creep and moisture content on the rod force level, and the cumulative effects of moisture cycling on deck behavior.

Anchorage System. The anchorage system for the stressing rods must distribute the rod forces into the deck without crushing the wood in the outer laminations. If crushing occurs, the rods can lose a substantial portion of their force. In the United States, stress-lam decks have employed either a steel channel or discrete plates to distribute the force (Fig. 3). The channel configuration was developed in Ontario. Canada and is currently a design requirement of the Ontario Highway Bridge Design Code. The discrete plate was developed in the United States and uses a single rectangular bearing plate at each rod. A third system that has been used employs a steel plate that is continuous over several rods, but only preliminary performance data are available.

The field performance of anchorage systems has varied. In general, performance of the steel channel configuration, designed in accordance with Ontario Highway Bridge Design Code procedures, has been very good. Although more expensive than the plate configuration, the steel channel minimizes wood crushing so that it has very little effect on rod forces. Performance of the discrete-plate configuration has been mixed. When used on softwood lumber species (Douglas-fir and southern pine), the plates have caused crushing in the outside laminations. Typically, this crushing has averaged 1/4 to 3/8 in., which is acceptable in most situations; however, crushing of 1 in. or more has been observed on three bridges. This severe crushing occurred on some of the first stress-lam bridges built in the United States, and was attributable primarily to plate undersizing and a failure to reduce wood compressive stress for wet-use conditions. When properly designed, the discrete-plate configuration used on red oak laminations has demonstrated virtually no crushing and has performed well. Several bridges built recently in the United States have used the discrete plates successfully on bridges constructed of softwood lumber, with red oak outside (edge) laminations.

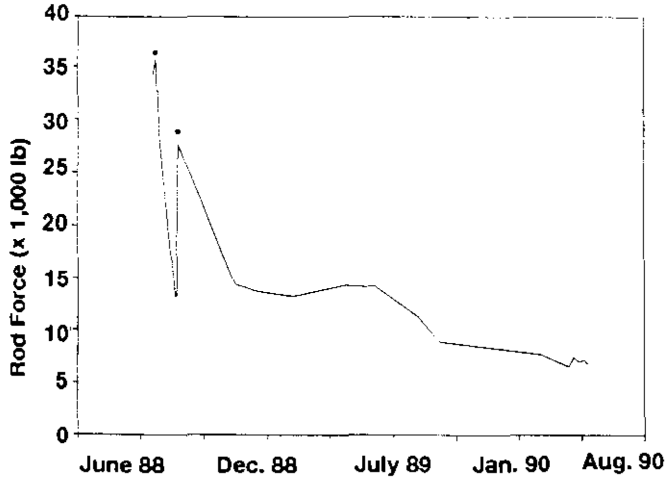

Figure 2. Rod force loss in a stress-laminated deck constructed of creosote-treated Douglas-fir (8 in. deep and 26 ft. wide).● denotes rod restressing completed as a part of the construction procedure.

Vertical Creep. As a structural material, wood can deform permanently as a result of long-term sustained loads. This phenomenon, known as creep, has been evidenced in stress-laminated decks. One advantage of stress-lam decks has been the ability to camber bridges with butt joints to offset the dead-load deflection and the additional creep deformation. On two of the monitored bridges, creep has resulted in a complete loss of camber and an additional sag in the deck of 3 to 4 in. In both cases, the decks were constructed of 16-in.-deep Douglas-fir timber at moisture contents >25% and spanned crossings >40 ft. In addition, the decks were prefabricated in stressed panels that were coupled and stressed together in the field. The resulting camber loss and sag are suspected to result from a combination of creep, because of the long bridge spans, high initial moisture contents, and the construction method used to join the panels.

Creep has not been a detectable problem in other stress-lam decks in which the live-load deflection for an HS20-44 design vehicle has been limited to 1/400 of the bridge span. Although not directly related to creep, this limit on live-load deflection has kept spans within limits where creep has not been a problem.

Load Testing. Load tests have been conducted on several stress-lam decks to assess behavior and to provide data for evaluating proposed design procedures. In all cases, the stress-lam decks acted as large orthotropic plates. A computer model has proved fairly accurate in predicting field performance of the bridges. However, alternative,

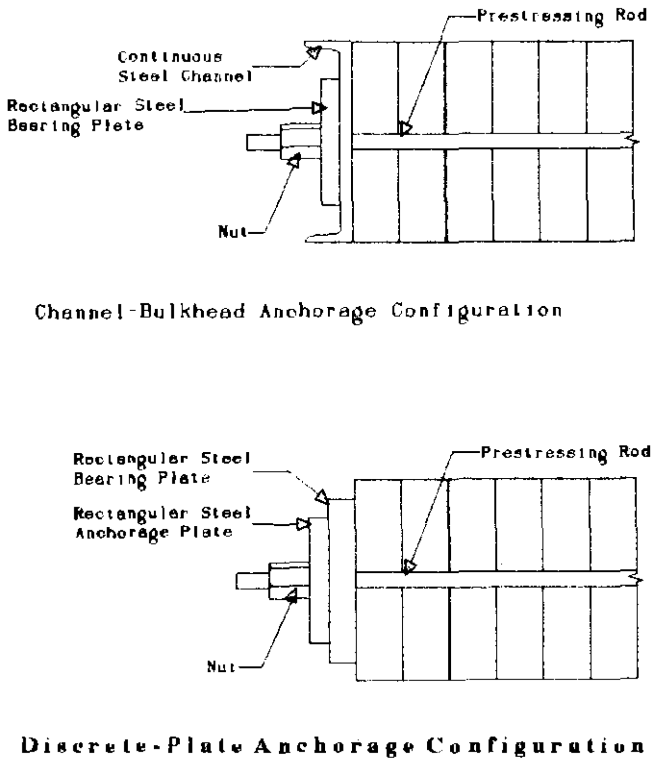

Figure 3. Stressing-rod anchorage configurations commonly used in stress-laminated bridge decks.

simplified procedures have provided varying results. Factors that contribute to this variability include the edge-stiffening effects of curbs and rails, variations in the location and frequency of butt joints, and differences between the assumed and actual lamination stiffness. A more complete understanding of these effects will be gained as more bridges are load tested.

Another factor that can affect the deflection of a stress-lam deck is the level of compressive stress between the lumber laminations. Although somewhat variable among bridges, load test results for one bridge showed a 20% increase in deflection when the interlaminar compressive stress was reduced by 45%. Therefore, when comparing load-test results with design procedures, it is important to acknowledge the increase in deflection as the stress level drops. Since most design procedures assume an eventual stress loss of 50%. the predicted deflection should be compared with the measured deflection at that stress level.

Wearing Surfaces. The performance of asphalt wearing surfaces on wood bridge decks has long been a concern of bridge engineers. In the past, several wood deck systems employing nail-laminated lumber or noninterconnected deck panels have been associated with cracking or disintegration of asphalt wearing surfaces. This is caused by differential movement between individual laminations or by vertical movement at joints. In stress-lam decks, the compressive stress prevents interlaminar slip and there are no discrete joints. Thus, asphalt cracking or deterioration has not been a problem on stress-lam decks. Of the decks that have been paved. the compacted pavement thickness has varied between 2 and 3 in. Even on decks designed for standard HS20-44 highway loads with a live-load deflection as large as 1/300 of the bridge span, no cracking or deterioration of the asphalt wearing surface has been apparent during the initial 2-year monitoring period.

Stressing System Corrosion. Adequate corrosion protection of the steel stressing system has been a primary concern since the development of stress-lam deck systems. Decks originally constructed in Ontario, Canada used a polyvinyl chloride tube filled with grease to enclose the stressing rods. In Ontario, galvanized rods are currently used, rather than grease-filled tubes. Bridges built in the United States have also used galvanizing as a means of corrosion protection for the stressing rods and anchorage hardware. Over a relatively short monitoring period of 2-1/2 years, no signs of rod corrosion have been observed on galvanized surfaces. However, in several cases in which anchorage nuts were not oversized to compensate for rod galvanizing, damage occurred to the rod galvanizing when the nuts were forced onto the rods during construction. Failure to adequately field coat the damaged areas resulted in minor corrosion at the rod ends. This situation can be avoided by using nuts of the proper size or by field coating damaged areas with a cold galvanizing compound.

Summary

Stress-laminated bridge decks constructed in the United States have generally performed very well. Serviceability has been the most common problem in the first bridges built and, generally, has resulted from high lamination moisture contents at the time of construction, wood crushing at the stressing-rod anchorages, and vertical creep. National guidelines for the design, fabrication, and construction of stress-lam decks are being developed and becoming available. We expect that most of the problems previously experienced in stress-lam bridge decks will be eliminated as improved guidelines are developed and distributed.

References

Dickson. B.D., and H.V.S. GangaRao. 1989. Field monitoring of the stressed timber bridge over Elk Two Mile Creek, West Virginia. West Virginia University, Morgantown, WV. 62 pp.

Gutkowski, R.M., and S.L. Lewis. 1989. Monitoring and testing of a prestressed longitudinal deck timber bridge. Colorado State University, Fort Collins, CO. 83 pp.

McCutcheon, W.J., R.M. Gutkowski, and R.C. Moody. 1986. Performance and rehabilitation of timber bridges. p. 65-69. *In* Transportation Research Record 1053. National Academy of Sciences, National Research Council, Transportation Research Board, Washington, DC.

Ministry of Transportation and Communications. 1983. Ontario highway bridge design code. Ministry of Transportation and Communications, Downsview. Ontario. Canada. 357 pp.

Mozingo, R.R., and G. DiCarlantino. 1988. Trout road bridge project. Pennsylvania State University. State College, PA. 22 pp.

Oliva, M.G., and A. Dimakis. 1988. Behavior of stress-laminated timber highway bridges. *Journal of Structural Engineering.* 114(8):1850-1869.

Taylor, R.J., B. Batchelor, and K. Van Dalen. 1983. Prestressed wood bridges. SRR-83-01. Ministry of Transportation and Communications, Downsview, Ontario, Canada.

Taylor, R.J., and P.F. Csagoly. 1979. Transverse post tensioning of longitudinally laminated timber bridge decks. Ministry of Transportation and Communications, Downsview, Ontario, Canada. 16 pp.

This report is based on. "Field Performance of U.S. Stress-Laminated Wood Bridges" by Michael A. Ritter and Michael G. Oliva, presented at the 1990 International Timber Engineering Conference, Tokyo, Japan. October 23-25, 1990.