

# Cold Temperature Effects on Stress-Laminated Timber Bridges

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## Abstract

Stress-laminated bridges perform well, if adequate bar force is maintained to provide the interlaminar friction and load transfer between adjacent deck laminations. Stress-laminated decks utilize both wood and steel components; therefore, different material thermal properties may cause bar force to change as the temperature fluctuates. In response to concerns about the performance of stress-laminated bridges in extremely cold climates, a cooperative research project with the University of Minnesota; the USDA Forest Service, Forest Products Laboratory; and the Federal Highway Administration was initiated to evaluate system performance at temperatures ranging from 21.1°C to -34.4°C. Stress-laminated bridge deck sections, constructed of Red Pine lumber and high strength steel stressing bars, were placed in cold temperature settings of -12.2°C, -17.8°C, -23.3°C, -28.9°C, and -34.4°C, while bar force measurements were collected. Testing was completed at three different moisture content levels: >30, 17, and 7 percent. At -34.4°C, bar force losses were high when the deck moisture content was greater than 30 percent and were moderate to low when the moisture content was less than 18 percent. In all cases, bar force loss was fully recovered after temperatures increased to 21.1°C.

Keywords: Stress laminated, bridge, timber, Red Pine, temperature, bar force.

## Introduction

Stress-laminated bridge decks consist of a series of wood laminations that are placed edgewise between supports and stressed together with high strength steel bars (Ritter 1990). The bar force, which typically ranges between 89 and 356 kN, squeezes the laminations so that the stressed deck acts as a solid-wood plate. (See Table 1 for English conversion factors.)

Stress-laminating technology was originally developed in Ontario, Canada, in 1976 as a means of rehabilitating nail-laminated lumber decks that delaminated as a result of cyclic loading and variations in wood moisture content. In the 1980s, stress-laminating technology was adapted for the design and construction of new bridges, and several structures were successfully built in Ontario using the stress-laminating concept.

**Table 1—Factors for converting SI units of measurement to English units**

SI unit	Conversion factor	English unit
millimeter (mm)	0.0393	inch (in.)
meter (m)	3.2808	foot (ft)
newton (N)	0.2248	pound (lb)
pascal (Pa)	0.0001451	lb/in <sup>2</sup> (stress)
°C	1.8(°C) + 32	°F

The first stress-laminated bridges in the United States were built in the late 1980s. Since then, several hundred stress-laminated timber bridges have been constructed throughout the United States, primarily on low-volume, rural roads. As a result of the experimental nature of the new bridge system, extensive field evaluations were implemented by the USDA Forest Service, Forest Products Laboratory (FPL), and the Federal Highway Administration (FHWA) to evaluate long-term field performance (Hislop and others 1996; Kainz, 1996; Ritter and others 1995; 1996a,b; Wacker and others 1996; Wacker and Ritter 1992; 1995a, b).

Preliminary data from several field bridges in the FPL/FHWA monitoring program indicate that bar force decreases when the temperature decreases. The magnitude of this decrease depends on a number of factors, including temperature decrease, duration of cold temperature, wood species, and moisture content. Short-term temperature declines, 24 hours or less, seem to have little effect on bar force because thermal conductivity of wood is very low. This cold temperature effect appears to be fully recoverable, and the bar force returns to the original level when the temperature increases.

Several stress-laminated bridges are located in northern climates where sustained cold temperatures are not uncommon. Therefore, concerns were raised that bar forces may temporarily drop below safe levels during the winter months. To further investigate this cold temperature effect on stress-laminated bridges, laboratory studies were necessary to evaluate the effect of subfreezing temperatures on bar force levels. This study, in conjunction with forthcoming field results, will determine if stress-laminated bridges in cold climates require special design considerations.

## Background

Thermal effects are usually not a consideration in the design of wood highway bridges. However, some bridge designs use materials that have unique thermal properties. If not compensated for, any differential between material thermal properties can lead to performance problems when exposed to large temperature changes. In these cases, the design needs to compensate for differential movement of bridge components while preserving structural integrity.

Because wood laminations are compressed with steel bars to form the stress-laminated deck, bar force levels could be adversely affected by large temperature fluctuations. The different materials will expand and contract

at various rates. The thermal coefficient for wood is approximately twice that of steel; therefore, temporary temperature-induced bar force losses may occur as both materials contract under cold temperature conditions. This thermal interaction is complicated by the thermal properties of wood, which is dependent upon many factors, including grain orientation. For stress-laminated decks, the grain orientation is randomly mixed between radial and tangential directions, which prevents a simplified mechanical analysis.

Thermal contraction of small, clear wood specimens has been investigated (Kubler 1973). An accelerated rate of thermal contraction was observed for moist samples at temperatures less than 0°C. At temperatures less than 0°C, a type of internal drying occurs and moisture diffuses out of the wet cell walls and condenses as ice crystals in the cell cavities. This internal drying causes additional shrinkage that superimposes with pure thermal contraction as a result of temperature change. Although these tests were not performed on wood members in a stress-laminated configuration, important information about moist wood behavior at cold temperatures was gained.

Other laboratory studies have investigated the effect of cold temperatures on stress-laminated bridge configurations. Pilot studies initiated at the University of Minnesota (Erickson and others 1990) and at the FPL (Kainz 1994) shortly after this phenomenon was suspected in field bridges found that bar forces decreased as the temperature dropped below 0°C. In addition, moisture content of the wood laminations seemed to influence the magnitude of bar force loss.

Based on these laboratory and field studies, stress-laminated bridges located in U.S. regions where extreme cold temperatures are common were suspected to encounter temporary bar force loss. In response to these concerns, a cooperative study was initiated with the University of Minnesota, FPL, and FHWA to evaluate stress-laminated deck bar forces over a wide temperature range and to further investigate this phenomenon and its possible design implications for cold climates.

## Objective

The objective of this research was to determine how bar force levels in stress-laminated decks change when exposed to temperatures between 21.1°C and -34.4°C.

## Test Methods

Testing was completed in the laboratory under controlled temperature and moisture content conditions.

Deck sections were sequentially placed in cold settings of  $-12.2^{\circ}\text{C}$ ,  $-17.8^{\circ}\text{C}$ ,  $-23.3^{\circ}\text{C}$ ,  $-28.9^{\circ}\text{C}$ , and  $-34.4^{\circ}\text{C}$ , while bar forces were monitored. To detect moisture content effect, three different moisture content levels were used in testing.

A typical configuration of the stress-laminated deck section used for testing is shown in Figure 1. Three identical deck sections were constructed to the following dimensions: 3.05 m long, 1.07 m wide, and 305 mm deep. The untreated lumber laminations were full-length Red Pine lumber (No. 2 grade), measuring nominal 51 by 305 mm. The prestressing elements were high strength steel bars, measuring 15.9 mm in diameter, and were spaced at 610-mm intervals, beginning 305 mm from the ends. Bar anchorage was provided with rectangular steel bearing plates and flat hex nuts. To measure bar force levels, three steel hollow-core load cells were placed at the interior bar locations of each deck section, between two steel anchor plates.

### Testing Procedures

Testing was completed in three phases using similar procedures (Table 2). The moisture content of the deck laminations differed in each phase and was greater than 30 percent for phase I, approximately 17 percent for phase II, and approximately 7 percent for phase III. For each phase, the same five temperature runs were conducted to increasingly lower temperatures to  $-34.4^{\circ}\text{C}$ . All tests were initiated with bar forces at approximately 120 kN, which is equivalent to an interlaminar compression level at 690 MPa. The procedures used during each phase were repetitive and are described as follows.

### Load Cell Calibration

A total of nine steel, hollow-core load cells were fabricated in accordance with previously developed specifications (Ritter and others 1991). The cells were designed to compensate for temperature-induced strain variations

and were verified at cold temperatures prior to testing. Before installing load cells, they were calibrated for compression loads up to 133 kN. In addition, the load cells were recalibrated with the data acquisition system prior to beginning each test phase.

### Wood Conditioning

The Red Pine laminations were purchased in “green condition” with a high variability in moisture content, between 40 and 70 percent. The laminations were air-dried for several weeks in an attempt to condition them to approximately 35-percent moisture content for phase I. Kiln drying was not used initially because of concerns that some laminations would drop below fiber saturation. Therefore, the actual moisture content of the laminations during phase I testing varied between 40 and 60 percent. For phases II and III, kiln drying was utilized to reduce the lamination moisture content to the desired level and provide more uniform lamination moisture content levels. Throughout testing, an electrical-resistance moisture meter and individual lamination weights were used to measure wood moisture content.

To prevent fluctuations in moisture content within each phase, deck laminations were wrapped with polyurethane plastic.

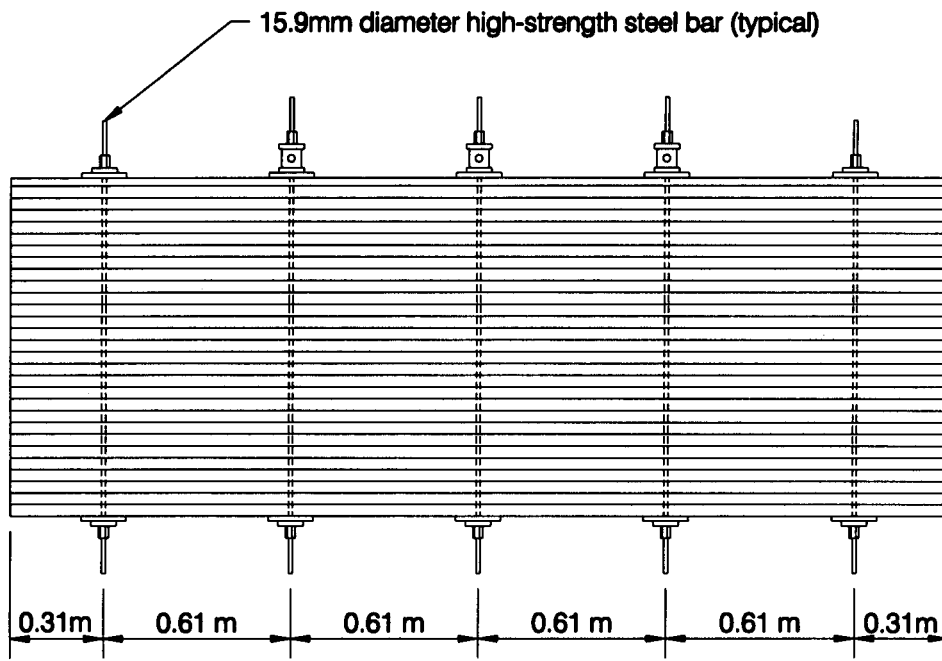
### Deck Assembly and Stressing

After the laminations were conditioned to the desired moisture content for each test phase, the deck sections were assembled and the bars were tensioned with hydraulic equipment. To assemble the deck sections, the laminations were placed on edge and stressing bars were inserted through 19-mm-diameter predrilled holes. Thermocouples were embedded at several locations within the deck to provide interior wood temperatures. Bearing plates and anchor nuts were then attached. At the completion of phase I testing, the laminations were numbered and the grain orientation was noted so they could be reassembled in the same manner for future test phases.

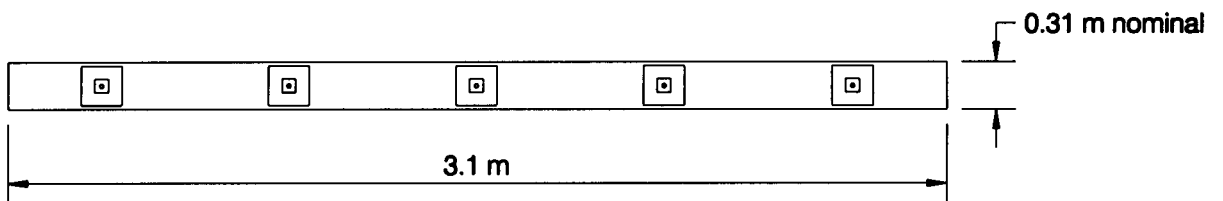
After assembly, the stressing bars were tensioned using a hydraulic pump and a single hollow-core ram. Beginning at one end, each bar was tensioned to 120 kN in a sequential manner until the entire deck was stressed together. Plate crushing into the outer laminations was a concern, especially at the high moisture content levels used in phase I, because it would cause bar forces loss and dilute any temperature effect data. To detect wood crushing, the outside laminations were visually inspected after removing bearing plates at the completion of each phase.

**Table 2—Moisture content and temperature conditions used during study.**

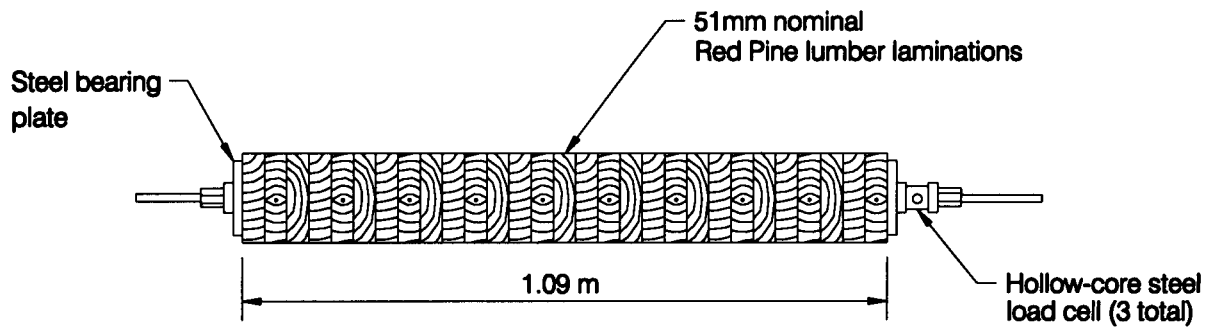
Phase	MC (%)	Temperature runs		
			$^{\circ}\text{C}$	$^{\circ}\text{F}$
I	>30	1	21.1 to $-12.2$	70 to 10
		2	21.1 to $-17.8$	70 to 0
II	17	3	21.1 to $-23.3$	70 to $-10$
		4	21.1 to $-28.9$	70 to $-20$
III	7	5	21.1 to $-34.4$	70 to $-30$



Plan View



Side View



End View

Figure 1—Typical configuration of stress-laminated deck section used in testing.

## Data Collection

After the decks were stressed together, data collection was initiated. A data acquisition system was used to monitor the bar forces, ambient air temperature, and interior wood temperature at 1-hour intervals for all temperature runs. Data collection typically began several hours before the decks were placed in the freezer room to ensure that the bar force was stabilized at a constant level. By ensuring constant bar force prior to initiating temperature runs, bar forces would be influenced solely by temperature effects. For each temperature run, the decks remained in the freezer until the embedded thermocouples indicated temperature equilibrium. Each temperature run was terminated several hours after removal from cold temperatures when the temperature equilibrated to 21.1°C.

## Results and Discussion

Results from all temperature runs for the three phases are summarized in Figure 2. Measured bar force changes from all three deck sections were approximately equal and were averaged for each test phase. To aid interpretation, data were normalized to the same initial bar force level and test duration. For all test phases, the initial bar forces were within 10 percent of the target level (120 kN), which corresponds to 690-MPa interlaminar compression. The test duration for the individual tests varied between 500 and 800 hours, with more time required to cool the decks to lower temperatures. In addition, no crushing was detected on the exterior laminations.

### Phase I

Bar force losses were high during phase I, at a moisture content greater than 30 percent. These losses became significantly greater as the temperature decreased from -12.2°C to -34.4°C. For the first temperature run to -12.2°C, bar force losses totaled approximately 40 kN, or 33 percent of the original bar force. Bar force losses for intermediate temperature runs to -17.8°C, -23.3°C, and -28.9°C were 52, 70, and 81 percent of the original bar force, respectively. For the last temperature run to -34.4°C, bar force losses were approximately 102 kN, or 85 percent of the original bar force.

### Phase II

Bar force losses were moderate during phase II, at a moisture content of approximately 17 percent. The losses became only slightly greater as the temperature decreased from -12.2°C to -34.4°C. For the first temperature run to -12.2°C, bar force losses were approximately 22 kN, or 19 percent of the original bar force. For the last temperature run to -34.4°C, bar

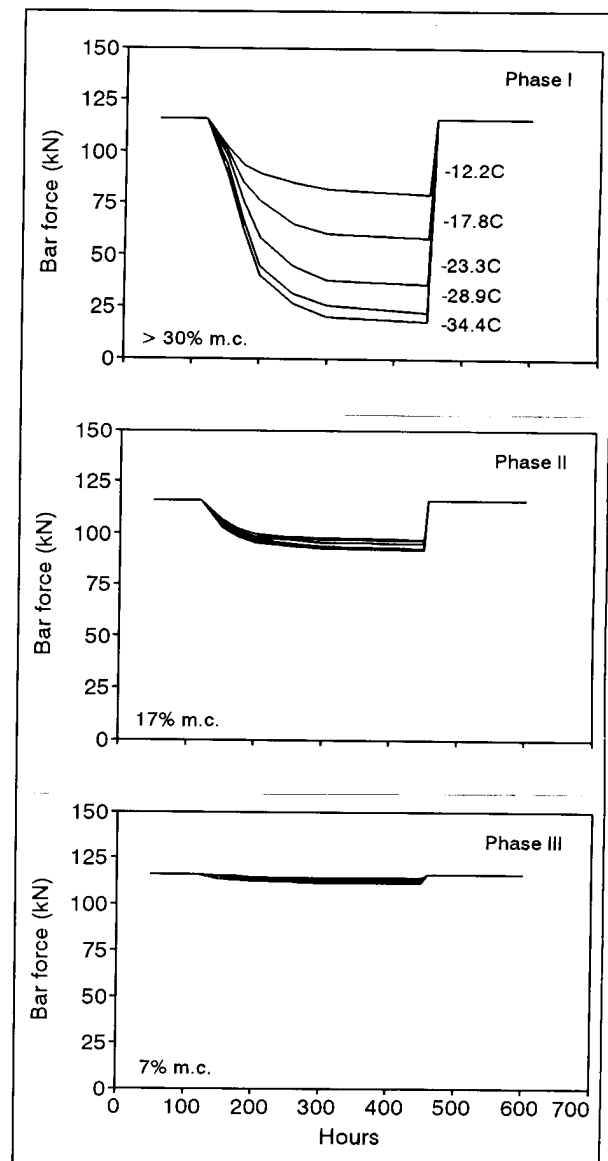


Figure 2—Normalized bar force from the three test phases. (m.c. is moisture content.)

force losses totaled approximately 29 kN, or 22 percent of the original bar force. Bar force losses for temperature runs to -17.8°C, -23.3°C, and -28.9°C were intermediate to these values.

### Phase III

Bar force losses were low during phase III, at a moisture content of approximately 7 percent. The losses were essentially constant as the temperature decreased from -12.2°C to -34.4°C. For the first temperature run to -23.3°C, bar force losses totaled approximately 6.7 kN, or 6 percent of the original bar force. For the last temperature run to -34.4°C, bar force losses were

approximately 8.9 kN, or 7 percent of the original bar force. Bar force losses for temperature runs to  $-17.8^{\circ}\text{C}$ ,  $-23.3^{\circ}\text{C}$ , and  $-28.9^{\circ}\text{C}$  were intermediate to these values.

### Phase Comparison

By comparing the bar forces from all three phases in Figure 2, a distinct moisture content effect is evident. Assuming a constant rate of thermal contraction for the steel bars, the wood laminations seem to contract under cold temperatures at an accelerating rate as the moisture content increases. At the lower moisture content levels of 17 and 7 percent used in phases II and III, the magnitude of bar force losses is small and increases only slightly as the temperature decreases from  $-12.2^{\circ}\text{C}$  to  $-34.4^{\circ}\text{C}$ . But at a moisture content greater than 30 percent in phase I, the magnitude of the bar force loss is greater and increases rapidly as the temperature decreases from  $-12.2^{\circ}\text{C}$  to  $-34.4^{\circ}\text{C}$ . Similar results from a study by Kubler (1973) using small wood samples also describe an accelerated rate of thermal contraction at higher moisture content levels.

These results indicate that large bar force losses are possible in stress-laminated bridges located in cold temperature climates. For these temporary bar force losses to occur, however, the lamination moisture content must be greater than 30 percent and the air temperature must remain below  $-17.8^{\circ}\text{C}$  for several days.

Results from monitoring several field bridges located in cold temperature climates have not detected substantial bar force losses as a result of temperature effects. This phenomenon has not been a problem for field bridges because it is very unusual for timber bridges to have a moisture content greater than 30 percent. Current AASHTO bridge specifications require that all lumber be conditioned to a maximum moisture content of 19 percent at installation (AASHTO 1992). In addition, a field study inspected several timber bridges across the northern United States and found that the deck moisture content averaged approximately 18 percent after several years in service (McCutcheon and others 1986).

Additional results from laboratory and field studies will be published soon (Kainz and others [in progress], Ritter and others [in progress]).

### Concluding Remarks

Bar forces were monitored on three stress-laminated deck sections as they were placed in cold temperature settings of  $-12.2^{\circ}\text{C}$ ,  $-17.8^{\circ}\text{C}$ ,  $-23.3^{\circ}\text{C}$ ,  $-28.9^{\circ}\text{C}$ , and  $-34.4^{\circ}\text{C}$ . Testing was completed at moisture content

levels of 7, 17, and  $>30$  percent. Based on the bar force measurements, the following conclusions are presented:

- Bar force loss observed at all cold temperature and moisture content conditions was fully recovered at the completion of each temperature run.
- At a given moisture content level, the maximum bar force loss was observed during the coldest temperature drop to  $-34.4^{\circ}\text{C}$ .
- The moisture content of the laminations has a significant effect on the magnitude of bar force loss. Maximum bar force loss totaled 85 percent of the original bar force at greater than 30-percent moisture content (phase I), 22 percent at 17-percent moisture content (phase II), and 7 percent at 7-percent moisture content (phase III).
- Although there was a significant reduction of bar forces at temperatures less than  $-17.8^{\circ}\text{C}$  and moisture content in excess of 30 percent, there is no indication that this phenomenon has been a problem for existing bridges. Field monitoring studies are currently being conducted by the FPL on several bridges in cold climates and additional findings will be published soon.

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