Field Performance of Stress-Laminated Timber Bridges on Low-Volume Roads

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Stress-laminated timber bridges were first introduced in the United States in the late 1980s. Since that time, the concept of stress-laminating has received a great deal of attention and hundreds of bridges have been built. Most of these bridges are located on rural low-volume roads. To evaluate the performance of stress-laminated bridges, the United States Department of Agriculture (USDA) Forest Service, Forest Products Laboratory, implemented a nationwide bridge monitoring program in 1988 that was subsequently expanded in 1992 to include a cooperative program with the Federal Highway Administration. This paper presents a summary of monitoring results and observations obtained through that program for stress-laminated bridges that have been continuously monitored for 2 years or more. Included are discussions related to bridge construction, moisture content, stressing-bar force, vertical creep, load test behavior, and condition evaluation. Based on the monitoring program results, performance of stress-laminated timber bridges is generally satisfactory, although observed performance can be improved in several areas.

S tress-laminated timber bridge decks consist of a series of wood laminations that are placed edgewise between supports and stressed together with high-strength steel bars (Figure 1). The bar force, which typically ranges from 111 to 356 kN (25,000 to 80,000 lb), squeezes the laminations together so that the stressed deck acts as a solid wood plate. The concept of stress-laminating was originally developed in Ontario, Canada, in 1976 as a means of rehabilitating existing nail-laminated lumber decks that delaminated because of cyclic loading and wood moisture content variations *(1,2),* In the 1980s the concept was adapted for the construction of new bridges, and numerous structures in Ontario were successfully built or rehabilitated using the stress-laminating concept. The first stress-laminated bridges in the United States were built in the late 1980s. Since that time, several hundred stress-laminated timber bridges have been constructed, primarily on low-volume roads. Although most stress-laminated bridges are slab-type bridge decks constructed of sawn lumber or glued laminated timber (glulam), the technology has also been extended to systems employing stress-laminated trusses and T-beam and box sections. The scope of this paper is limited to slab-type deck applications.

Stress-laminated timber decks are characterized by several features that make them particularly attractive for low-volume roads where relatively short single spans up to approximately 11 m (36 ft) are required. From a materials aspect, stress-laminated bridges generally require smaller-sized, lower-quality lumber than
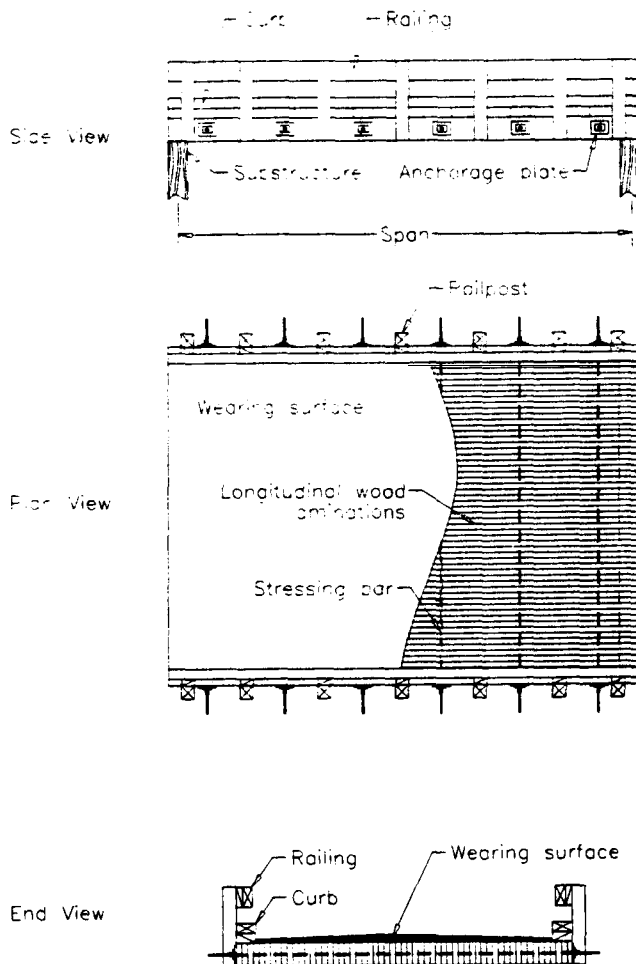
FIGURE 1 Typical configuration of stress-laminated timber deck bridge.

is typically required for other types of mechanically laminated timber decks. Because load transfer between the deck laminations is developed by friction, all laminations need not be continuous over the bridge span, and butt joints are permitted within certain limitations (Figure 2). This reduces the length of lumber required and is more conducive to the use of locally available wood species. In addition, the laminating process disperses natural defects in the wood so that variability is reduced and higher design values are possible. The bridges are also relatively simple to build and are often assembled by local crews in one day or less.

Design procedures for stress-laminated decks were first included in the Ontario Highway Bridge Design Code (OHBDC) in 1983 (3). In the United States, research on stress-laminated bridges in the late 1980s led to the development and publication of several design methods (4,5). In 1991, stress-laminated timber decks were recognized in a national design specification published by AASHTO (6). Since 1991, most stress-

laminated timber decks have been designed in accordance with AASHTO specifications, which recommend a maximum live load deflection equal to 1/500 of the bridge span. When this approach is used, the design is normally controlled by serviceability requirements for stiffness rather than strength requirements.

To evaluate the field performance of stress-laminated bridges, the Forest Products Laboratory (FPL) of the U.S. Department of Agriculture (USDA) Forest Service, implemented a nationwide bridge monitoring program in 1988. In 1992, this program was expanded through a cooperative program with the Federal Highway Administration (FHWA). The purpose of the program is to monitor and evaluate bridge performance and behavior in order to develop, confirm, or improve methods of design, fabrication, and construction by obtaining representative information on the performance of different bridge designs and materials under various geographical and environmental conditions. This paper presents monitoring results for stress-laminated bridges that have been continuously monitored for 2 years or more. Included are observations and discussions related to bridge construction, moisture content, stressing-bar force, thermal response, vertical creep, load test behavior, and condition evaluation.

BRIDGE MONITORING

Bridges included in the bridge monitoring program are selected on the basis of location, configuration, wood species, and preservative treatment. In most cases, the monitoring is undertaken as a cooperative research venture with the bridge owner. Local personnel play a key role in collecting field data. Data on each bridge are normally collected over a period of 2 to 3 years and involve monitoring methods developed by FPL (7). Key monitoring activities and methods are summarized below.

• Bridge construction: Information on bridge construction is obtained by visiting the bridge site and documenting the construction sequence and methodology. This task is commonly completed by the monitoring cooperator in the form of written and photographic documentation of the construction process.

• Moisture content: The moisture content of the bridge deck is typically measured with a electrical resistance-type moisture meter at 6 to 12 locations. Moisture content readings are generally taken on a monthly or semiannual basis depending on various bridge parameters. In addition, core samples may be removed from the deck to determine moisture content in the laboratory and calibrate electrical resistance readings more accurately. Core samples may also be taken
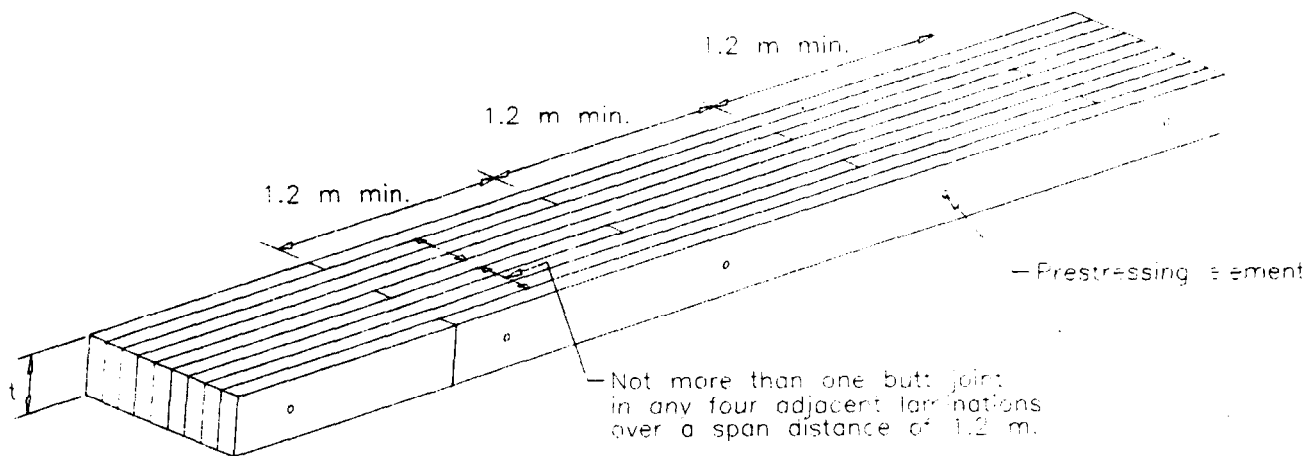
1 m = 3.31 ft.

FIGURE 2 Common butt joint configuration used in stress-laminated timber bridges.

when the accuracy of the electrical resistance meter is questionable, such as when waterborne preservatives are used or when the deck moisture content exceeds the fiber saturation point (approximately 30 percent).

• Stressing-bar force: To monitor stressing-bar force, two to three load cells are installed on each bridge. The strain in the load cell is measured manually with a portable strain indicator or automatically through a remote data acquisition system. The measured strain is then converted to an equivalent stressing-bar force. Manual readings are normally taken on a monthly basis but may be as frequent as weekly for a period immediately after construction. With a remote data acquisition system, readings are automatically recorded several times a day.

• Thermal response: The response of stress-laminated decks to temperature changes is measured with thermocouples installed at various locations in the bridge deck. Deck temperatures are then compared with ambient temperatures and load cell readings to evaluate bridge response to temperature change. Thermal response requires the use of a remote data acquisition system, and readings are recorded automatically at the same frequency as load cell readings.

• Vertical creep: Long-term vertical creep is measured by referenced elevation readings taken on the bridge underside at centerspan. Such readings are typically obtained with a survey rod and level or with calibrated rules that are suspended from the bridge underside and read relative to a reference stringline.

• Load test behavior: Bridge behavior under vehicle loading is determined for various vehicle positions by measuring the relative displacements of the bridge deck from an unloaded to loaded condition. For single-lane bridges, one vehicle is used. For two-lane bridges, one vehicle is used in each lane, and both lanes are loaded simultaneously. Deflection measurements are obtained by suspending calibrated rules from the deck underside and reading the relative position of the rules with a surveyor's level or by measuring the bridge deflection directly with displacement transducers.

• Condition evaluation: A condition evaluation of each bridge is completed several times during the monitoring period and involves intensive visual inspections and photographic documentation. Specific evaluation areas include the general structure condition, stressing system corrosion, and wearing surface performance.

The FPL/FHWA bridge monitoring program currently includes approximately 40 stress-laminated timber bridges located across the United States. Each year, five to eight new bridges are added, and approximately the same number of bridges are completed. The information presented in this paper is based on the data obtained over the past 6 years from 24 bridges that have been continuously monitored for periods of 2 years or more. Performance trends and conclusions are representative of the general behavior demonstrated by the bridges. More specific information on individual bridges will be available in the future as more information is obtained and detailed reports are published. Additional information on stress-laminated bridge performance is also available in reports published by Wacker *(8),* Dickson and GangaRao *(9),* Gutkowski and Lewis *(10),* and Mozingo and DiCarlantino *(11).*

FIELD PERFORMANCE OF STRESS-LAMINATED DECKS

The field performance of stress-laminated timber deck bridges has generally been satisfactory. When proven design and construction practices are followed, performance has typically been good. However, deviations from recommended practice have resulted in unexpected performance problems in some cases. The majority of these problems have been related to serviceability rather than the structural (safety) features and have resulted from the evolutionary nature of the stress-laminated system in the United States. Although proven design and construction criteria have been developed in Ontario for a number of years, definitive guidelines on design, construction, and maintenance practices have taken time to evolve in the United States. In addition, many U.S. designs have differed from those in Ontario and do not necessarily fit within existing standards of practice. One method to improve field performance of stress-laminated timber bridges is to learn from past experience and incorporate proven technology into future bridges.

The following is a summary of the field performance information related to stress-laminated timber bridges included in the FPL/FHWA bridge monitoring program. Included are information and observations related to bridge construction, moisture content, stressing-bar force, vertical creep, load test behavior, and condition evaluation.

Bridge Construction

A number of methods have been used to construct stress-laminated timber bridges *(4)*. When laminations are continuous (i.e., no butt joints), they can be individually placed on abutments, bars can be inserted, and the bridge stressed in place. When butt joints are used, the bridge can be prefabricated into nailed or banded panels that are stressed together in the same manner.

In addition, bridges may be prefabricated into prestressed panels that are joined with bar couplers at the bridge site. Regardless of the construction method used, current practice requires that stress-laminated timber bridges be stressed three times during the construction process: at initial assembly, 1 to 2 weeks after the first stressing, and 4 to 6 weeks after the second stressing *(4)*. Most bridges in the United States have been stressed using one jack rather than the multiple jacks commonly used in Ontario. This issue is primarily economic because the high cost of a multiple-jack system cannot be justified unless a large number of stress-laminated bridges are built on a continuing basis. A single-jack system can be purchased for approximately $1,200 and

provides similar results if proper bridge stressing procedures are followed.

Field monitoring has shown that construction methodology and practices can affect bridge performance and appearance. When using a single jack for stressing, the most frequent problems result from a failure to recognize that, as the bars are stressed during construction, the laminations are compressed and the bridge width narrows. This narrowing is generally most pronounced during the first stressing but may also occur during the second stressing at a decreased level. By the third stressing, deck narrowing is minimal. The magnitude of deck compression during the first stressing can vary from 25 to 75 mm (1 to 3 in.) depending on a number of factors including the bridge width, wood species, and the straightness of the lumber laminations. More compression occurs as the bridge width increases, and most softwoods compress more than dense hardwoods. Also, warped laminations result in more compression as the laminations are straightened during the stressing operation.

For the bridges evaluated in the monitoring program, the most frequent construction problems, insufficient prestress, deck distortion, and deck attachment damage, were encountered during the stressing procedure.

Insufficient Prestress

For acceptable bridge performance, all bars must be uniformly stressed to the full design level during each of the three required stressings. Field observations indicate that, when a single jack is used, stressing one bar compresses the deck at that location and reduces the force in adjacent bars. In bridges where each bar was stressed only one time, substantial variations in bar force were noted. To prevent these variations, each bar must be stressed several times as the deck compresses until the prestress level is uniform for all bars. The most successful construction method for accomplishing this uniformity is to begin stressing at one bridge end and sequentially stress each bar along the bridge length. This process is repeated until three to six passes have been made along the bridge length and the force reaches the designated level in all bars.

Deck Distortion

Compression of the laminations during stressing led to deck distortion in numerous bridges. To keep the bridge edges parallel and straight, the initial bridge stressing must be gradual, starting at a low prestress that is gradually increased. If the full prestress level is placed initially in one bar, the deck will compress significantly at that location and deck distortion can result. Field observations have shown that this can lead to an hourglass

shape (the bridge is narrower at centerspan than at the ends) if the midspan bar is fully stressed first or a reverse hourglass shape (bridge ends are narrower than centerspan) if the end bars are fully stressed first. Other patterns of distortion have also been observed. To minimize deck distortion during the initial stressing, field observations indicate that a low initial prestress of 10 to 25 percent of the design level should be placed in the bars and the deck shape observed. If distortion of the deck is evident, the prestress is adjusted accordingly until the distortion is removed. The prestress is then increased to 25 to 50 percent of the design level, and the bridge is restressed again. This process is repeated until the deck is completely stressed to the full design level.

Deck Attachment Damage

When attachments to the bridge deck are made before deck narrowing, damage to the deck and attachments may occur. This damage is most evident when curbs are bolted in-place or the bridge is attached to the substructure before stressing is complete. As a result, fasteners and other metal components may bend, and wood may be damaged. To prevent such damage, field observations indicate that deck attachments should be made only after the second bridge stressing is complete.

Moisture Content

The moisture content of wood at installation and in-service is a primary consideration 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 to design values, when applicable. Of primary concern in stress-laminated bridges is the dimensional stability of the wood as changes in moisture content occur. Below the fiber saturation point (approximately 30 percent), wood will expand as moisture is gained and contract when moisture is lost. In stress-laminated bridges, these dimensional changes can affect bridge performance. Moisture content changes in stress-laminated decks generally can be considered as global changes and localized changes. Global changes affect the entire structure and occur slowly as the moisture content of the bridge laminations at the time of construction moves toward an equilibrium moisture content with the environment *(4)*. Localized changes affect the exposed portions of the bridge and occur more rapidly in response to surface wetting or seasonal fluctuations in equilibrium moisture content.

Global Moisture Content Effects

The effect of global moisture content changes in stress-laminated timber bridges depends on the moisture content of the wood laminations at the time of construction and the average equilibrium moisture content for the bridge site. With few exceptions. bridges included in the monitoring program were made of sawn lumber with a relatively high moisture content. Typical moisture content values at the time of construction ranged from 25 to 29 percent; however, moisture contents in excess of 30 percent have been measured on numerous bridges. At such high levels, the wood moisture content substantially exceeds the expected equilibrium moisture content, which typically averages 16 to 20 percent depending on the bridge location *(12)*. Conversely, several stress-laminated timber bridges constructed with glulam laminations have been installed with average moisture contents as low as 12 percent. Field measurements have shown that global moisture content changes toward an equilibrium level are relatively slow. As a result, the observed effects of global moisture content changes are minimal during the first several months after bridge construction. However, the effects become much more pronounced as the decks eventually lose or gain moisture. Such global moisture content changes directly affect stressing bar force levels, which decrease when moisture is lost and increase when moisture is gained. Based on field evaluations, the best bridge performance has been observed when the moisture content of the wood laminations at the time of construction averages 10 to 16 percent. Acceptable performance has been observed when the moisture content is 16 to 20 percent. As the moisture content increases above 20 percent at the time of construction, adverse performance becomes more pronounced as the moisture content is increased.

Localized Moisture Content Effects

Field data indicate that localized moisture content changes caused by surface wetting and seasonal moisture content changes can also affect the performance of stress-laminated timber bridges. The most pronounced affect appears to occur in relatively deep decks, 300 to 400 mm (12 to 16 in.) thick, when the top deck surface is exposed or covered with a lumber plank wearing surface. In such cases the deck surface absorbs moisture more rapidly than the inner and lower portions. As a result, repeated wetting or standing water may cause the upper portion of the deck volume to swell in relation to the lower portion. Although no adverse structural effects have resulted from this response, evidence of differential moisture content is observed as a slight transverse crown in the deck, wood crushing in the outside edge laminations along the top of the bar anchorages,

and/or an increase in stressing-bar force. 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 combination with a waterproof geotextile membrane.

Stressing-Bar Force

The structural integrity and serviceability of stress-laminated decks depends on the compressive stress maintained among the lumber laminations. For acceptable performance, this compression must be sufficient to prevent vertical slip because of shear and opening between the laminations because of transverse bending. Current design procedures recommend a minimum interlaminar compression of 690 kPa (100 lb/in.^{2}) at the time of bridge construction. This initial compressive stress is based on the assumption that 50 to 60 percent of the stress will be lost over the life of the structure because of wood stress relaxation and minor changes in wood moisture content (4). Research has shown that slip between the laminations does not begin until the interlaminar compression has been reduced to 140 to 165 kPa (20 to 24 lb/in.^{2}).

As previously discussed, construction procedures for stress-laminated timber bridges recommend that bridges be stressed three separate times over a period of six to eight weeks. Based on monitoring program results, it appears that this stressing sequence is not adequate in many cases. Many of the bridges in the monitoring program required restressing within the first two years after construction. For bridges constructed of sawn lumber, field observations indicate that the bar force should be checked at annual intervals for the first 2 years after construction and every 2 years thereafter. After bar force stabilizes, this period may be extended to 2- to 5-year intervals. For bridges constructed of glued laminated timber, field observations indicate that bar force should be checked every 2 years for the first 4 years after construction and every 5 years thereafter. These observations are based on the behavior of numerous bridges and should be adjusted for site specific conditions.

Of the bridges included in the monitoring program, bar force loss resulted in structural problems on one bridge. In this case it was known that the bar force was rapidly dropping, yet no corrective action was taken to restress the bridge. Vertical slip of the laminations resulted from heavy truck traffic and was evident in one lane at centerspan as a depression where truck wheel lines were tracking. After the slip occurred, the bridge continued to carry traffic at a reduced load level until it was restressed and subsequently repaired. When slip

of this type occurs, the stressing bars act as dowels among the laminations, and the initial failure primarily affects serviceability and is very evident. Thus, ample warning is given so that appropriate repair can be made before further problems develop.

For monitoring purposes, compressive stress among the laminations is determined by measuring the stressing-bar force. Field performance of stress-laminated bridges has shown that bar force, and thus interlaminar compression, is a complex interaction of many effects including wood stress relaxation. moisture content changes, bar anchorage performance, and temperature fluctuations. When evaluating the causes of loss of stressing-bar force for field bridges, it is impossible to determine the individual effect of the numerous contributing factors accurately. However, we can make the following observations relative to the general performance of bridges included in the monitoring program.

Stress Relaxation

When laminations are subjected to the long-term loads applied by stressing bars, the wood slowly deforms over the entire bridge width, and the bar force is reduced. This phenomenon, known as stress relaxation, is similar to creep. The rate of stress relaxation is greatest when the bridge is initially stressed and normally decreases with each subsequent stressing. Field observations indicate that bar force loss because of stress relaxation continues at a slow rate that gradually decreases after construction, depending on several factors. Stress-relaxation losses increase as the moisture content of the wood increases and are greater for softwoods such as Douglas fir and pine than for dense hardwoods such as oak or maple. In addition, bar force loss because of stress relaxation increases as the bridge width increases (the volume of wood between the bar anchorages increases).

Moisture Content

The moisture content at the time of construction is one of the most influential factors on maintaining bar force. The best performance occurs when the wood laminations are installed at an average moisture content less than 16 percent. At this low level, global increases in lamination moisture content toward an equilibrium level result in swelling, which increases bar force, offsets loss because of stress-relaxation, and is beneficial. When installed at moisture contents above 20 percent but less than 30 percent, moisture content decreases are gradual but result in a loss in bar force of as much as 80 percent over an 18 month period. When lumber laminations are above the fiber saturation point at the time of construction, drying is slow. At such high moisture contents, no

loss in bar force because of wood shrinkage is evident until the wood dries below the fiber saturation point; however, as the moisture content decreases below fiber saturation, bar force losses are substantial.

Anchorage System Performance

The purpose of the anchorage system for stressing bars is to distribute the bar force into the deck without causing wood crushing along the outside laminations. When crushing does occur, force reduction in the stressing bars can be substantial. Historically, anchorage systems used for stress-laminated decks have used a steel channel or discrete plate configuration (Figure 3). The channel configuration was developed in Ontario and is currently a design requirement of the OHBDC. The discrete plate was developed in the United Stares and uses a single rectangular bearing plate at each bar. With few exceptions, the bridges included in the monitoring program use the discrete plate anchorage because it is less expensive than the steel channel and provides acceptable performance when properly designed. When properly sized plates are used on softwood lumber species (Douglas fir and pine), crushing into the bridge outside laminations has typically averaged 3 to 6 mm (1/8 to 1/4 in.). On dense hardwood laminations, such as oak and maple, properly designed plates show virtually no crushing. Field observations indicate that anchorage performance on softwood bridges is improved when two more dense hardwood laminations are used along the bridge edges.

Thermal Response

Bridges included in the FPL monitoring program are located throughout the United States. Numerous bridges are subjected to annual temperature variations of 38°C (100°F) or more. Two bridges have been instrumented to measure the effect of large temperature decreases on the stressing bar force. These bridges are located in regions where ambient temperatures have reached 38°C (100°F) in the summer and –40°C (-40°F) in the winter. Data collected for both bridges indicate that bar force decreases when temperature drops. The magnitude of this decrease depends on a number of factors including the magnitude of the temperature change, the duration of cold temperature, the wood species, and the moisture content. The temperature effect is most pronounced when the wood moisture content is at or above fiber saturation. Short-term temperature declines over periods of 24 hours or less have little effect on bar force because thermal conductivity of wood is very low. The cold temperature effect appears to be fully recoverable, and the bar force returns to the original level when the temperature is increased. At this time, no evidence indicates that temperature effects alone result in any structural or serviceability problems in stress-laminated timber bridges; however,
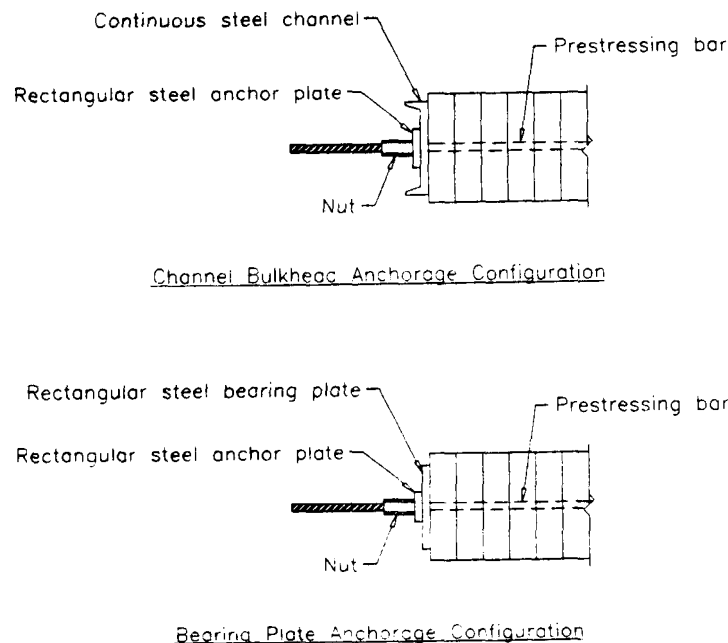
FIGURE 3 Stressing bar anchorage configurations commonly used on stress-laminated bridge decks.

extensive laboratory and field work in this area is continuing, and more definitive conclusions will be forthcoming.

Vertical Creep

As a structural material, wood is subject to permanent deformation because of long-term sustained loads. This deformation, known as creep, depends on a number of factors and is more pronounced when the magnitude of applied loading and the moisture content of the wood increase. For timber bridges, creep results in vertical deformation of the bridge span and, in extreme cases, a noticeable sag. Although this is not a significant structural problem, a sagging bridge is alarming to the public. In addition, creep can disrupt bridge drainage and facilitate water ponding, which may be a hazard to bridge users. To offset the effects of creep, stress-laminated timber bridges made with glulam timber or lumber with butt joints can be cambered; however, bridges made with continuous lumber cannot be cambered.

In general, creep has not been a problem in stress-laminated timber bridges. Three bridges, which were among the first built in the United States, are exceptions in that creep caused a sag at centerspan of 50 to 75 mm (2 to 3 in.). In each case, the bridges have a high span/ depth ratio, were installed with a high lamination moisture content greater than 28 percent, and had butt joints.

In comparing the behavior of these bridges to that of other stress-laminated timber bridges, the most important factor affecting creep appears to be the magnitude of the permanent load bending stress. Although the moisture content of the laminations and the spacing and frequency of butt joints also affect creep, the relative contribution of these factors compared to permanent load bending stress appears to be small. Currently, there are no design provisions for limiting creep; however, span limitations resulting from live load deflection requirements appear to be sufficient to limit permanent load bending stress adequately and control creep to an acceptable level. Creep has not been a detectable problem in stress-laminated bridges when the live load deflection for standard highway loading is limited to 1/360 to 1/400 of the bridge span, regardless of the presence of butt joints or the moisture content of the laminations.

Load Test Behavior

Load tests were conducted on all stress-laminated timber bridges in the monitoring program to assess structural behavior under a static loading condition. Each bridge is load tested twice: shortly after construction and at the end of the monitoring period, 2 to 3 years later. Additional load tests may be conducted if the further evaluation of unique features is considered beneficial. In addition to static tests, dynamic load tests were also conducted on nine bridges. In all cases, load tests showed that stress-laminated timber decks act as large orthotropic plates. The magnitude of the deck displacements and the deformed shape of the loaded bridge depend on a number of factors including the bridge span and width, vehicle weight and configuration, deck material properties, the location and frequency of butt joints, the prestress level, and the edge stiffening effects of curb and rail systems. Based on results from the static and dynamic tests and analytical modeling. revised methods for predicting the behavior of stress-laminated timber bridges are currently being developed at FPL.

Condition Evaluation

The condition of each bridge in the monitoring program is evaluated several times during the monitoring period. In the course of these evaluations, information is collected relative to the general bridge condition, stressing system corrosion, and asphalt wearing surface performance.

General Condition

General condition assessments are performed on stress-laminated timber decks to evaluate the performance of various components and design features unrelated to the features associated with stress-laminating. The majority of the noted deficiencies have been relatively minor but typically could develop into more serious problems as time passes without corrective action. In general, most deficiencies are directly attributable to poor design detailing and/or construction methods. Unfortunately, many of the same deficiencies are also common on other types of timber bridges primarily because of the inexperience of most engineers and contractors in wood design and construction methodology. As time progresses and more information on timber bridges becomes available, engineers and contractors will become more experienced, and these problems should be minimized.

Several of the common observations related to the general condition of stress-laminated timber decks are summarized below.

1. *Increased emphasis is needed in the area of field treating.* Ideally, all wood used in bridge construction should be completely fabricated before it is treated with wood preservatives. This method is difficult for stress-laminated decks because the location of bolt holes for

deck attachments cannot be confirmed until the bridge is stressed. Consequently, deck holes for curbs, railing, and substructure attachment must often be field drilled. When this is done, the exposed untreated wood must be field treated with wood preservative. On numerous bridges, evidence of field drilling and cutting without field treatment has been evident. This method exposes untreated wood and can lead to premature deterioration. Proper field treating in accordance with American Wood Preservers' Association (AWPA) Standard C14 *(13)* will significantly reduce deterioration potential.

2. *improved design detailing and maintenance are needed for debris control.* Accumulations of dirt and debris on wood bridges can trap moisture and create an environment suitable for deterioration. Although wood preservatives effectively protect the wood, deterioration is possible when field fabrication has been used or the preservative treatment is incomplete. On many of the stress-laminated bridges in the monitoring program, significant debris accumulations were observed on the bridge deck, under curb openings, and at the bearings. Although no adverse effects were noted, the potential for future deterioration was evident. To some degree, debris accumulation can be reduced by proper design detailing. However, periodic maintenance to remove debris is essential for maximizing bridge performance and longevity.

3. *Special attention is needed to ensure proper wood treatment.* Wood used in stress-laminated decks is typically treated with oil-type preservatives in accordance with AWPA Standard C14 *(13).* Dripping of the preservative from the bridge has not been a widespread problem; however, minor preservative dripping has been observed on several bridges. In such cases, the bridges were treated to preservative retentions substantially above those required by AWPA standards. The subsequent compression among the laminations because of stressing forced minor amounts of preservative from the laminations. Preservative dripping does not appear to be a problem when the laminations are properly treated in accordance with AWPA stadards to the required preservative retention.

Stressing System Corrosion

Adequate corrosion protection of the steel stressing system has been a primary consideration since the development of stress-laminated timber bridges. The original bridges constructed in Ontario used a plastic tube filled with grease to protect the stressing bars. Bridges built in the United States have typically used galvanizing as a means of corrosion protection, although several bridges have been built with galvanized bars placed in grease-filled tubes. Over the past 6 years of the bridge monitoring program, corrosion has occasionally been observed in exposed bar locations where anchorage nuts were not oversized to compensate for bar galvanizing. This corrosion resulted when the nuts were forced onto the bars during construction and the galvanizing was damaged. Properly sizing nuts or applying a cold galvanizing compound to the damaged areas will eliminate this problem. At interior bar locations inside the deck, bar corrosion has not been a problem; however, the monitoring period has been relatively short and definitive conclusions on long-term corrosion potential cannot be made. Based on preliminary observations, enclosing the bars in grease-filled plastic rubes may be warranted if the bridge is subjected to corrosive deicing chemicals in winter months. In addition, protective tubes may be warranted when the lumber laminations are treated with waterborne preservatives containing copper and it is anticipated that the lamination moisture content will exceed 20 percent. Under these conditions, depletion of zinc in the galvanizing is possible because of an electrochemical reaction with copper in the wood preservative.

Asphalt Wearing Surface Performance

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 non-interconnected deck panels have been associated with cracking or disintegration of asphalt wearing surfaces. This deterioration is caused by differential movement among individual laminations or vertical movement at joints. Many of the stress-laminated timber bridges in the monitoring program were paved with an asphalt wearing surface. In most cases, the asphalt was placed to a compacted thickness of 50 to 75 mm (2 to 3 in.) at centerline and tapered to a compacted thickness of approximately 40 mm (1.5 in.) along the deck edges. Because stress-laminated decks act as large wood plates and the applied prestress sufficiently prevents vertical movement of the individual laminations, asphalt cracking and deterioration related to bridge performance were not observed on any of the stress-laminated decks. Even on decks designed for full highway loads with a design live-load deflection as high as 1/250 of the bridge span, no asphalt cracking or deterioration has been apparent during the monitoring period.

SUMMARY

Several hundred stress-laminated timber bridges have been built in the United States since 1988. Based on observations of 24 bridges that were monitored over a period of 2 years or more, bridge performance has generally been satisfactory although performance can be

improved in several areas. Key recommendations based on monitoring program observations follow.

1. When bridges are stressed with a single jack, three to six stressing passes should be made along the bridge length to ensure uniform prestress at the required level. In addition, the stress level should be gradually increased over the first several passes to minimize deck distortion.

2. Attachments to the bridge superstructure including curbs, railings, and substructure attachments should not be made until after the bridge has been fully stressed two times.

3. The average moisture content of the wood laminations at the time of bridge construction should preferably be 10 to 16 percent but should not exceed 20 percent.

4. For bridges constructed of sawn lumber, bar force should be checked at annual intervals for the first two years after construction and every two years thereafter. This period may be extended after bar force stabilizes to 2- to 5-year intervals. For bridges constructed of glued laminated timber, bar force should be checked every 2 years for the first 4 years after construction and every 5 years thereafter.

5. Bridge live-load deflection should be limited to a maximum of 1/360 to 1/400 of the bridge span.

6. When oil-type wood preservatives are used, the preservative retention should not exceed that recommended in AWPA Standard C14 *(13)*.

7. Consideration should be given to enclosing stressing bars in grease-filled plastic tubes if the bridge is subjected to corrosive deicing chemicals or if the lumber laminations are treated with waterborne preservatives containing copper and it is anticipated that the lamination moisture content will exceed 20 percent.

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