EFFECT OF COLD TEMPERATURES ON STRESS-LAMINATED TIMBER BRIDGE DECKS

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This paper summarizes Forest Products Laboratory research on stress-laminated timber bridge decks subjected to below-freezing temperatures. The effect of temperature change was investigated in test decks in the laboratory and bridges in the field. The results indicate that the magnitude of the temperature effect depends on the moisture content of the wood laminations. In addition, changes in interlaminar compression resulting from below-freezing temperatures are fully recoverable when the temperature rises above freezing.

1. INTRODUCTION

Approximately 30% of the bridges in the United States are classified as structurally deficient or functionally obsolete [1]. In response to this problem, ongoing research has focused on identifying new options for rehabilitating or replacing bridges. Of prime concern are bridges located on secondary roads, where the percentage of structurally deficient or functionally obsolete bridges is highest. Over the past decade, wood bridges have become a more accepted and viable option for replacing bridges on secondary roads. In most situations, timber bridges offer advantages for secondary roads because they can be quickly constructed using local materials and labor under a wide range of climatic conditions. Wood bridges also have a proven performance record, and, when property designed, constructed, and maintained, their service life equals or exceeds that of bridges made from other materials.

One relatively new type of wood bridge that has become popular for use on secondary roads is the stress-laminated (stress-lam) timber bridge. A typical stress-lam bridge consists of solid-sawn lumber laminations that are placed edgewise between supports and are squeezed together by high-strength steel bars (Fig. 1). The resulting deck performs as a large orthotropic wood plate. The stress-lam deck has better performance characteristics than those of the traditional nail-laminated lumber deck because it has no panel joints or mechanical fasteners, which can loosen over time.

The concept of stress-lam bridges originated in Ontario, Canada in the late 1970s as a means of rehabilitating longitudinal nail-laminated decks that had delaminated under repeated loading [2]. The stress-lam system performed well and was subsequently adapted to new bridge construction. Stress-lam bridges were first built

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Fig. 1 Typical stress-laminated timber bridge.

in the United States in the late 1980s; since then, more than 400 stress-lam bridges have been constructed.

The structural integrity of a stress-lam bridge depends on the level of interlaminar compression between the wood laminations. In most designs, the steel bars are initially tensioned to provide 690 kPa of compression between the wood laminations. In service the steel bars act like springs, compressing the wood laminations together. Dimensional changes in the wood laminations resulting from stress relaxation, moisture content, and temperature can reduce bar force. Slip between the laminations does not occur until the level of interlaminar compression fails to approximately 173 kPa.

2. BACKGROUND

As the construction of stress-lam bridges increased in the United States, concerns arose about the integrity of the stress-lam system in cold climates. These concerns were first expressed in 1990 after construction of the Ciphers stress-lam bridge in northern Minnesota near the U.S.-Canada border. The Ciphers bridge is a single-lane, two-span continuous structure constructed of red pine solid-sawn lumber. During field monitoring of the bridge, researchers noted that when the temperature dropped below freezing, the force in the steel bars also dropped [3,4]. Observed loss in bar force was as great as 50% when the temperature dropped to -18°C. The researchers suspected that this loss in bar force was the result of temperature change in the wood laminations.

The thermal properties of wood have been largely ignored in structural design because of the notion that expansion and contraction caused by moisture movement has a much greater effect on dimensional stability than does temperature. A study at the University of Wisconsin [5] suggested that moisture content also plays a significant role in the thermal expansion of wood. In these tests, small wood blocks were heated under controlled conditions to determine the thermal expansion coefficient. Results indicated that as moisture content in a wood member increases, the coefficient of thermal expansion of that member also increases.

The coefficient of thermal expansion for wood varies depending upon species and grain orientation. In the stress-lam bridge system, the coefficient of thermal expansion for wood in the direction perpendicular to grain is approximately 2.5 times greater than the coefficient of thermal expansion for steel [6.7]. Considering material mechanics and the nature of the stress-lam system, material shrinkage of the wood laminations resulting from temperature change could cause a significant loss in bar force and interlaminar compression.

In response to the observed cold temperature behavior of the Ciphers bridge, researchers at the University of Minnesota performed limited laboratory tests on two stress-lam wood blocks measuring 610 mm long by 305 mm deep by 381 mm wide (10 lumber laminations per block) [3]. Each block was stress laminated with a single 25.4-mm-diameter high-strength steel bar. One block was maintained at approximately 10% moisture content and the other at approximately 35% moisture content. The stress-laminated blocks were subjected to a 50°C temperature change, from 20°C to -30°C. Results indicated that the high moisture content block lost approximately 76% of original interlaminar compression and the low moisture content block, 25%. These results appeared to support the trend in bar force loss observed in the Ciphers bridge. However, the test block configuration was significantly different from the actual bridge configuration and further study was considered essential before correlations could be formulated.

In 1992, the University of Minnesota, the Forest Products Laboratory of the USDA forest Service, and the Federal Highway Administration initiated a cooperative research study to examine the effects of temperature on stress-lam decks [8]. At the University of Minnesota, three stress-lam test decks constructed from red pine sawn lumber were placed in an environmental chamber where the temperature was incrementally lowered from 21.1°C to five temperature settings ranging from -12.2°C to -34.4°C. Each freeze/thaw cycle was completed at three levels of wood moisture content: greater than 30% (green), 17%, and 7%. Results from these tests indicated that wood lamination moisture content plays a significant role in bar force loss resulting from below-freezing temperatures. When wood moisture content was above 30%, bar force loss was 81% to 85% of original force, depending on the temperature decrease. At 17% wood moisture content, bar force loss was approximately 20% of original force and at 7% wood moisture content, only 7% of original force was lost. This supports the trend observed in the earlier tests at the University of Minnesota [3]. However, definitive testing to compare laboratory test data to field performance of actual bridges has not been performed.

In this paper, we summarize the results of tests conducted by the Forest Products Laboratory on the effects of temperature on stress-lam timber bridge decks.

3. RESEARCH METHODOLOGY

To further evaluate the performance of stress-lam bridge decks under changing temperature, researchers at the Forest Products Laboratory (FPL) conducted a laboratory study and several field evaluations of actual bridges.

3.1 Laboratory Tests

Four stress-lam decks were tested in the laboratory. Two decks were constructed of Douglas Fir sawn lumber; one deck was pressure treated with creosote preservative and the other had no preservative treatment. The third deck was constructed of Southern Pine sawn lumber and treated with chromated copper arsenate (CCA). The fourth deck was constructed of Douglas Fir laminated veneer lumber and was not treated with wood preservative. Each deck measured 1.5 by 1.5 m and was stress-laminated with three 15.9-mm-diameter high-strength steel bars.

To evaluate the test decks, load cells were placed on the steel bars to monitor bar force and thermocouples were installed to measure interior and exterior temperature change. The decks were stressed under ambient conditions of

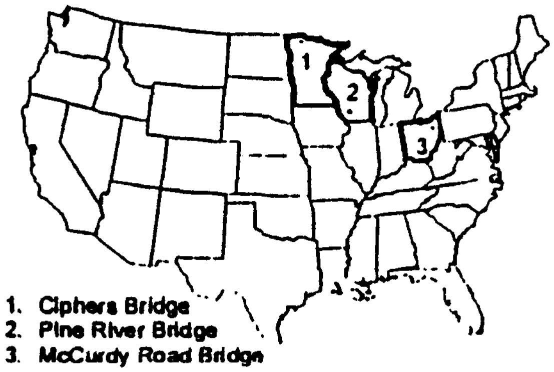

Fig. 2 Location of bridges monitored for thermal variations.

approximately 25°C and were then placed in an environmental chamber at approximately -18°C until the temperature equilibrated. The decks were then moved back to ambient temperature. During this temperature cycle, bar force and temperature were continuously monitored.

Each deck was tested at three levels of wood moisture content (12%,18%, and >30% [approximate fiber saturation point]) and four levels of initial interlaminar compression (172, 276, 517, and 690 kPa). These moisture content and interlaminar compression values were chosen to represent typical conditions for actual stress-lam bridges.

3.2 Field Tests

Three timber bridge structures were monitored in the field: the Ciphers bridge in northern Minnesota, the Pine River bridge in southwestern Wisconsin, and the McCurdy Road bridge In northeastern Ohio (Fig. 2). These bridges were selected for monitoring because they provided a range of materials and preservative treatments. The Ciphers bridge, the same bridge previously monitored by the University of Minnestoa, was constructed of red pine sawn lumber treated with creosote. The Pine River bridge was made from red pine glued-laminated timber treated with pentachlorophenol in heavy oil solvent. The McCurdy Road bridge was constructed of Southern Pine sawn lumber treated with ammoniacal copper quat (ACQ).

Each bridge was monitored for at least 2 years. Load cells were used to measure changes in bar force, and thermocouples were used to measure interior deck and ambient temperatures. A moisture core or electrical resistance moisture meter was used to measure moisture content of the wood laminations according to ASTM standards [9,10].

4. RESULTS

Results of FPL laboratory and field tests were used to assess the effects of temperature on bar force for various bridge materials and wood moisture content levels. These results are summarized here. Detailed reports on laboratory tests and field bridge monitoring are in preparation and will be available through FPL.

4.1 Laboratory Tests

Figure 3 shows bar force and temperature data for the untreated Douglas Fir deck with initial interlaminar compression of 517 kPa and lamination moisture content of 12%, 18%, and >30% (fiber saturation). To eliminate slight variations in initial bar

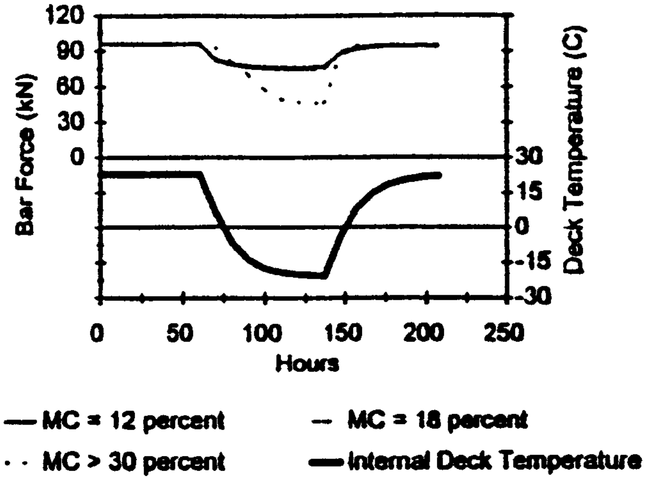

Fig. 3 Results of FPL thermal study. Bar force data were normalized at 98 kN for three different wood moisture content levels.

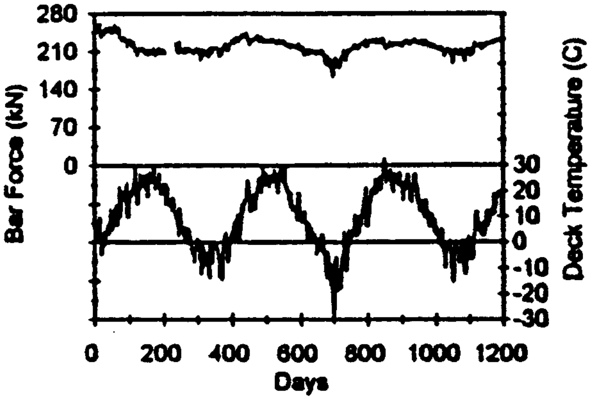

Fig. 4 Bar force and temperature data from Pine River stress-lam deck bridge.

force for different wood moisture content levels, the curves were normalized to the same initial bar force level. The behavior of this deck was typical of that observed for the other decks in the study. The interior deck temperature was cycled from an initial level of 25°C to -18°C, then returned to 25°C. At 12% wood moisture content, bar-force declined 21% during the temperature reduction. Loss of bar force was similar at 18% wood moisture content (23% reduction in force). At >30% wood moisture content, bar force declined 57%. At all wood moisture content levels, bar force returned to the initial level when the deck was removed from the cold temperature and returned to the initial temperature of 25°C.

4.2 Field Test

Bar force and deck temperature as a function of time are shown for the three field bridges in Figs. 4 to 6. Field measurements indicated that lamination moisture

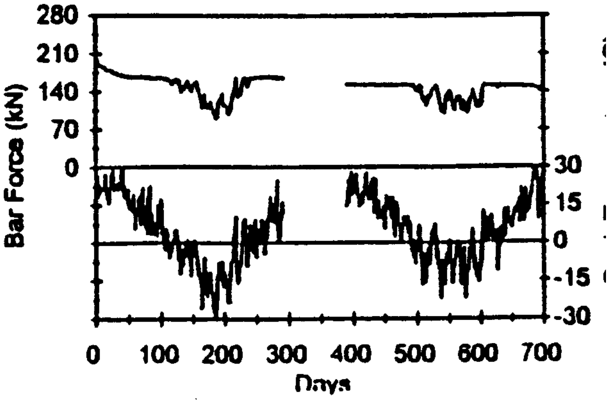

Fig. 5 Bar force and temperature data from Ciphers stress-lam deck bridge.

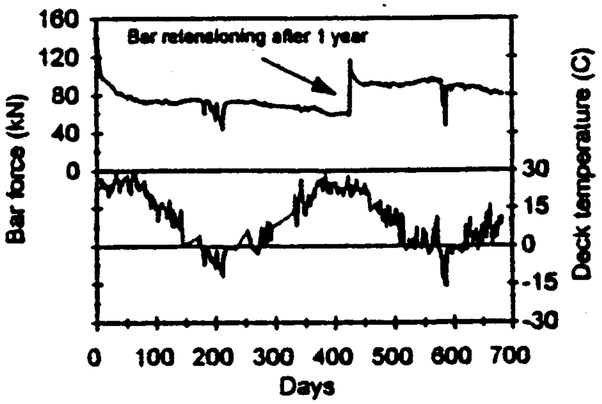

Fig. 6 Bar force and temperature data from McCurdy Road stress-lam deck bridge.

content remained at approximately 16% for the Pine River bridge, 26% for the Ciphers bridge, and >30% for the McCurdy Road bridge. As shown in Fig. 4, the Pine River bridge was monitored for 1200 days over three cold temperature (winter) periods. Between days 300 and 400, the temperature drop to a minimum of -12°C resulted in a bar force loss of only 5%. The greatest temperature drop, to -28°C at day 700, yielded the maximum loss in bar force of approximately 23%. Between days 1000 and 1100, the maximum temperature drop to -12°C, which was the same as that in the first cold period, resulted in a bar force loss of approximately 12%. In all cases, bar force appeared to recover to its original level when the temperature rose.

Data for the Ciphers bridge for 700 days over two winters are shown in Fig. 5. The break in data between approximately day 300 and day 375 resulted from an equipment malfunction during data reduction. During the first winter at approximately day 200, the maximum bar force loss of 46% was recorded when the interior deck temperature dropped to -29°C. The following winter, bar force declined 31% when the temperature dropped to -14°C. Drops in temperature below the freezing point

Bridge or test deck	Lamination moisture content %	Maximum below-freezing temperature °C	Maximum bar force loss %	Ratio of percent bar force loss to temperature
Pine River bridge	16	-28	23	0.82
Ciphers bridge	26	-29	46	1.59
McCurdy Road bridge	>30	-16	50	3.13
Laboratory deck	12	-18	21	1.17
Laboratory deck	18	-18	23	1.28

Table 1 Effect of wood moisture content on bar force loss in stress-lam test decks and field bridges at below-freezing temperatures.

had an immediate effect on bar force. When the temperature rose above freezing, bar force appeared to recover fully and stabilize.

Like the Ciphers bridge, the McCurdy Road bridge was monitored for approximately 700 days over two winters (Fig, 6). During this time, a decline in bar force unrelated to temperature required retensioning of the bar at approximately day 425. Minimum temperatures of -12°C at approximately day 220 and -16°C at approximately day 580 resulted in bar force loss of 42% and 50%, respectively. Again, the figure shows the immediate effect on bar force of a drop in temperature below the freezing point and the lack of a permanent effect related to temperature.

6. DISCUSSION

Test results indicate that wood lamination moisture content has an effect on bar force loss caused by below-freezing temperatures. For laboratory test decks, bar force loss was about the same at 12% and 18% wood moisture content. The greatest bar force loss occurred when wood moisture content was above the fiber saturation point (>30%) (Table 1).

To compare bridge decks, the percentage of bar force loss was divided by the drop in temperature below freezing. The ratio of percent bar force loss to temperature was similar for test decks and field bridges with similar wood moisture content. However, the high moisture content of the Ciphers bridge suggests a greater bar force loss per temperature degree than that indicated by the data. The relatively low bar force loss for the Ciphers bridge may have been a result of the preservative treatment and is being investigated further.

6. CONCLUSIONS AND RECOMMENDATIONS

The results from the laboratory and field tests on the thermal performance of stress-laminated timber bridges led to the following conclusions and recommendations:

- Stress-lam bridges are affected by temperature. Reductions in temperature below 0°C alter the dimensions of the wood laminationss, changing bar force and potentially affecting the performance of the bridge.
- Loss in bar force caused by below-freezlng temperatures appear to be fully recoverable when the temperature rises above freezing.
- Moisture content of the wood laminations augments bar force loss in stress-lam bridges when the temperature falls below freezing. Results from both laboratory and field tests showed that bar force loss from temperature change is substantially greater at higher levels of wood moisture content. This effect can be prevented by following American Association of Highway and Transportation Official specifications [11], which state that all wood should be at or below 19% moisture content at installation.

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