Behavior of a Red Oak Stress-Laminated Bridge in Rhode Island

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The results of a 15-month monitoring program of a red oak stress-laminated timber bridge are evaluated. The bridge is the first of its kind in the state of Rhode Island and one of the earliest of its type constructed of red oak in the United States. The monitoring program included inspecting the bridge periodically, reading the load cell, measuring the wood moisture content, and recording the ambient temperature and relative humidity at the bridge site. The evaluation demonstrates that additional design factors may need to be considered before red oak is completely accepted as a construction material for stress-laminated bridges. Specifically, the monitoring program revealed fluctuations in the wood moisture content, and ambient temperature affected the stress levels in the steel rods to an extent that these factors may need to be considered in the design of this type of bridge. The loss of the initial rod stresses in the bridge were investigated; these losses correlated very well with exponential functions. The exponential functions are used to predict when and if the bridge will have to be restressed to maintain the design minimum stress levels.

Stress-laminated timber deck bridges were initially conceived in Ontario, Canada, in the mid-1970s as a method of rehabilitating structurally deficient nail-laminated timber bridges. The process involves threading steel rods transversely through the wide face of the timber deck and tensioning the rods so the individual laminae are compressed together. Loads are distributed through the structure via friction developed between the laminae as opposed to nail-laminated deck bridges in which the loads are transferred through the nails. Today, stress laminating is used not only as a method of strengthening existing bridges but also as a method of designing new bridges. In Europe, the rods are sometimes outside the laminations to avoid reducing the wood section.

A number of stress-laminated timber bridges have been constructed in the United States under the Timber Bridge Initiative, which was sponsored by Congress in 1989 and has been administered by the USDA Forest Service (*1*). Traditionally, short-span bridges have been replaced with concrete and steel; however, many design engineers favor timber as a viable alternative, mainly because timber is not subject to the detrimental effects of salt and corrosion. Also the initiative promotes the use of locally grown timber; therefore, many municipalities are replacing the structurally deficient or functionally obsolete bridges within their jurisdictions with new stress-laminated timber bridges constructed of local materials and by local labor.

NORTH ROAD BRIDGE

The North Road Bridge over Hemlock Brook in the town of Foster is the first stress-laminated timber deck bridge in Rhode Island. Funding for the construction of the bridge was partially provided by the USDA Forest Service through the Timber Bridge Initiative. The bridge is a single-span structure on a 6-degree skew. An elevation and cross section are shown in Figures 1 and 2, respectively. The bridge replaces an older steel beam bridge that had severely deteriorated. The new superstructure rests on the original concrete abutments that were modified slightly to accommodate the new superstructure width.

The superstructure consists of red oak laminations 50.8 × 64.5 mm that are not continuous over the bridge span. Instead, staggered butt joints are provided (Figure 3). The bridge span is 6.405 m measured parallel to the road centerline. The out-to-out bridge width measures 7.32 m perpendicular to the road centerline. The bridge is covered with a bituminous wearing surface that measures approximately 76.2 mm at the crown and 50.8 mm at the curbs. The wearing surface is composed of 38.1 mm of binder and a varying amount of surface course.

The stressing system consists of 13 ASTM A722 steel rods 15.875 mm in diameter. The spacing of the rods is shown in Figure 4. This figure also shows the location of the load cells that were placed on four of the rods to monitor rod stress levels. The rods have an ultimate strength of 1033.5 MPa, and the plans called for the rods to be galvanized or epoxy coated. The bulkhead system consists of ASTM A36 bearing plates 203.2 × 203.2 × 19.05 mm and ASTM A36 anchorage plates 76.2 × 76.2 × 19.05 mm. The red oak was green when ordered and was dried to a 17 percent moisture content just before treatment with creosote. Figures 5 and 6 show the elevation of the bridge and a detail of the bulkhead system, respectively.

The deck was originally assembled on the bridge approach roadway. The rods were initially stressed to 124.6 kN, and the deck was lifted and positioned on the abutments. One week later, the rods were stressed again to the same level. Final stressing (to 124.6 kN again) was completed 5 weeks after the second stressing. A single hydraulic jack was used for all stressings, and multiple passes were completed each time that the bridge was stressed to ensure a uniform stress.

MONITORING PROGRAM

When construction of the bridge was completed in the fall of 1992, a monitoring program was started to evaluate the performance of the actual structure. Although it is in general expensive and not usually used for bridge construction, red oak is in abundance in the area and

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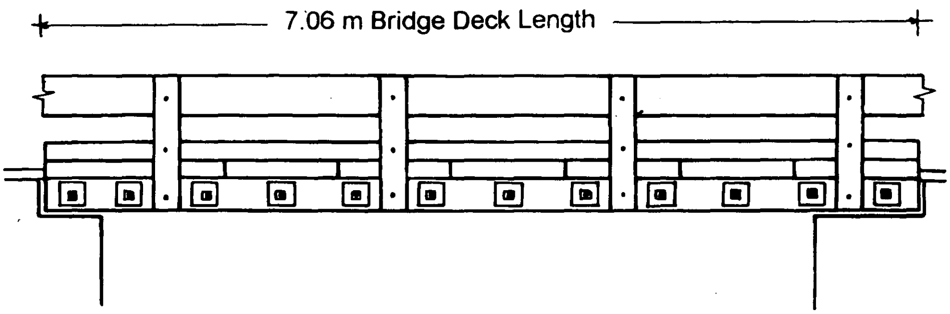

FIGURE 1 Elevation of the North Road Bridge.

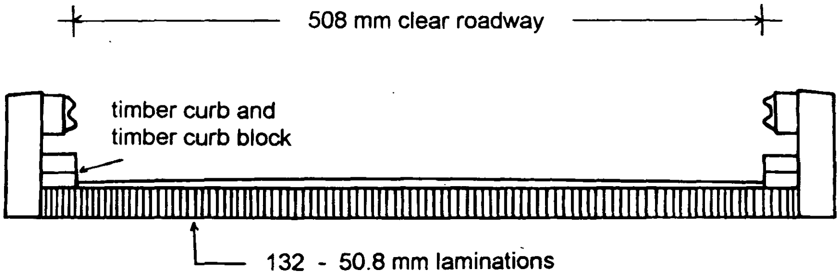

FIGURE 2 Cross section of the North Road Bridge.

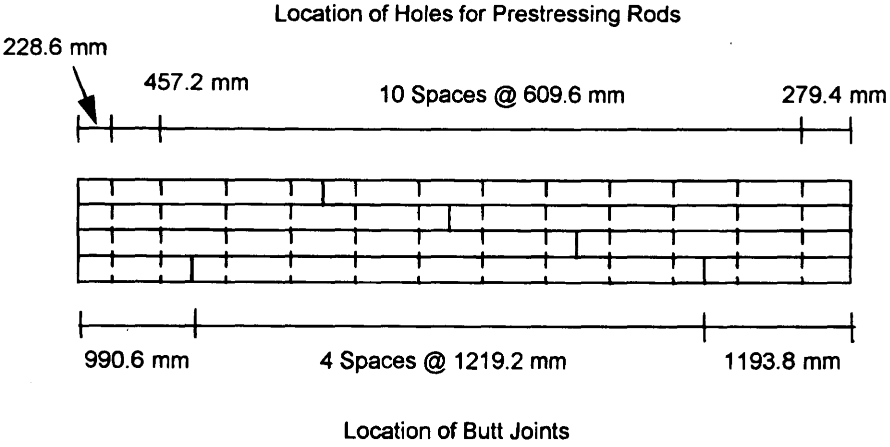

FIGURE 3 Butt joint pattern of the North Road Bridge.

was selected as the natural choice. The monitoring program included the following procedure.

General Condition of the Bridge

The bridge was visually inspected several times during a 15-month period. The performance of the wearing surface was monitored; specifically, it was inspected for cracks and for signs of how well it was binding to the timber deck. The timber deck was visually inspected at the abutments for signs of crushing and also for signs of crushing near the anchor plates at each rod. In the areas exposed to drainage, the deck was also inspected for signs of decay. The deck underside was investigated for splitting, sagging, checking, cracks, and water penetration. Overall, the deck was inspected for signs of distress and delamination.

Stress Levels

Four load cells were installed to monitor the force in the corresponding rods. These were numbered 1458, 1459, 1460 and 1461 by the manufacturer and are referred to by these numbers in this paper. Figure 4 shows the exact positioning of the load cells. The

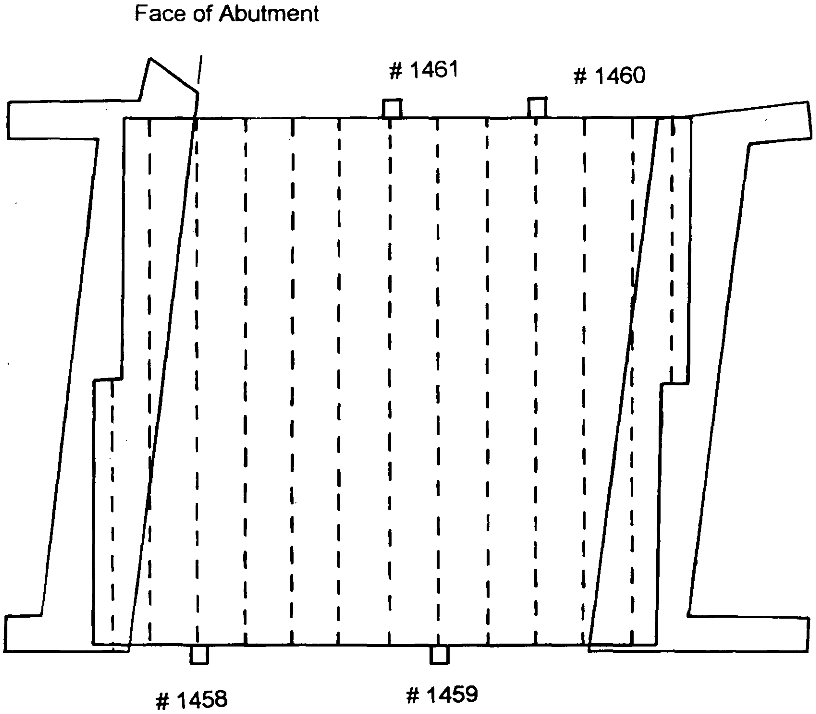

FIGURE 4 Plan view of bridge showing spacing of prestressing rods and location of load cells.

FIGURE 5 Side view of bridge.

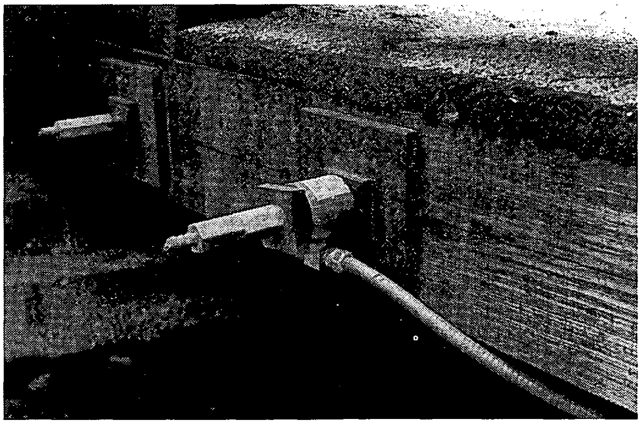

FIGURE 6 Detail of load cell attachment.

force in each rod was measured beginning on the day the superstructure was lifted into place, which coincided with the second stressing of the bridge. Daily readings were taken beginning on that day for 10 consecutive days; thereafter, weekly readings were taken for 11 consecutive weeks. The weekly readings were followed by 11 monthly readings.

MOISTURE CONTENT

Two moisture meters were used to monitor the moisture of the red oak laminae. The first meter was a "protimeter mini" and measured moisture at a depth of 12.7 mm. The second, known as a "hammer electrode," measured moisture at a depth of 44.45 mm. The moisture content of the bridge timber was measured beginning with the first weekly stress reading. Therefore, 11 moisture content measurements were taken weekly, and 11 moisture content measurements were taken monthly. The moisture content was measured on the underside of the deck at ten random locations each time. The average of the ten measurements was calculated and recorded. Because 2 different probes were used, a total of 20 measurements were made each time.

Ambient Temperature and Relative Humidity

A pocket psychrometer was used to obtain the ambient temperature and relative humidity at the bridge site. The ambient temperature was recorded weekly for 11 weeks and monthly for 11 months on the same days as those for which the wood moisture content was measured. In addition, the ambient temperature was recorded 15 times during one 24-hr period. The relative humidity at the bridge site was measured each time the ambient temperature was recorded.

EVALUATION OF RESULTS

General Condition

In general, the pavement on the North Road Bridge was found to be performing very well after more than 1 year in service. There were fine transverse cracks in the pavement along the bridge end joints, running across the full width of the bridge, but these appeared because the pavement inadvertently was not sawn and sealed at these joints. The steel rods exhibited light rusting at their ends where they were field cut but not treated with a protective coating. The rods were field cut so they would not extend more than 152.4 mm beyond the nuts. There was a split (a longitudinal crack parallel to the wood grain) extending the full length of the bridge in the fascia laminae on both sides of the bridge. The split occurred sometime after the bridge was assembled. There was also some light crushing of the fascia laminae near the bearing plates at most of the rods. (Crushing of the fascia laminae has occurred in many other stress-laminated bridges.) The underside of the deck revealed that two inside laminae were split. This splitting probably occurred during the first stressing, which was used primarily to eliminate the warps in the wood.

Loss of Rod Stresses

Adequate stress levels in the steel rods are essential for this type of timber bridge construction. Many factors affect the prestressing force, including creep in the wood, moisture content, temperature, and humidity (*2,3*). It is difficult to separate the effects of each individual factor in the total loss of prestressing force. Loss of prestress caused by creep is predominant in the early stages of the bridge life. However, contrary to laboratory tests, it is difficult in the field to capture the initial effect. In this particular bridge, stressing was done during assembly as a means of flattening warped planks. The load cells were placed on the rods during the second stressing (Day 7); therefore, the loss of prestress in the interim between Days 0 and 7 was not recorded. Between the second stressing (Day 7) and the final stressing (Day 43), the rod equipped with Load Cell 1461 exhibited the sharpest decline in prestress, losing 39 percent of its initial value. The rods equipped with Load Cells 1458, 1459, and 1461 lost 13, 22, and 30 percent, respectively, during this period. It can be assumed that most of this loss was attributable to creep in the wood.

The rod instrumented with Load Cell 1461 showed the greatest loss of prestress over the monitoring period of 415 days; however, it maintained 47 percent of its initial prestress, which was considered acceptable in other stress-laminated bridges constructed of other wood species. The rods instrumented with Load Cells 1458, 1459, and 1460 have maintained 76, 86, and 58 percent of their initial prestress levels, respectively. These have been considered high retention levels in other stress-laminated bridges constructed of other wood species.

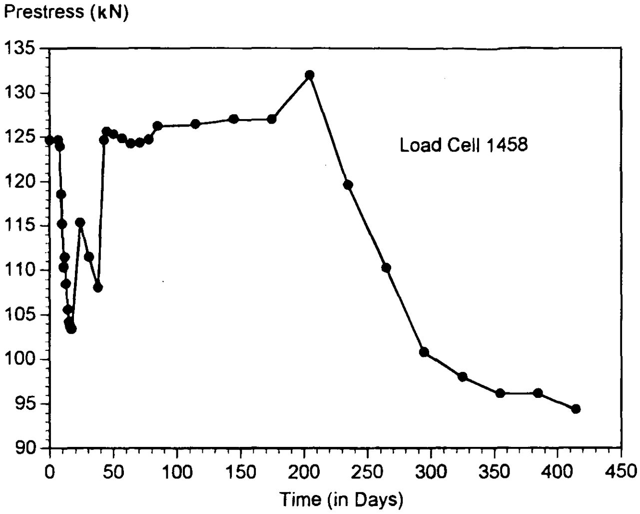

FIGURE 7 Variation of stressing force in Cell 1458.

Figures 7 through 10 show the loss of prestress over time for the instrumented rods. The graphs show that the prestress levels did not constantly decline between readings. After an initial decrease that was attributable again to creep, increases as well as decreases in prestress levels were evident. The variation in prestress levels can be attributed to fluctuations in the wood moisture content, relative humidity, and ambient temperature as discussed in the following paragraphs.

Of further interest, the force in the rod instrumented with Load Cell 1458 remained at or above 124.6 kN for 3 weekly readings from the third stressing (Day 43) up to and including Day 57. It is suspected that this rod actually was stressed to a value greater than 124.6 kN on the third stressing.

A power regression analysis and an exponential regression analysis were performed on the data from each of the rods. The results for Load Cells 1458 and 1461 are shown graphically in Figures 11 and 12. The analyses incorporated only the load cell readings after

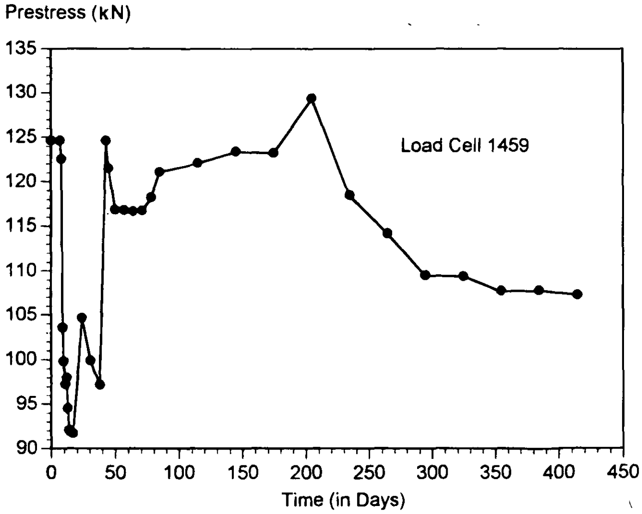

FIGURE 8 Variation of stressing force in Cell 1459.

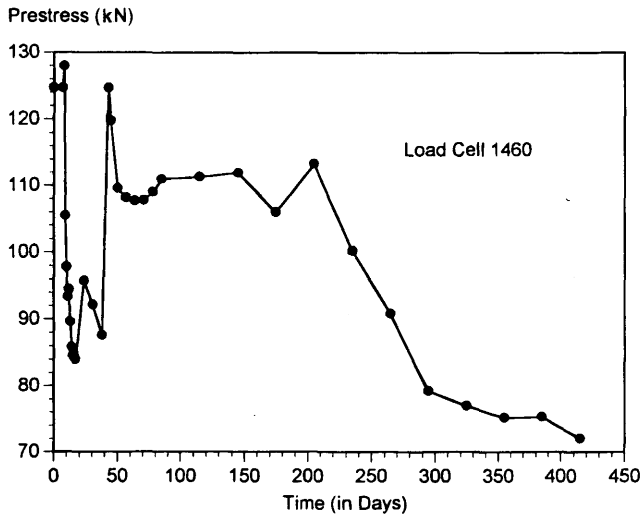

FIGURE 9 Variation of stressing force in Cell 1460.

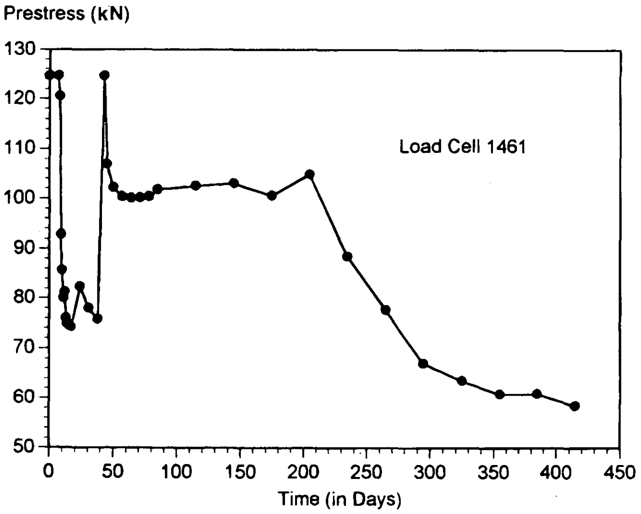

FIGURE 10 Variation of stressing force in Cell 1461.

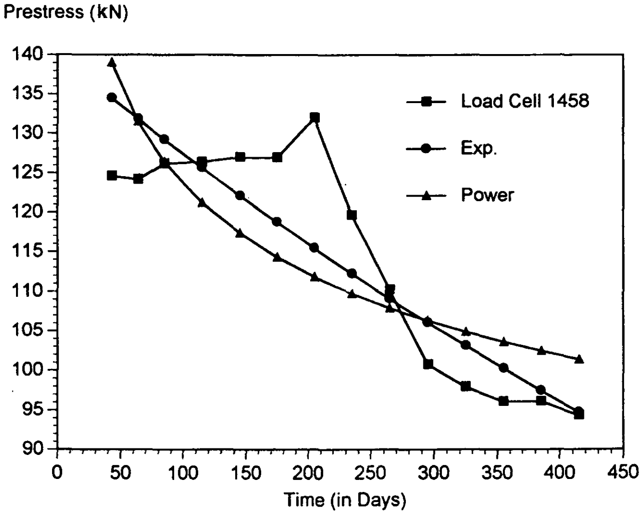

FIGURE 11 Regression curves for Cell 1458.

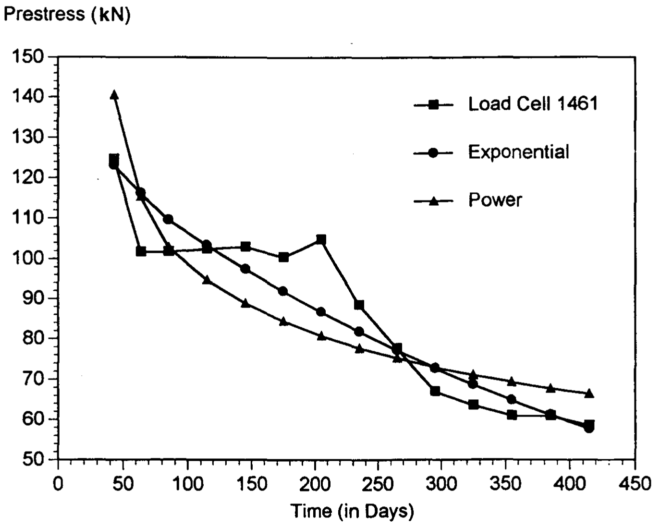

FIGURE 12 Regression curves for Cell 1461.

the third stressing. Most of the readings after the third stressing were taken monthly; however, the first few were taken weekly. The weekly readings were averaged to represent monthly readings before the regression analyses were attempted. The figures and the associated equations can be used to predict the stressing forces at various times. For instance, for the rod instrumented with Load Cell 1458, the exponential regression curve gives $P = 99.235$ kN and the power regression curve gives $P = 102.35$ kN after 385 days of the stressing.

According to AASHTO, the loss of prestress in a stress-laminated bridge caused by wood creep varies in an exponential way. AASHTO further gives the minimum level of prestress in service as 40 percent of the initial prestress (*4*). Therefore, for the North Road Bridge, the minimum level of prestress allowed by AASHTO is 49.84 kN. Using this minimum, the regression functions can be used to predict whether the bridge will have to be restressed and when this restressing would have to occur. The exponential regression curve predicts that the North Road Bridge will have to be restressed on the 484th day from the initial stressing on the basis of Load Cell 1461, which gave the most critical results. Similarly, the power regression curve predicts that the bridge will have to be restressed in 939 days from the initial stressing. Study of the individual correlation coefficients of the regression analyses indicates that the exponential fit represents the data slightly better than the power one. In the exponential case, the coefficients varied from 0.87 to 0.93, but under the power law assumption they varied from 0.73 to 0.85.

A better estimate can be obtained by performing regression analyses on the average forces from all load cells. The equation for the case of the exponential regression is found to be

$$P = 129.05\ (0.999)^T \tag{1}$$

and the equation for the power regression is given by

$$P = 259.435\ T^{-0.178} \tag{2}$$

where P is the prestress force in kilonewtons and T is the number of days from the initial stressing. The results are shown graphically in Figure 13. The exponential regression function for the average of

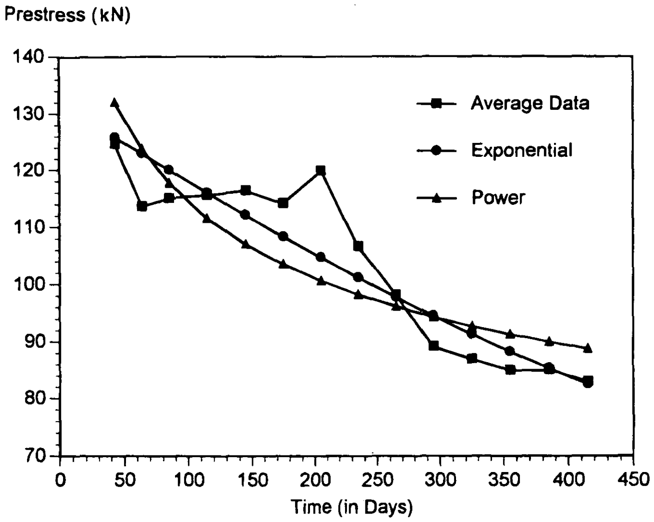

FIGURE 13 Regression curves for average of all cells.

the forces in all four instrumented rods predicts that the bridge will have to be restressed in 3 years from the initial stressing, whereas the power regression predicts that it will have to be restressed in 29 years from the initial stressing. The correlation coefficients reveal that the data correlated better with the exponential regression curve; however, the difference between the correlation coefficients is not as great as the difference between those of the individual load cells.

The regression analyses mentioned earlier for the loss of prestress over time represent the loss of prestress not only caused by wood creep but also by changes in the wood moisture content, ambient temperature, and relative humidity.

The variation of the wood moisture content with time is shown in Figure 14. When moisture is gained in the wood, the wood expands. This causes the prestress forces to increase. Similarly, as the wood dries, it shrinks, which can contribute to a decrease in the prestress levels. This in general held true for the North Road Bridge. By comparing Figures 14 and 8 it is evident that the moisture versus time curve follows a similar pattern as the force versus time curves. Generally, as the percent change in moisture content increased, the percent change in prestress force also increased. However, the data show some exceptions, which are probably caused by other factors, such as temperature variations.

The variation of temperature with time is shown in Figure 15. It has been reported that stressing forces decline with lower temperatures because of the different coefficients of thermal expansion for timber and steel. However, a temporary gain in the prestress forces was recorded during the winter months, which is attributable to the high moisture content in the bridge during this time. The high levels of precipitation during the winter months in Rhode Island caused the moisture content in the wood to increase, thereby causing a swelling of the wood and an increase in the prestress forces. The drop in temperature during the winter months may have caused the wood to shrink; however, the shrinkage was counteracted by the tendency of the wood to swell because of increases in moisture content.

Daily fluctuations in the prestress forces in the North Road Bridge did occur. The prestress levels and the temperature at the bridge site were monitored during a 24-hr period. The data reveals that the prestress levels in a stress-laminated bridge will fluctuate proportionately to fluctuations in temperature. However, the fluctuation appeared to be of the order of 4.45 kN for an 11C° temperature variation.

Relative humidity at the bridge site was recorded first weekly and then monthly. Results indicate that the ambient humidity level does not have a very pronounced effect on the prestressing force other than it can affect the wood moisture. The high levels of relative humidity at the bridge site during the summer had little effect on the prestress levels. The low levels of precipitation during that summer in Rhode Island must have caused the wood to shrink, thereby counteracting any tendency of the wood to swell because of high humidity.

CONCLUSIONS

The North Road Bridge, the first stress-laminated timber deck bridge in Rhode Island and one of the earliest of its type constructed of red oak in the United States, has been in service for almost 2 years, and its behavior has been monitored. This paper presents

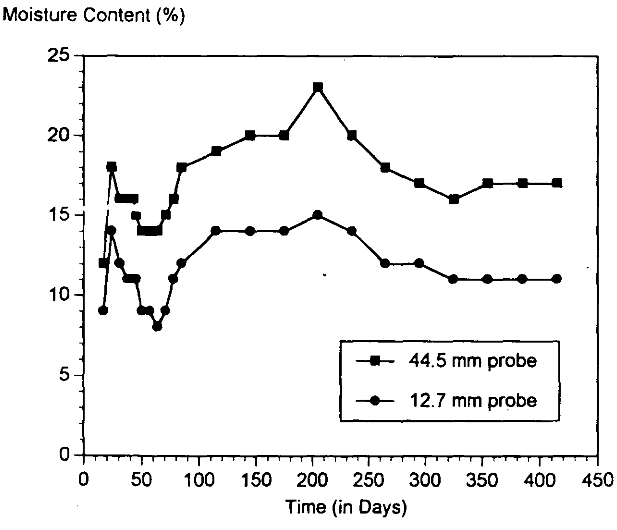

FIGURE 14 Variation of moisture content.

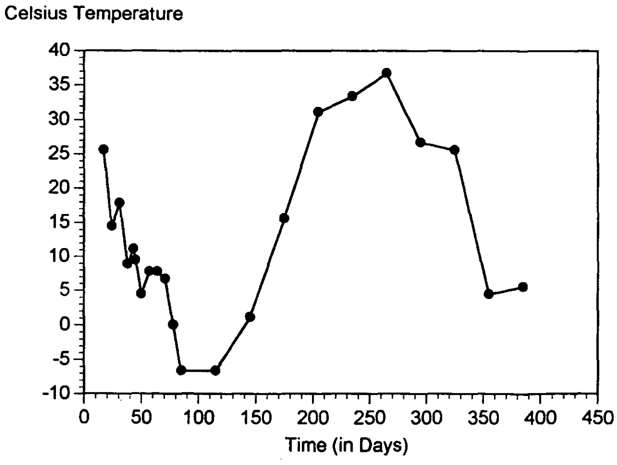

FIGURE 15 Variation of ambient temperature.

and evaluates the results of the first 415 days of the monitoring program, which included monitoring the loss of prestress over time, the variation of wood moisture content, the fluctuation in ambient temperature and relative humidity at the bridge site.

The study found that the four instrumented steel rods have maintained 47 percent or more of their initial prestress values. The residual stress levels are acceptable according to the AASHTO Guide, which requires the prestress levels to be 40 percent or more of the initial values. The loss of prestress over time was found to be more of an exponential nature than of a power nature. The data for each instrumented rod correlated well with exponential curves as did the data for the average of the forces in each instrumented rod. Exponential functions were empirically derived and were used to predict when and if the bridge would have to be restressed on the basis of the 40 percent minimum level of prestress allowed by AASHTO. On an individual rod basis, the functions predict that the rods will have to be restressed very soon. However, on an average basis, the functions predict that more time is allowed before restressing is necessary. The prestress levels in other stress-laminated bridges constructed of other wood species have leveled off much sooner than the levels in the North Road Bridge.

The study has found that besides wood creep, the wood moisture content plays an important role in the fluctuations of the stressing forces. On the other hand, fluctuations in ambient temperature at the bridge site had a minor influence on the prestress levels. During one 24-hr period, the forces in the rods were seen to fluctuate proportionately with ambient temperature; that is, a rise in temperature was accompanied by an increase in rod forces and vice versa. However, the effect of seasonal temperature changes on the prestress levels was opposite. A seasonal decrease in temperature at the North Road Bridge site was accompanied by an increase in rod forces. This was attributed to the increase in precipitation during the winter months of this monitoring program.

The general condition of the bridge was monitored, and it was found that the outside laminae were crushing in the vicinity of the bearing plates, which is typical of many stress-laminated timber deck bridges, and the fascia laminae exhibited full-length splits. Besides these and minor problems with the pavement at the joints, the general condition of the bridge is satisfactory. One of the steel rods exhibited much higher stress loss than the remaining three. This rod is located at the midspan point of the bridge. It is possible for higher stress levels in that location to have caused higher creep levels as well as increased crushing around the bearing plates. Also, higher warping levels may have existed in the planks in that location.

The conclusions reported herein correspond to this particular bridge and may not be applicable to all stressed timber bridges. However, the results of this monitoring program have contributed to the pool of data needed to develop a reliance on red oak as a viable material to be used for stress-laminated timber bridge construction. The monitoring program will be continued for some time to assess the long-term effects of moisture cycles. Specifically, it has been suggested that during high moisture periods when the wood expands and the force increases, higher creep losses occur, and the losses do not reverse when the moisture levels reduce. These additional periodic creep losses can contribute to increased loss of prestress over time.

ACKNOWLEDGMENTS

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