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Analysis of Thermal Change in Stress-Laminated Timber Bridge Decks

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Abstract

As the timber bridge design has evolved, some engineers have been concerned about the integrity of the stress-laminated system in cold climates. The structural integrity of a stress-laminated bridge depends on the level of interlaminar compression (between the wood laminations). Temperature change can cause material shrinkage, which could lead to substantial performance problems based on material mechanics and the nature of the stress-laminated system. In this study, to determine the effects of thermal change on interlaminar compression, four stress-laminated timber deck sections were put through a warm–cold–warm cycle. Various interlaminar stress levels and three moisture content levels were tested. Results showed that interlaminar compression in stress-laminated decks of this size was not affected by extremely cold temperatures when the moisture content was less than 19% and when initial bar force was sufficient.

Keywords: timber, bridge, stress-laminated, temperature, freezing

Contents

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Analysis of Thermal Change in Stress-Laminated Timber Bridge Decks

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Introduction

In recent years, the U.S. Federal Highway Administration has reported that nearly 30% of all U.S. bridges have been rated either functionally obsolete or structurally deficient. In response to this problem, research has been ongoing to find new methods to rehabilitate or replace these bridges. Many of the functionally obsolete or structurally deficient bridges are located on rural or secondary roads.

One type of bridge developed for these situations is the stress-laminated timber bridge. A typical stress-laminated bridge consists of sawn lumber laminations that are set on edge longitudinally between supports. These laminations are then squeezed together using high strength steel bars or strands until an interlaminar compressive stress of 690 kPa (100 lb/in^2) is achieved. The resulting deck creates a "plate" of wood that has orthotropic bending characteristics. The stress-laminated deck bridge concept originated in Canada in the late 1970s as a means of rehabilitating longitudinal nail-laminated decks that were delaminating under repeated loading. The stress-laminated deck performed even better than the traditional nail-laminated deck. Because of the superior performance characteristics, the concept was also applied to new bridge construction.

The relationship between the wood laminations and the steel tensioning rods controls the performance of the stress-laminated system. The wood laminations are compressed by the steel rods and are in the state of equilibrium. A change in the dimension of the wood and steel members can change the equilibrium of the system. The performance of the system is dependent upon retaining compression between the laminations, because friction is the only shear transfer between laminations.

As timber bridge design evolved, there was some concern regarding the integrity of the stress-laminated system in cold climates. Based on material mechanics and the nature of the stress-laminated system, differential material shrinkage between steel bars and wood laminations caused by temperature change could cause substantial performance problems.

Background

The cold climate concerns began after the construction of the Ciphers bridge, a stress-laminated bridge in northern Minnesota, near the United States–Canadian border. The Ciphers bridge is a single-lane, two-span continuous bridge constructed of red pine lumber. For the entire monitoring period, the interior lamination moisture content remained at or greater than 30%. Researchers noted during monitoring that when the temperature was below freezing, the bar force in the steel bars decreased. Losses in bar force were as much as 50% when the temperature dropped to −18°C (0°F) (Wacker and others 1998).

In response to the observed behavior of the Ciphers bridge when subjected to freezing temperatures, the University of Minnesota performed some laboratory tests (Erickson and others 1990). They constructed two stress-laminated blocks of wood that were 610 mm long, 305 mm deep, and 381 mm wide (10 laminations per block). Each block was stressed with a 25.4-mm (1-in.) steel tensioning bar. One block had approximately 10% moisture content; the other block had approximately 35% moisture content. The blocks were then subjected to a temperature change from 20°C to −6°C (68°F to 22°F). Results indicated that the high moisture content block lost approximately 76% interlaminar compression, and the low moisture content block lost 25% of the original interlaminar compression. These results seem to support the trend of bar force loss observed in the Ciphers bridge. However, the test blocks used for the experiments did not conform to the specifications of the Ciphers or any stress-laminated bridge. In addition, the use of larger diameter bars and an unrepresentative amount of wood probably exaggerated the results of the study by Erickson and others (1990).

As a result of the anistropic nature of wood, the coefficients of thermal expansion (or shrinkage in this case) in the longitudinal, tangential, and radial directions are different.

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The tangential and radial coefficients of thermal expansion are 5 to 10 times greater than that in the longitudinal direction. Most wooden structures are designed so that only the longitudinal direction is a critical load path. In addition, the thermal properties of wood are largely ignored because expansion and contraction as a result of moisture movement over time has a much larger effect. A study completed at the University of Wisconsin suggested that moisture content also plays a large role in the thermal expansion of wood (Kubler and others 1973). Their results indicate that as moisture content increases in a wood member, the coefficient of thermal expansion of that member increases. The combined effect of moisture content and thermal expansion creates a larger resultant change in the dimension of the wood member than does either individual mechanism.

Another study that investigated thermal effects was completed by the University of Connecticut (Sarisley and Accorsi 1990). In this study, a sample bridge was constructed to explore the phenomenon of time-related interlaminar compression losses in stress-laminated bridges. Part of the study examined the performance of these decks during thermal change. In an attempt to predict the thermal effect, researchers developed models based on simple mechanics and measured coefficients of thermal expansion. Although they were able to use the coefficients to predict thermal bar force behavior, conclusions from the study were tied to the test bridge constructed by the University of Connecticut and cannot be used for other bridges.

A partnership that included the University of Minnesota; the USDA Forest Service, Forest Products Laboratory; and the Federal Highway Administration completed a study that examined the effects of thermal change on stress-laminated decks (Wacker and others 1996). This study was completed in a laboratory at the University of Minnesota. In this study, three test decks of red pine sawn lumber were constructed. These decks were placed in an environmental chamber where the temperature was decreased from 21.1°C (70°F) to five freezing temperatures that ranged from −12.2°C to −34.4°C (10°F to −30°F). In addition to the variation of temperature, the moisture content of the red pine laminations was altered. Each freeze–thaw run was completed at three levels of moisture content: above fiber saturation or green, 17%, and 7%. Results from this study indicate that moisture content when combined with temperature change plays a significant role in the amount of bar force lost.

Results from these previous studies indicate that the effect of thermal change on stress-laminated decks needs additional investigation.

Objective and Scope

Our objective was to determine if large temperature decreases significantly affect the interlaminar compression level of stress-laminated deck sections. Because of some limitations, some aspects that might affect stress loss were not considered in this study. The size of the stressing bar and the resulting stiffness change in the system were not examined, because larger bars would not have been representative of actual bridges. In addition, alternative species and preservatives were not examined.

Experimental Methods

To test the effects of thermal change, four stress-laminated deck sections were constructed and tested at various interlaminar stress levels and three moisture content levels. Three deck sections were constructed of 40 sawn lumber laminations each, with a final measured dimension of 1.5 m by 1.5 m by 285.8 mm (5 ft by 5 ft by 11.25 in.). The fourth deck section was constructed using 34 laminated veneer lumber (LVL) laminations, with a final measured dimension of 1.5 m by 1.5 m by 305 mm (5 ft by 5 ft by 12 in.). Each deck section was stress laminated with three 15.9-mm-(5/8-in.-) diameter high strength steel bars that were spaced every 610 mm (24 in.) along the length of the deck section (Fig. 1). These steel bars conformed to ASTM 722 (ASTM current edition) for uncoated, high strength steel bars. The make-up of each deck section is given in Table 1.

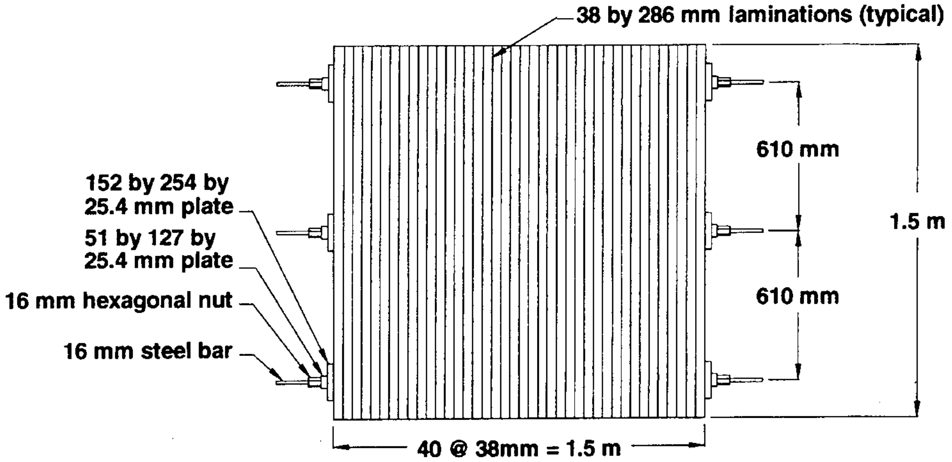
The study was divided into three phases. The first phase included monitoring the interlaminar compression and relative deformations of the deck sections at a moisture content of approximately 10% to 12%. The second and third phases were similar to phase 1 except that the moisture content of the deck sections was 18% to 19% in phase 2 and above fiber saturation (approximately 50%) in phase 3.

Instrument Calibration

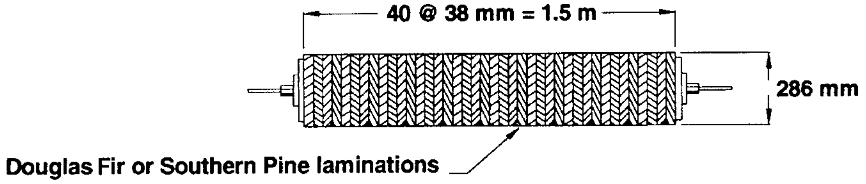
The tension in the bars was measured through the installation of a hollow core load cell on each bar. Each load cell detected tension in the bar by measuring compressive strain. The strain was then converted to kilonewtons (pounds) using a calibration factor obtained through methods previously used in the laboratory (Ritter and others 1991). This calibration was performed at room temperature.

The load cells were also calibrated for use with a data logger. A conversion factor was determined as the ratio of the difference in force and the difference in voltage. This value was entered into a program that would read the load cells at 30-minute intervals.

After the calibration process was completed, data were entered into a spreadsheet to determine a conversion factor. Data were also compared for correlation between the load applied and the measured strain from the load cell. The resulting correlation was strong (0.99) for all load cells. This indicates that the load cells read the strain in a linear manner, and bar forces were obtained directly from strain when using



Plan view



Cross section

Figure 1—Typical stress-laminated deck section using sawn lumber laminations. The deck section made with Douglas Fir LVL laminations had fewer (but thicker) laminations and followed the same general layout.

Table 1—Makeup of deck section

			Lamination		
Deck	Lumber	Preservative treatment	Type	Number	Final deck dimension
1	Douglas Fir	None	Sawn lumber	40	1.5 m by 1.5 m by 285.8 mm
2	Southern Pine	Chromated copper arsenate	Sawn lumber	40	1.5 m by 1.5 m by 285.8 mm
3	Douglas Fir	Creosote	Sawn lumber	40	1.5 m by 1.5 m by 285.8 mm
4	Douglas Fir	None	Laminated veneer lumber	34	1.5 m by 1.5 m by 305 mm

the conversion factor. The agreement between the strain box and the load applied was good. Therefore, we can assume that the correlation between the load applied and voltage obtained for the data logger was also good because both used the same method of measurement.

Time-dependent losses were not considered in the calibration of the load cells, because steel does not relax at a rate that could be observed during this time. However, the load cells have been shown to "shift" zero points over time. This is due to creep in the epoxy used to adhere the stress–strain rosette to the steel load cell barrel. The shift was monitored by periodically checking the reading of the load cell at no load and adjusting the data logger program for the new zero point. Creep losses in the load cells would probably not affect the measured temperature losses observed, because the zero shift was checked before and after the calibration cycle.

Deck Evaluation

The following six steps were completed for each of the four deck sections at each moisture content level (phases 1–3). For all tests, data logger readings were taken at 30-minute intervals.

1. Disassemble deck section, install thermocouple wire, measure moisture content, and reassemble deck.

   Each deck section was disassembled, and the laminations were stacked in an environment room to maintain proper moisture content, if applicable. When all laminations in one deck section were at the required moisture content, the numbered laminations were assembled in a predetermined order so that each time the deck section was assembled, a similar order was used. During assembly, thermocouple wires were installed on the middle stressing bar and between the wood laminations (Fig. 2). The thermocouple wires were installed with similar distances and penetrations for all deck sections. (The thermocouple spacing of the LVL deck was adjusted because it had fewer laminations.)

2. Install steel stressing bars, load cells, and width measuring device; begin data acquisition.

   After the deck section was reassembled, the stressing bars were placed through the laminations and bearing plates and nuts were installed. The deck section was then lifted onto a modified cart with an overhead crane. A load cell was placed on each steel stressing bar between the bearing and anchor plates (Fig. 3), and the bars were tensioned to 32 kN (7,200 lb). This provided an interlaminar compression level of approximately 172 kPa (25 lb/in^2). The load cells were then connected to the data logger and monitored until the effects caused by time-related bar force losses were minimized. If necessary, the deck was tensioned again to maintain steady interlaminar compression.

3. Move deck section to subzero temperature room.

   When the bar forces were stabilized, the deck section and data logger were transported to a subzero (−19°C (−2°F)) environment room. After all portions of the deck reached equilibrium temperature (that is, all thermocouples read within ±5°), the deck section remained in the room for an additional 24 h to ensure that it was completely frozen.

4. Remove deck section from subzero environment room.

   After the deck section was completely frozen, it was moved to the original environment room. Data collection continued for approximately 24 h after the deck section reached warm equilibrium temperature (22°C (72°F)). Moisture content readings were taken with an electrical resistance moisture meter after removal from the subzero room to verify the moisture content after the cold cycle.

5. Repeat procedure for additional bar force levels.

   Procedures in steps 3 and 4 were repeated for bar force levels of 51 kN (11,520 lb), 96 kN (21,600 lb), and 128 kN (28,800 lb), which corresponded to interlaminar compression levels of 275 kPa (40 lb/in^2), 517 kPa (75 lb/in^2), and 690 kPa (100 lb/in^2), respectively. These levels were chosen to represent bar force levels observed in actual bridges. By selecting these levels, a variety of bar force levels could be studied. Each time the deck section achieved warm temperature equilibrium after a cold cycle, data were imported into a spreadsheet for future analysis.

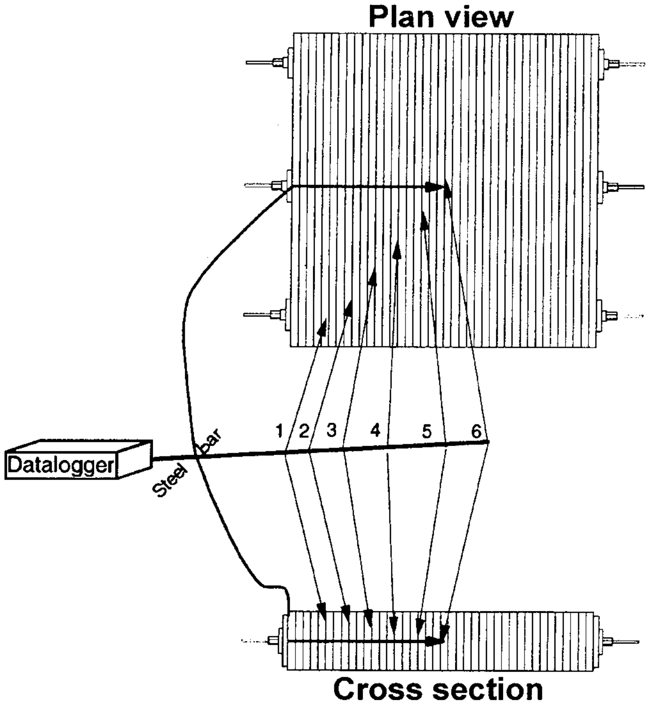


Figure 2—Typical thermocouple locations in the stress-laminated deck section using sawn lumber laminations. Because of the different configuration of the Douglas Fir LVL deck, the spacing was altered but the distance and depth of the thermocouples were as close as possible to those of the sawn lumber laminations.

The following summarizes the warm–cold–warm cycles (22°C → −19°C (72°→ −2°F)) for each of the four deck sections for phases 1 to 3:

Phase	Warm–cold–warm cycle	Moisture content (%)	Interlaminar compression levels (kPa (lb/in^2))
1	1	10 to 12	172 (25)
	2		275 (40)
	3		517 (75)
	4		690 (100)
2	1	18 to 19	172 (25)
	2		275 (40)
	3		517 (75)
	4		690 (100)
3	1	Above fiber saturation	172 (25)
	2		275 (40)
	3		517 (75)

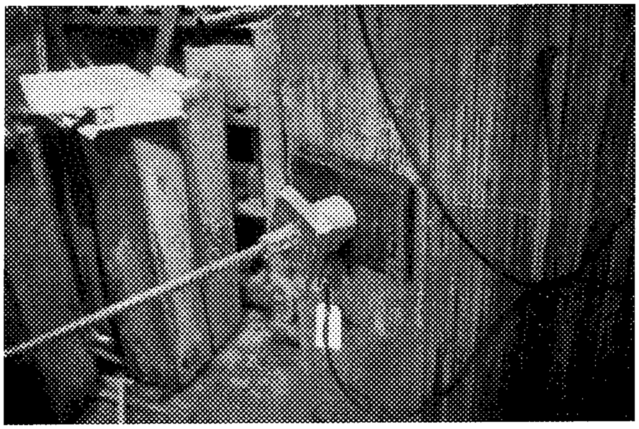


Figure 3—Load cell placement on the stress-laminated deck section.

6. Disassemble deck section and repeat procedure for remaining deck sections.

   At the completion of all bar tension levels for one deck section, the bar force was released and the load cells and thermocouple wires were removed. The deck section was retensioned to 128 kN (28,800 lb) and placed in noncontrolled storage for future runs at higher moisture content levels. Steps 1 to 6 were repeated for the three remaining deck sections.

Testing at 12% Moisture Content

During phase 1, laminations were placed in an environmental room maintained at 65% relative humidity and 22.2°C (72°F), which corresponded to a moisture content of 12% (Forest Products Laboratory 1999). A moisture meter was used periodically to check the moisture content level of each deck section during testing (ASTM 1992a). Deck evaluation steps 1 to 6 were performed on each deck section.

Testing at 18% Moisture Content

In phase 2, deck evaluation steps 1 to 6 were repeated for the four decks with moisture content at 18%. This was accomplished by dismantling the deck sections and placing the laminations in a 22.2°C (72°F) and 90% humidity room for 3 to 4 months (Forest Products Laboratory 1999). After each lamination had attained the proper moisture content, the deck section was reassembled and testing resumed. Moisture content was confirmed through moisture meter measurements (ASTM 1992b) before and after each run.

Testing Above Fiber Saturation

For this phase, deck evaluation steps 1 through 6 were again completed on deck sections that had moisture content above the fiber saturation point. The moisture content of the laminations was increased by dismantling the deck sections and placing the laminations in a pressure-treating cylinder. After the laminations were placed in the cylinder, water was pushed back into the wood in a similar manner that is used for pressure treatment with preservatives. When the laminations increased in weight to a moisture content above fiber saturation, the laminations were removed and reassembled. Testing then resumed and was completed on each deck section.

Moisture meter readings were not used when the deck sections were above fiber saturation, because the accuracy of this method is not acceptable above approximately 30% moisture content. However, moisture content was determined by the ovendry method (ASTM 1992a) at the conclusion of testing.

Results

A large amount of data was collected during this study. A sampling of data plots is included to show trends.

An average of the three load cells was used to simplify and aid analysis. After the initial plot of each cycle was completed, the variation between load cells was determined. The variation was small compared with the amount of bar force loss. The average was also used to compensate for fluctuations in force as a result of the location of load cells (that is, the end rods had a faster relative temperature change than did the center rod). As described, each cycle consisted of an equalization period in a room that was 22°C (72°F), a cold period in a room at −19°C (−2°F), and a second equalization period at 22°C (72°F). The entire cycle lasted between 14 and 21 days, and readings were taken every 30 minutes with a data logger.

Four interlaminar compression levels were attempted for each deck section. The corresponding force in the rods was determined from these levels. However, the bar tensioning process did not always allow exact application of force, because the decks were stressed with a hydraulic pump and ram. A stressing force was obtained by checking the force level in the load cell. The deck sections were stressed one rod at a time. When one rod reached the desired force level, the next rod was stressed. This continued until the three rods were stressed. However, the force level in the first rod changed when the second rod was stressed. For this reason, the force level in the rods was considered acceptable if the desired prestress level was within ±10% of the actual level.

To determine the loss of force caused by cold temperatures, time-dependent losses were separated out of the change in force of the cycle. However, time-dependent losses are difficult to quantify. Studies performed by Taylor and others (1983) displayed a time-dependent loss curve for a simulated stress-laminated bridge. Results showed that time-dependent losses occur over many weeks and the rate of loss is not constant. The three-stage stressing procedure was an attempt to minimize the initial time-dependent losses. It was assumed that the majority of losses occurred after the initial stressing. With time, the losses had less magnitude and the deck section approached a period of modest time-dependent loss between readings. This "tail" of the curve had minimal curvature and could be assumed linear. The time-dependent losses in this study were assumed to be on the tail of the time-dependent loss curve.

Figure 4 shows a sample curve from this study and displays bar force and temperature for the entire cold cycle. An early attempt was made to fit the curve, before and after the loss as a result of temperature, with a polynomial function. This was unsuccessful because the curve, when magnified (Fig. 5), varied substantially from reading to reading. The observed result was similar to a rolling wave. The curve was not representative of the overall trend displayed by data at full scale.

12% Moisture Content

Results caused by temperature change are represented in Figure 6, which displays a normalized plot of all data from all four decks at four interlaminar compression levels. As shown, only small differences can be seen between different deck materials at 12% moisture content. Differences are less than 10 kN between decks. The plots were normalized by picking one set data point every 10 h at the start of freezing and continuing through the cycle until completion. The bar force level was also adjusted on each run to equal the projected starting point of each bar force level.

Table 2 lists the actual bar force loss from the four decks tested at 12% moisture content. All force losses were based upon an average of the three load cells.

Several observations can be made when examining these data. The first observation is that as the original bar force increased, the amount of bar force lost as a result of temperature also increased. However, this greater bar force loss did not result in a greater effect on the deck section because of the high initial bar force.

The second observation is that all decks performed similarly at the various bar force levels. Differences in bar force losses between deck sections caused by cold were small, ranging from 6.7 to 4.0 kN (1,500 to 900 lb).

18% Moisture Content

Figure 7 displays the normalized plots from the cold temperature testing at 18% moisture content. As shown, similar bar force losses were observed at each bar force level. The Douglas Fir creosote-treated deck was not tested at this moisture content level because of conditioning room constraints. Table 3 gives the actual bar force loss data from the three decks tested at 18% moisture content. Again, all force losses are averages of the three load cells.

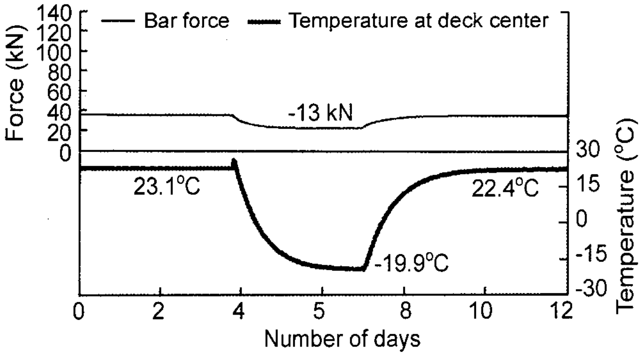


Figure 4—Typical warm–cold–warm cycle on one stress-laminated deck section at 12% moisture content (Douglas Fir untreated, 172 kPa, 35 kN).

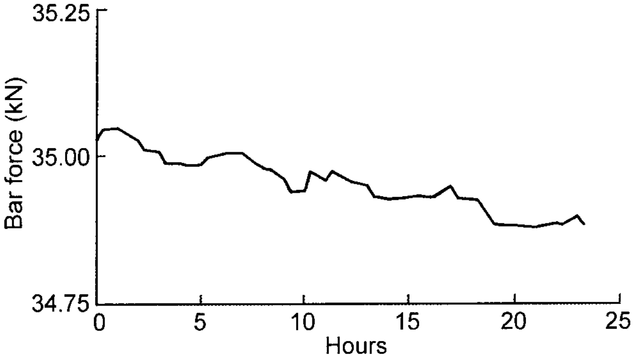


Figure 5—Magnified view of bar force data displayed in Figure 4. Note fluctuations between readings.

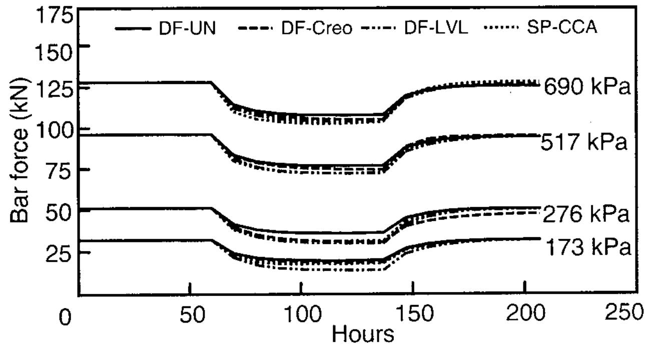


Figure 6—Normalized bar force at 12% moisture content. All four interlaminar compression levels are represented (DF-UN, Douglas Fir untreated; DF-Creo, Douglas Fir creosote-treated; DF-LVL, Douglas Fir laminated veneer lumber; SP-CCA, Southern Pine CCA-treated).

Several trends were evident from these data and plots. Similar to the previous moisture content level, as the initial bar force increased, the amount of bar force loss caused by the cold temperature also increased. At the lower bar force levels, nearly 60% of the original bar force was lost as a result of temperature change. These substantial decreases in bar force could lead to performance changes in a stress-laminated deck.

Table 2—Summary of test results at 12% moisture content

	Warm–cold–warm cycle	Total temperature change (°C)	Force loss due to temperature (kN)	Force loss due to temperature (%)	Force loss of the cycle (kN)	Force loss of the cycle (%)
Douglas Fir	1	42.9	12.6	36	0.2	1
Untreated	2	41.4	15.1	30	0.8	2
	3	45.2	19.3	21	1.8	2
	4	41.8	20.2	16	2.4	2
Douglas Fir	1	44.3	18.4	51	0.3	1
LVL	2	43.9	21.6	41	0.9	2
	3	46.7	23.8	26	1.7	2
	4	41.6	24.1	19	1.9	2
Southern Pine	1	41.6	14.1	41	0.4	1
CCA-treated	2	43.8	19.8	36	1.2	2
	3	49.1	23.4	25	2.0	2
	4	45.3	24.4	19	–0.1	0
Douglas Fir	1	42.9	15.5	39	0.1	0
Creosote-treated	2	45.6	20.7	40	3.3	6
	3	43.0	21.6	24	0.8	1
	4	44.2	22.8	19	1.0	1

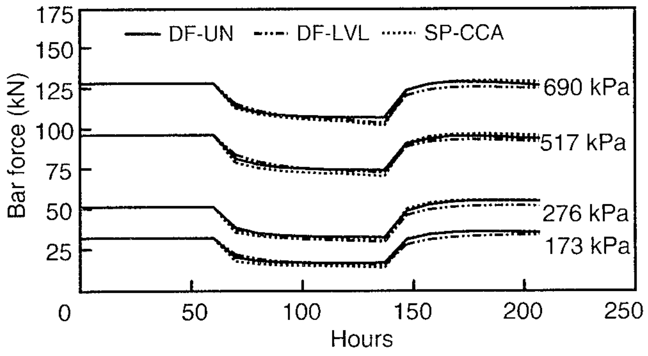


Figure 7—Normalized bar force at 18% moisture content. All four interlaminar compression levels are represented (DF-UN, Douglas Fir untreated; DF-LVL, Douglas Fir laminated veneer lumber; SP-CCA, Southern Pine CCA-treated).

At this moisture content, there was relatively little difference in bar force loss between decks at the same bar force level, which indicated the deck was acting as a system. Although it decreased dramatically at this moisture content level, the bar force was fully or nearly recovered by the end of the cycle when the deck was rewarmed.

Above Fiber Saturation

Only three bar force levels were examined above the fiber saturation point. The stresses at the highest bar force level created crushing problems underneath the plate because of the high moisture content of the laminations. Table 4 lists actual data from each cycle completed at above fiber saturation moisture content. To display the results effectively, one plot was done for each bar force level (Fig. 8).

Again, several observations were evident. Not all species and preservative treatments performed similarly at this moisture content. Two decks, the Southern Pine untreated and the Douglas Fir untreated, performed similarly with near complete bar force loss at the lower two bar force levels and nearly 60% loss at the 96 kN level. The Douglas Fir LVL deck lost the entire bar force at each run. The negative values were a result of the normalization of bar forces. Finally, the Douglas Fir creosote-treated deck performed much better than did the other decks. In fact, this deck performed similarly to the other decks at 18% moisture content. As was evident in the 12% and 18% moisture content runs, the bar force was fully recoverable upon warming the decks at above fiber saturation.

Table 3—Summary of test results at 18% moisture content

	Warm–cold–warm cycle	Total temperature change (°C)	Force loss due to temperature (kN)	Force loss due to temperature (%)	Force loss of the cycle (kN)	Force loss of the cycle (%)
Douglas Fir Untreated	1	46.2	15.2	50	–2.4	–8
	2	44.9	18.8	44	–2.5	–6
	3	48.1	22.0	23	2.8	3
	4	45.9	21.4	20	1.8	2
Douglas Fir LVL	1	44.4	16.6	59	–1.8	–6
	2	44.8	21.5	43	–0.2	0
	3	42.7	23.3	24	7.1	7
	4	45.4	24.7	24	5.4	5
Southern Pine CCA-treated	1	43.6	18.2	55	–2.7	–8
	2	44.5	20.9	46	–3.5	–8
	3	44.4	25.8	28	2.1	2
	4	41.9	26.2	25	1.0	1

Table 4—Summary of test results above fiber saturation moisture content[a]

	Warm–cold–warm cycle	Total temperature change(°C)	Force loss due to temperature (kN)	Force loss due to temperature (%)	Force loss of the cycle (kN)	Force loss of the cycle (%)
Douglas Fir Untreated	1	44.9	32.3	96	3.4	10
	2	40.2	40.6	90	–0.1	0
	3	41.6	50.4	57	1.0	5
Douglas Fir LVL	1	41.3	33.2	108	0.0	0
	2	41.4	51.9	106	0.0	0
	3	42.6	91.9	96	12.5	13
Southern Pine CCA-treated	1	43.7	40.1	93	5.3	12
	2	41.1	47.3	92	5.9	11
	3	40.8	55.2	56	10.8	11
Douglas Fir Creosote-treated	1	44.4	21.9	64	0.9	3
	2	46.6	23.4	58	–0.3	–1
	3	45.4	23.9	28	5.1	6

[a] Only three bar force levels were examined at this moisture content level. The stresses at the highest bar force level created crushing problems underneath the plate because of the high moisture content of the laminations.

Conclusions

In all, four stress-laminated timber deck sections were examined at various interlaminar stress levels and three moisture content levels. Data from this study support the following conclusions:

- Stress-laminated deck sections of this size (1.5 m by 1.5 m by 285.8 mm and 1.5 m by 1.5 m by 305 mm) perform well in extremely cold temperatures provided the moisture content is less than 19% (AASHTO 1991) and initial bar force is sufficient.

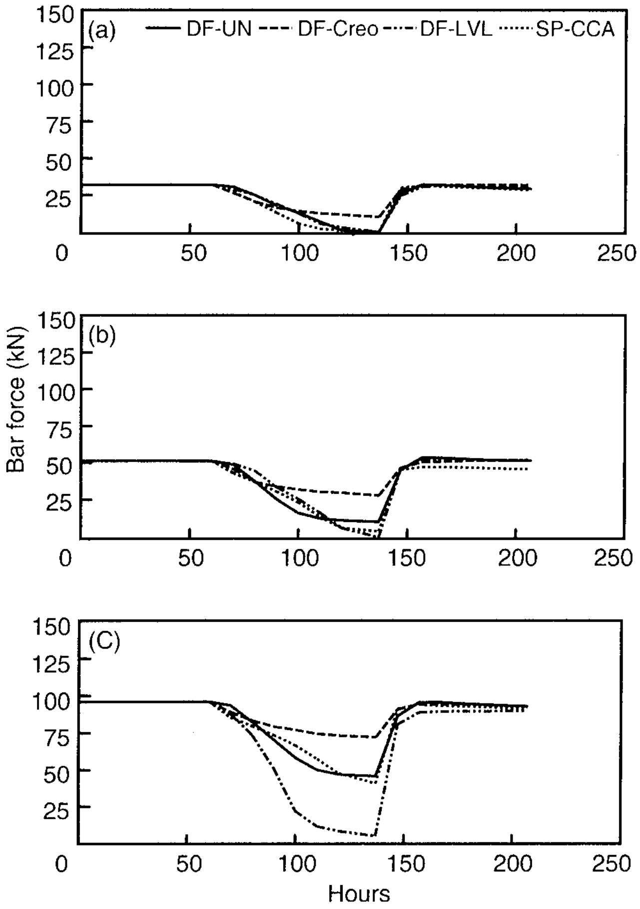


Figure 8—Normalized bar force at above fiber saturation: (a) 172 kPa (25 lb/in^2) interlaminar compression level; (b) 275 kPa (40 lb/in^2) interlaminar compression level; (c) 517 kPa (75 lb/in^2) interlaminar compression level (DF-UN, Douglas Fir untreated; DF-Creo, Douglas Fir creosote-treated; DF-LVL, Douglas Fir laminated veneer lumber; SP-CCA, Southern Pine CCA-treated).

- Stress-laminated deck sections of this size do not perform well in freezing temperatures when the moisture content is above fiber saturation. In deck sections above fiber saturation, large bar force losses ranged from 28% to 96%. These losses decreased the bar force to levels below minimum design standards.
- As the initial bar force level increased in the stress-laminated deck section, the amount of bar force loss as a result of temperature change also increased. However, this greater bar force loss did not result in a greater effect on the deck section because of the high initial bar force.
- The bar force loss, as a result of temperature change in the stress-laminated deck sections, was fully recoverable upon warming of the deck.

Although this study looked at deck sections of different size than the full-scale stress-laminated bridges, it is recommended that moisture content levels of bridges placed in potentially cold climates be scrutinized. It is not known if the smaller size of the decks increased or decreased the amount of bar force loss during periods of cold temperature. Future reports will examine these results on full-scale stress-laminated bridges.

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