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METHODS FOR ASSESSING THE FIELD PERFORMANCE OF STRESS-LAMINATED TIMBER BRIDGES

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

A national program to improve wood utilization in bridge applications is currently being administered by the U.S. Department of Agriculture (USDA), Forest Service. As a part of this program, the USDA Forest Service, Forest Products Laboratory (FPL), has developed a bridge monitoring program to determine the field performance of timber bridges. This paper presents an overview of the methods used by the FPL to assess the field performance of stress-laminated timber bridges. Included are discussions related to the equipment and procedures used to monitor the force in prestressing bars, moisture content in lumber laminations, vertical creep, and behavior of the structure under static loading conditions.

INTRODUCTION

Interest in timber bridge systems has increased significantly in the United States over the past several years. The majority of this interest can be attributed to the programs and activities sponsored by the Timber Bridge Initiative, which was passed by the U.S. Congress in 1988 (4). The purpose of this legislation, which has continued on an annual basis since 1989, is to provide the funding and national emphasis to further develop the utilization of timber as a bridge material. Within this Initiative, the three major program areas include (1) a demonstration bridge program that provides matching funds to local governments to build timber demonstration bridges, (2) a research program to develop new technology related to timber bridge systems and materials, and (3) a technology transfer and information management program to transfer appropriate technology on timber bridges through direct technical advice and information distribution.

Responsibility for administration of the Timber Bridge Initiative has been directed to the USDA Forest Service. Within this agency, leadership for research and development has been assigned to the Forest Products Laboratory (FPL). One large task within this research has been the structural monitoring and evaluation of numerous demonstration bridges built across the United States. Many of these bridges employ stress-laminated technology and frequently include design innovations that have not been previously evaluated. This paper

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*Research General Engineer, +Supervisory Electronics Technician, **Research General Engineer, ++Supervisory Research General Engineer, ***General Engineer, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. +++Civil Engineer, USDA Forest Service, San Dimas Technology and Development Center, San Dimas, California. The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

presents an overview of the FPL bridge monitoring program and describes some of the methods used to assess the field performance of stress-laminated bridges.

OBJECTIVE AND SCOPE OF THE BRIDGE: MONITORING PROGRAM

To evaluate the performance of stress-laminated bridges, the FPL implemented a nationwide bridge monitoring program in late 1988 (3). The objectives of the program are to monitor and evaluate bridge performance and behavior in order to develop, confirm, or improve methods of design, fabrication, and construction. Given the large number of bridges included in the demonstration program (>140 through 1990), it has not been possible to include all demonstration bridges in a comprehensive monitoring program. Rather, the FPL monitoring program has focused on obtaining representative information on the performance of different bridge systems and materials under various geographical and environmental conditions. This is accomplished by selecting a limited number of bridges as representatives of a larger bridge population with similar structure type, wood species, preservative treatment, and environmental exposure conditions.

Given the wide geographic distribution of the demonstration bridges and the associated personnel and travel requirements to conduct bridge monitoring activities, the FPL bridge monitoring is normally conducted in cooperation with the government agency that owns the bridge. A monitoring project is initiated when the agency contacts the FPL and requests assistance in bridge monitoring. The FPL representatives then develop a comprehensive monitoring plan for the specific bridge based on the structure type and materials and the site environmental conditions. After the plan is developed and concurrence of the cooperator is obtained, the FPL representatives visit the bridge site, install instrumentation, conduct testing, and train local personnel on data collection. Data are then collected by local personnel and forwarded to the FPL for evaluation and analysis. Approximately 1 year later, the FPL representatives again visit the site for further testing, to conduct an intense visual inspection, and to recalibrate instrumentation. Data collection continue by local personnel for approximately another year, after which a formal report of the bridge performance is prepared and published by the FPL. Most monitoring projects continue for 2 years, although this period may be extended if the collection of additional data is deemed beneficial or if unforeseen conditions develop during the monitoring.

BRIDGE MONITORING METHODS

The development of the FPL bridge monitoring program occurred in two phases. First, the scope of the monitoring activities were defined and specific data requirements were identified. Given the characteristics of the stress-laminated system, it was determined that minimum data collection from each bridge would include the force in prestressing bars, moisture content in the lumber laminations, vertical creep of the bridge over time, and behavior of the structure under static loading conditions. Additionally, intense visual inspections were included to assess the performance of items such as bar anchorage performance, stressing system corrosion, and wearing surface performance.

After the specific monitoring activities were defined, methods for obtaining the data were developed. Given economic constraints and the cooperative nature of the monitoring program, it was determined that monitoring methods should (1) provide accurate, reliable information that is easily recorded and reported, (2) minimize cost for equipment purchase, and (3) require minimal personnel time to install instrumentation and to collect data. Since many cooperators are unfamiliar with timber bridge systems and data collection techniques, the concern for simplicity and ease of application became important considerations.

The remainder of this paper describes the methods currently used by the FPL to monitor stress-laminated timber bridges. These methods have evolved over several years and reflect periodic refinements to improve both the effectiveness and efficiency of the program.

Measurement of bar force

For stress-laminated bridges to perform properly, an adequate level of interlaminar compression must be maintained between the lumber laminations. This compression is placed into the bridge through high strength steel bars that are jacked to a high tensile force at the time of bridge construction. Depending on the bridge design, 15.9-mm- (5/8-in.-) or 25.4-mm- (l-in.-) diameter bars are most commonly used. These bars are capable of providing a maximum tensile force of 154.8 kN (34,800 lb) and 453.7 kN (102,000 lb), respectively, although the actual design force used for bridge applications is considerably less. After bridge construction, the bar force and interlaminar compression decrease with time as a result of transverse stress relaxation and moisture content reductions in the wood laminations (1). If the bar force falls below minimum levels, serviceability or structural problems may result. Thus, the magnitude and rate of bar force loss are important considerations when evaluating bridge behavior.

Historically, the bar force in a stress-laminated bridge has been obtained by jacking the bar with a hydraulic jack and recording the hydraulic gage pressure where the attachment nut loosens or where the load “picks up.” This method has proven to be reliable within certain limits but is somewhat subjective in that the point at which the nut loosens or the load picks up may be interpreted differently by different individuals. In using this method, the FPL encountered two problems. First, most bridge cooperators did not have the stressing equipment necessary to check bar force levels. Second, the time and effort required to obtain force readings with a jack was more than many cooperators wished to expend. As a result, it was necessary to develop an alternative method of monitoring bar force that did not require jacking equipment.

To monitor stressing bar force, the FPL developed a load cell that is placed between the stressing bar bearing plate and anchorage plate (Fig. 1). The body of the cell is manufactured from a 63.5-mm- (2-1/2-in.-) diameter elevated temperature drawn, steel round stock with a yield strength of 862 MPa (125,000 lb/in^2) and a proportional limit equal to 80% of yield. This grade of steel was selected to provide the least amount of creep with time and the best cyclic loading performance. To make the cell, the round stock is cut into 76.2-mm (3-in.) lengths and the diameter of the center portion of the cell is machined so that the cross-sectional area is stressed to approximately 50% of yield at maximum bar loading. A 31.8-mm- (1-1/4-in.-) diameter hole is then drilled lengthwise through each cell to allow for placement on 15.9-mm- (5/8-in.-) or 25.4-mm- (1-in.-) diameter bars.

Each load cell is provided with two, 90° strain gage rosettes placed on opposite sides of the cell in the arrangement (Fig. 2). The rosettes are bonded to the cell body with strain gage adhesive and are wired in a full-bridge wheatstone configuration. One gage in the rosette is parallel to the compressive force, and the other is perpendicular. To obtain maximum sensitivity and temperature compensation, gages having the same orientation are wired *in* opposite legs of the bridge. After the rosettes are applied, a waterproof protective coating consisting of one layer of rubber sealant and two layers of air-dried plastic are applied over each rosette. An outer protective shield constructed from 63.5-mm- (2-1/2-in.-) diameter polyvinylchloride pipe is then placed over the cell and sealed to prevent damage from weather, vandals, or animals. Electrical connection is made through a cannon connector with cap mounted to the side of the shield. After assembly, the entire unit is painted with aluminum paint to reduce solar heating effects.

After fabrication, each load cell is calibrated in a test machine where a zero balance is obtained, and a calibration curve is developed to convert micro-inch readings of strain to pounds force. Once installed on a bridge, readings are taken with a portable digital strain indicator. A prefabricated, color-coded cable with a cannon connector is provided to connect the strain box to the load cell. In general, two load cells are installed on each stress-laminated bridge: one on the stressing bar at centerspan and another on the second bar in from the bridge end. Readings are normally taken weekly for the first 2 months after construction, when bar force losses are most rapid, and monthly thereafter. If the bridge is restressed for any reason, the reading frequency is repeated beginning with weekly readings.

The FPL load cells have been successfully used on many bridges over the past 3 years. In field applications, the cells have proven to be reliable, simple to operate, and require little time for data collection. Field damage has been minimal, although cells have been rendered inoperable when struck with a hammer to remove ice buildup. As a result of the continual high loads, it has been found beneficial to recalibrate and correct load cell data for creep after approximately 1 year.

Moisture content measurements

The moisture content. of the lumber laminations can play a significant role in the performance of stress-laminated timber bridges. After construction, subsequent losses in moisture content can cause the laminations to shrink and the prestress level to decrease. Gains in moisture content ran cause the wood to swell and the prestress level to increase. Through field experience, the primary concern has been with moisture decreases where the reduction in prestress can have adverse effects on serviceability and structural performance. Moisture content increases have been of little concern because increases in prestress as a result of moisture gain tend to offset losses caused by wood creep and have generally resulted in little overall change.

The FPL has used several methods to measure the moisture content. of stress-laminated bridges. Currently, an electrical resistance moisture meter with probe and 76.2-mm (3-in.) pins is used almost exclusively. The pins are driven into the wood surface, and the moisture content is read from a gage. Corrections are then made for temperature and wood species to determine the moisture content, level. The moisture meter has proven to provide acceptable trends in wood moisture content but readings may be inaccurate when the wood is treated with waterborne salts or when thin laminations are glued, such as in laminated veneer lumber. In special cases where the validity of the readings is in question, core samples may be removed and ovendried to accurately assess moisture content. and calibrate future readings.

At the beginning of the FPL monitoring program, moisture probes were also tried as a method for determining moisture content. These probes were constructed from small maple blocks with two probe wires placed in the block. A small hole was drilled in the bridge and the probe permanently inserted. Readings were taken by connecting the wire probes to a moisture meter. After initial installation, the probes provided accurate information for a relatively short period, after which the readings because erratic and inconsistant. The method has since been abandoned in favor of the simpler, more reliable moisture meter.

Field experience has shown that moisture content changes gradually in stress-laminated bridges. Thus, moisture readings are normally taken on a bimonthly or quarterly basis. More frequent readings that require additional effort have not provided additional benefit. Currently, moisture readings are consistently taken at 10 to 20 locations on the bridge underside, edges, and top, when accessible. At each location, the readings are preferably taken at depths of 25.4, 50.8, and 76.2 mm (1, 2, and 3 in.) to assess the moisture gradient near the wood surface.

Measurement of vertical creep

Like some bridge materials, wood will creep under sustained load. For stress-laminated timber bridges, vertical creep may be a serviceability concern, especially when it occurs at levels that cause a sag in the superstructure. For monitoring purposes, vertical creep is measured as the cumulative decrease in bridge centerspan elevation at 1 to 6 locations across the bridge width.

Two methods are used by the FPL for measuring creep. The first method, which requires access to the bridge underside, involves elevation readings with a surveyor's rod and level. Such readings are referenced to a vertical benchmark, and the cumulative bridge movement is measured relative to the benchmark. The second method involves suspending calibrated rules from the bridge underside. Several variations of this procedure are used depending on the accessibility of the bridge underside and the availability of surveying equipment. When access is limited, rules are suspended at the time of construction and are left in place. Readings are obtained with a surveyor's level, which is referenced to a benchmark. When the bridge underside is accessible, rules can also be suspended at fixed locations and read relative to a stringline placed between permanent locations at the bridge ends. With this method, brackets are installed on the bridge underside and rules are permanently placed or temporarily suspended. Readings are visually taken by noting the stringline location on the rule. Movement of the rule relative to the stringline provides the magnitude of elevation change.

Both creep measuring methods have shown to provide an adequate representation of bridge movement. The rod and level method provides the greatest accuracy, but it requires surveying equipment and the most time for data collection. The suspended rule and stringline method is less accurate, but it requires no additional equipment and data collection is very quick. The suspended rules may also be subject to vandalism and cannot be used when winds cause excessive movement of the rules.

Creep is generally a slow process that is reflected in the frequency of data readings. When the FPL program started, creep readings were taken on a monthly basis. This proved to be too frequent as differences in monthly readings were often less than the precision of the reading methods. Currently, creep readings are taken on a quarterly or semiannual basis. This frequency has shown to provide acceptable trends with a minimum impact on personnel requirements.

Load test behavior

To determine the behavior of stress-laminated bridges under static loading conditions, one or more load tests are normally conducted on each bridge. These tests involve the measurement of bridge deflections from an unloaded to loaded condition using several load positions. The information obtained from these tests is used to refine and improve design procedures and evaluate the effects of various design variables on bridge performance. The tests are conducted by the FPL personnel with the assistance of the cooperator. The cooperator also provides the test vehicles that are normally fully loaded three-axle dump trucks, but two-axle trucks have also been used. For double-lane bridges, two vehicles are preferable, while one vehicle is required for single-lane bridges.

To improve load test efficiency and to insure that all required data are collected, the FPL has developed a somewhat standardized procedure for vehicle positioning and data-point layout. In the longitudinal direction, vehicles are positioned for maximum deflection, which is determined from computations based on the span length and vehicle configuration and weight. Most bridges are of sufficiently short span so that this loading most often results in the rear axle(s) placed at centerspan. In the transverse direction, vehicle position depends on the bridge width. For double-lane bridges, 6 vehicle positions are generally used, 3 for centered loading and 3 for outside loading (Fig. 3). For centered loading, the truck wheel line nearest the bridge centerline is placed 0.61 m (2 ft) from the bridge centerline. Positions 1 and 2 involve individual vehicle loads in each lane, and position 3 includes both vehicles. For outside loading, the renter of the outside wheel line is placed 0.61 to 0.91 m (2 to 3 ft) from the bridge edge. Load positions 4 and 5 involve one vehicle in each lane, and position 6 includes both vehicles. When load testing single-lane bridges, the same type of positioning is used, but only 3 vehicle positions are required. Load positions 1 and 2 are the outside positions on the left and right bridge edges, respectively. For load position 3, the vehicle is centered on the bridge centerline.

Deflection readings during load tests are taken at data points located across the bridge centerspan, where maximum deflection occurs, and across each quarter point. The transverse position of data points at these locations is directly related to the number of vehicle positions and the bridge width. For all cases, points are located at centerline, at each bridge edge, and under each wheel line. Additional points are added as necessary, especially on wide bridges where data points are widely spaced. This typically results in 11 to 16 data points for double-lane bridges and 9 to 12 data points for single-lane bridges, across centerspan and across each of the span quarter points. This number of readings has proven to provide sufficient data to accurately plot displacement profiles.

Load tests are generally conducted shortly after bridge construction, when prestress is near the maximum value, and again 1 to 2 years later, after same prestress losses have occurred. To minimize the obstruction of data points, data readings are always taken from the bridge underside. Zero (unloaded) readings are taken before testing begins, after the third load position, and at the conclusion of the testing.

The three methods used by the FPL to measure deflection include the rod and level method, rule and level method, and rule and stringline method. For the rod and level method, a surveyor’s rod is placed against the bridge underside and repetitive readings are taken with a surveyor’s level at each data point, each load position, and zero reading. The rule and level method is similar, but calibrated steel rules are attached at each datum point on the bridge underside and remain in place for the entire test. Deflections are read with a surveyor’s level as the relative movement of the rule from the unloaded to loaded position. The rule and stringline method also involves rules attached to the bridge underside, but deflection is read relative to a stringline stretched between the bridge ends. Of the three methods, the rod and level method is the most adaptable to varying site conditions and is most commonly used. The rule and level method is generally preferable because repetitive readings for different. load positions can be taken very rapidly, which reduces bridge closure time. However, a major drawback with the rule method is that it cannot be used under windy conditions. The rule and stringline method is not often used because of the large number of stringlines and the setup time required. However, the method has proved useful when high water under the bridge restricts access or when a surveyor’s level cannot be placed to view all data point, locations.

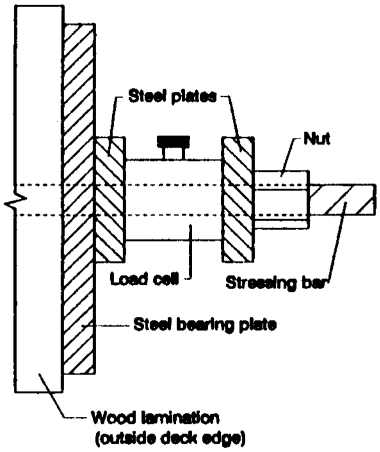

Figure 1 Typical load cell placement.

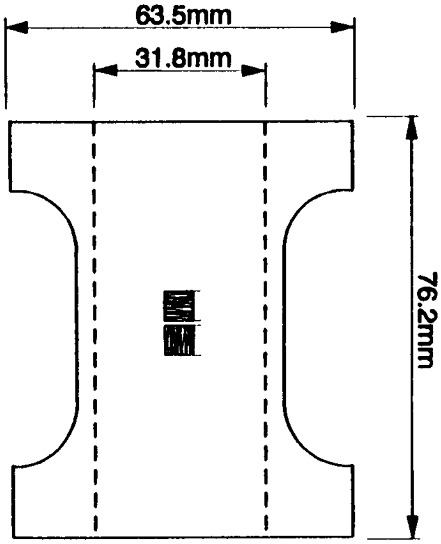

Figure 2 Placement of a strain gage rosette on the load cell body.

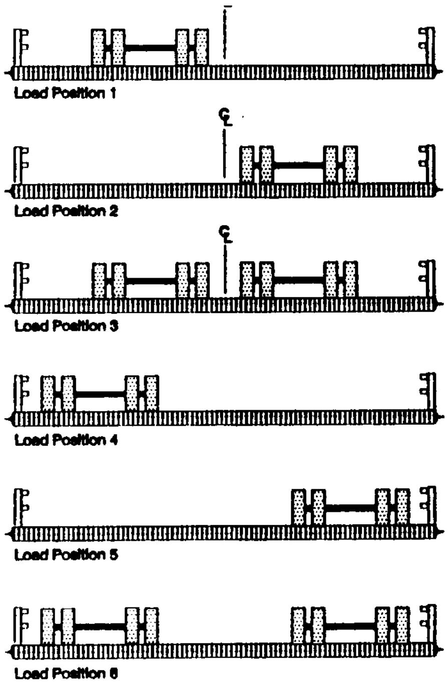

Figure 3 Vehicle positions used for load testing a double-lane bridge.

BRIDGE MONITORING RESULTS

As of March 1991, more than 50 bridges were included in the FPL bridge monitoring program. Preliminary results have been presented in a recent publication (1). Generally, stress-laminated bridges constructed in the United States have performed well. Serviceability has been the most common problem in the first bridges built and has generally resulted from high lamination moisture content levels 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-laminated bridges have been developed and will be available in the near future (2). We expect that. most problems previously encountered in stress-laminated bridge decks will be eliminated as improved guidelines are developed and distributed.

CONCLUDING REMARKS

The FPL has been involved in the monitoring of stress-laminated timber bridges since 1988. To effectively and economically implement this cooperative monitoring program, the FPL developed unified test procedures that employ simple, reliable methods to assess bridge performance. Included are methods to evaluate stressing bar force, lamination moisture content vertical creep, and bridge behavior under load. The methods used have been refined over several years and have proven to reliably reflect bridge performance.

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