Performance of Stress-Laminated Timber Highway Bridges In Cold Climates

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ABSTRACT

This paper summarizes recent laboratory and field data studies on thermal performance of stress-laminated timber highway bridges. Concerns about the reliability of stress-laminated deck bridges when exposed to sub-freezing temperatures triggered several investigations. Two laboratory studies were conducted to study the effects of wood species, preservative, moisture content, and temperature variations on pre-stressing bar forces (critical factor) in stress-laminated decks. The field performance of several stress-laminated timber bridges were monitored within a Nationwide Timber Bridge Monitoring Program, a cooperative effort by the U.S. Forest Service, Forest Products Laboratory and Federal Highway Administration. Bar-force and temperature data from a subset of bridges were continuously monitored for a period of 2 to 5 years with remote data acquisition systems. Significant pre-stressing bar-force losses were observed in laboratory studies when the moisture content of deck laminations were at 30 percent and greater and the deck temperature reached 0°F (–18°C) and below. The field study concluded that the magnitude of cold-temperature induced bar-force losses were not significant enough to warrant special considerations in the U.S. bridge design code. However, it may warrant special considerations in cold weather regions outside the United States whenever deck lamination moisture contents exceeding 20 percent are combined with ambient temperatures remaining below 0°F (–18°C) for extended periods of time.

INTRODUCTION

Stress-laminated deck bridges are longitudinal deck (i.e., slab-type) superstructures that can be manufactured using sawn lumber, glued-laminated timber (glulam), laminated veneer lumber (LVL), or structural-composite lumber products for the deck laminations. The configuration (Figure 1) of a stress-laminated deck bridge consists of deck laminations (placed on edge) and laminated together with a high degree of compressive force, or stress, provided by high-strength steel bars that pass through the mid-depth of the deck in pre-bored holes. Mechanical fasteners such as nails or adhesives are not required in the deck system, and decks can employ butt-joints to achieve longer or multiple span continuous arrangements. A key advantage of stress-laminated structural systems is their ability to easily restore structural efficiencies in the deck system by re-tensioning the pre-stressing bars to their original

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design force levels. Stress-laminating technology was first used to rehabilitate nail-laminated decks that had loosened after many years in service. In this case, the stress-laminating hardware was retrofitted externally to the timber deck and embedded with the asphalt-wearing surface.

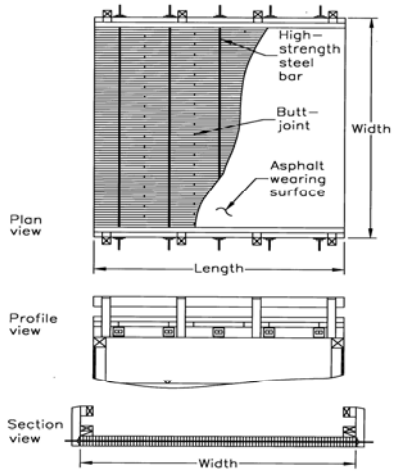

Figure 1. General configuration of stress-laminated deck bridge superstructure.

Over 1,000 stress-laminated bridges are estimated to have been built in the past 20 years in the United States. Their field performance has been generally satisfactory, but most bridges have required periodic pre-stressing bar re-tensioning because of the creep of moist deck laminations. This periodic maintenance task has been problematic and the primary reason stress-laminated decks have not become more popular in the United States. Some engineers have successfully mitigated this problem by replacing wet lumber laminations with dry glulam beams or replacing the steel pre-stressing members with fiber-reinforced polymer strands.

Concerns about stress-laminated deck performance in cold environments were initially raised by a bridge owner in northern Minnesota who detected severe bar-force losses (Erickson et al. 1990). Heavy trucks were transporting logs from wetland areas during the winter while the roadway was frozen. The combination of inadequate bar forces and heavy truck loading presented a potentially critical issue that warranted investigation. Therefore, the Forest Products Laboratory (FPL) in cooperation with the Federal Highway Administration (FHWA) launched a series of laboratory and field investigations to determine if stress-laminated bridges required special design considerations for cold weather climates. This paper summarizes those laboratory and field data regarding the cold temperature performance of stress-laminated timber highway bridges.

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LABORATORY AND THEORETICAL EVALUATIONS

Two separate laboratory investigations along with a theoretical analysis were conducted and are summarized below.

Initial Study. The initial study conducted by FPL examined the behavior of bridge deck sections as they were placed into a controlled environment of 0°F (–18°C). The configuration of the 1.5 m^2 bridge test deck sections is provided in Figure 2. The deck laminations included CCA-treated Southern Pine, creosote-treated Douglas-fir, untreated Douglas-fir, and untreated laminated-veneer-lumber (LVL). Bar forces were measured with hollow-core steel load cells, and temperatures were measured by thermal couple wires embedded into the deck sections. A datalogger automatically collected data at 15-minute intervals throughout testing. The bridge deck sections were initially tensioned to several different pre-stress levels (690kPA, 517kPA, 276 kPa, 173 kPA) before entering the cold-temperature chamber. In addition, testing was repeated under three separate wood moisture content levels (12%, 18%, and >30%). For additional details on this research effort, refer to Kainz et al. (2001).

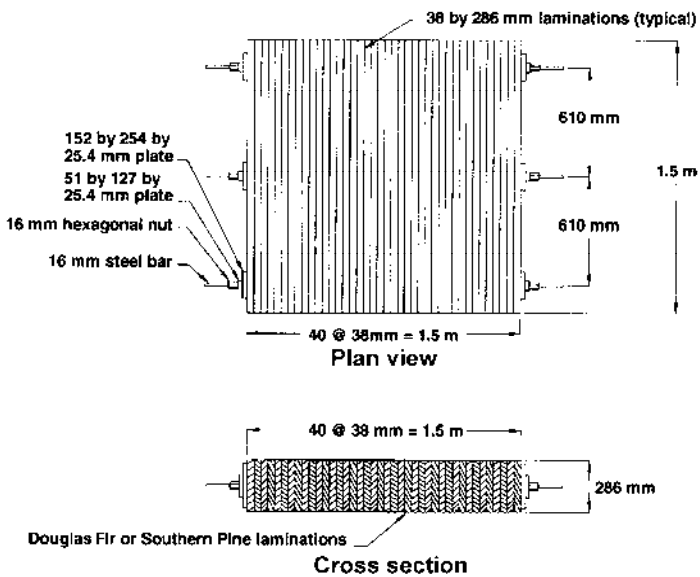

Figure 2. Configuration of initial lab study test deck specimens.

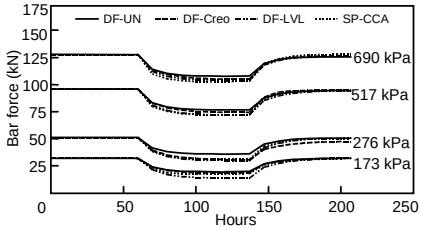

Figure 3. Summary of results of Lab Study 1 at 8% moisture content for several different pre-stress levels.

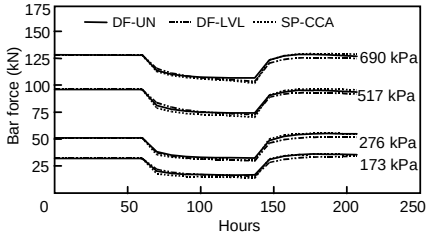

Figure 4. Summary of results of Lab Study 1 at 18% moisture content for several different pre-stress levels.

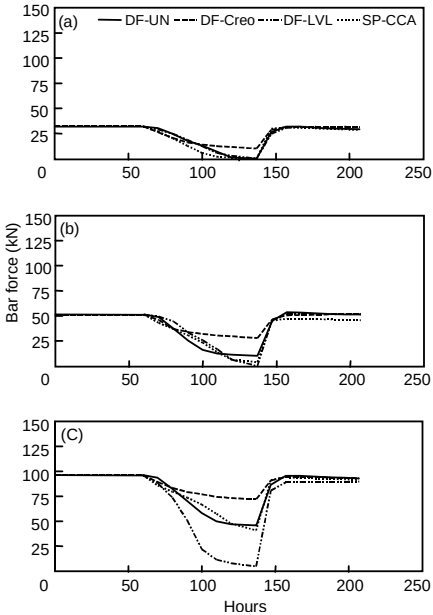

Figure 5. Results of Lab Study 1 at 30% moisture content at three different pre-stress levels (a) 173 kPa; (b) 276 kPa; (c) 517 kPa.

The initial study results indicated that species, preservative, and pre-stress levels did not have a significant effect on the thermal behavior of the stress-laminated deck sections. However, the wood moisture content seemed to be a major contributor in the behavior of deck sections at very low temperatures. When the wood laminations were dried to a very low moisture content of 8%, the magnitude of bar-force losses when equilibrated at cold temperatures of –18°C (0°F) averaged approximately 25kN regardless of the pre-stress level (Figure 3). Similar behavior was observed when the wood laminations were tested at a dry moisture content of 18% (Figure 4). When the wood laminations were at fiber saturation near 30% moisture content, dramatic bar-force losses were observed, especially for the LVL test deck section (Figure 5).

This suggests that the specimen configuration and more importantly, the lamination moisture content, determined the magnitude of the temperature-induced bar-force losses for any cold temperature scenario. Even though the rate of thermal contraction for steel is much higher than those reported for wood, saturated wood clearly has a significantly higher rate of contraction, exceeding that of steel. This mechano-sorptive phenomenon where wood contracts at a faster rate than the steel pre-stressing bars confirms previous work by Kubler et al. (1973) where testing focused on small-clear specimens. It was also noted in the initial study that these temperature-induced losses in pre-stressing bar force were fully recovered once the internal deck temperatures stabilized above 0°C (32°F).

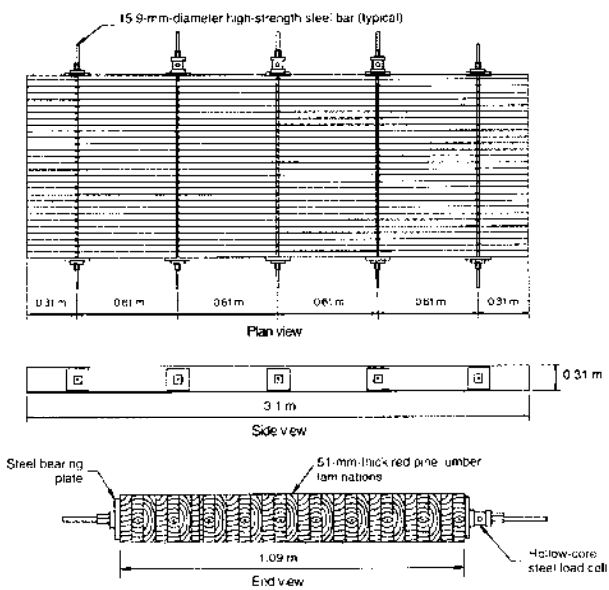

Figure 6. Configuration of Laboratory Study 2 test deck specimens.

Second Study. A follow-up laboratory study was conducted cooperatively by the University of Minnesota and FPL. These tests were very similar to the initial study but eliminated some variables (species, preservative, pre-stress level) and achieved even colder temperatures reaching –34.4°C (–30°F). Three replicate test decks of red pine sawn lumber (Figure 6) 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, 18%, and 8% (Wacker 2003).

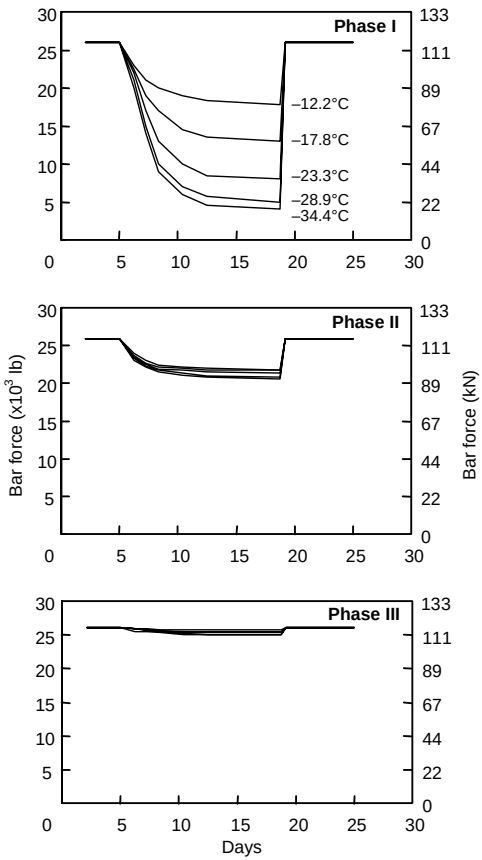

Figure 7. Summary of results from the Laboratory Study 2 at the three moisture content levels tested (phase I – 30%, phase II – 18%, phase III – 8%).

These experimental results (Figure 7) further characterized this mechano-sorptive behavior at sub-freezing temperatures ranging from 0°F (–18°C) down to –34.4°C

(–30°F). During Phase III with wood moisture content equilibrated at approximately 8%, pre-stressing bar-force losses observed during each successive sub-freezing temperature test were insignificant. During Phase II with wood moisture contents equilibrated at approximately 18 percent, pre-stressing bar-force losses observed during each successive sub-freezing temperature test were slightly higher at 10-15 kN. During Phase I with wood moisture contents exceeding fiber saturation, pre-stressing bar-force losses were very significant. As the target cold temperature decreased from -12.2°C (10°F) down to –34.4°C (–30°F), the magnitude of the pre-stressing bar-force losses became more dramatic. During the last temperature test where the test deck section was placed in a controlled environment of –34.4°C (–30°F), the pre-stressing bar-force losses were estimated at 90 kN, or nearly 80% of their original level. These results seemed to be on the magnitude of the initial field report, so field investigations were initiated to determine how widespread was this thermal phenomenon of cold temperature-induced pre-stressing bar-force losses.

Theoretical Modeling. Theoretical modeling of the thermal behavior of sawn wood laminations pre-stressed with steel bars was performed in conjunction with initial study experiments (Kainz 1994). The model represented the steel pre-stressing bars and the wood laminations as linear-elastic springs in parallel, predicted higher pre-stressing bar-force losses than were observed in the experimental studies. One of the larger challenges was assigning accurate thermal coefficients to a large number of deck laminations with varying grain orientations.

FIELD EVALUATIONS

The field performance of several stress-laminated timber bridges was monitored within a Nationwide Timber Bridge Monitoring Program (Appendix A, Wacker 2003), a cooperative effort by FPL and FHWA. Bar-force and temperature data from a subset of bridges were continuously monitored for a period of 2–5 years with remote data acquisition systems. In other cases, bar-force and temperature data were collected periodically with portable strain indicators and hand-held thermometers by on-site personnel.

Minnesota Bridge. The Ciphers Bridge (Figure 8) is a single-lane stress-laminated deck bridge with a total length of approximately 12.19 m (40 ft). It is located in northern Minnesota, one of the coldest U.S. regions during the winter season. This bridge was also the origin of the initial reports of dramatic bar-force losses. So, it was one of the first stress-laminated bridge decks to have its field performance monitored for period of two years beginning three years after installation (Wacker et al. 1998). At the initiation of field monitoring, all pre-stressing bars were re-tensioned to the full design force. The deck laminations were measured to be near fiber saturation (~30%) even after three years in service.

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Figure 8. Ciphers stress-laminated deck bridge located in northern Minnesota.

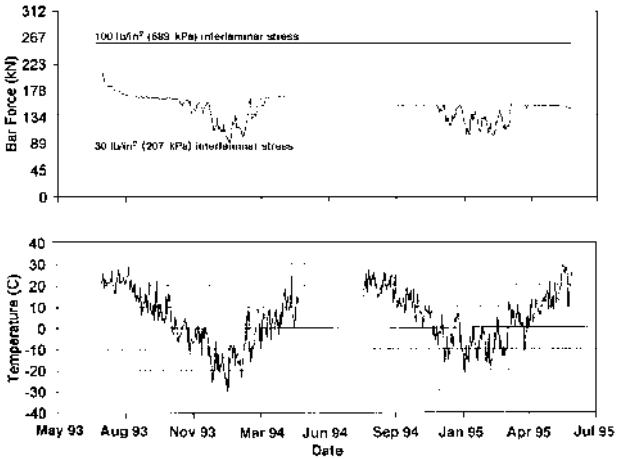

Figure 9. Two-year record of bar-force and deck temperature data from the Ciphers Bridge in northern Minnesota.

The results from the monitoring study of the Ciphers Bridge are summarized in Figure 9. The monitoring period included two winter cold seasons where the internal deck temperatures reached –20°C (–4°F) and –30°C (–22°F) below freezing. Pre-stressing bar-force losses were observed each winter season and were fully recovered during the spring. The pre-stressing bar-force losses were on the magnitude of 50 kN, which represented nearly 50 percent losses from the pre-winter level. However, during the entire monitoring period, the bar forces did not fall below the long-term threshold level of 207 kPa (30 lb/in.^{2}) interlaminar stress established in the design procedure.

Pennsylvania DOT Bridges. Several stress-laminated deck bridges constructed of hardwood lumber were investigated over a 5-year period (Wacker et al. 2004) in conjunction with the Pennsylvania Department of Transportation. The effect of cold-

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temperature-induced bar-force loss was observed over several consecutive winter periods on the Birch Creek Bridge located in Sullivan County (Figure 10). The magnitude of the pre-stressing bar-force losses were relatively small compared with those observed at the Minnesota bridge or the second laboratory study. In the present study, the moisture content levels were near fiber saturation (~28%), but ambient temperatures did not drop low enough. A close-up view of a winter cold-temperature data set from the Laurel Run Bridge (Figure 11) clearly shows that the internal deck temperature is more stable with a time-lag behind the rapidly changing ambient temperature because of the insulating characteristics of wood.

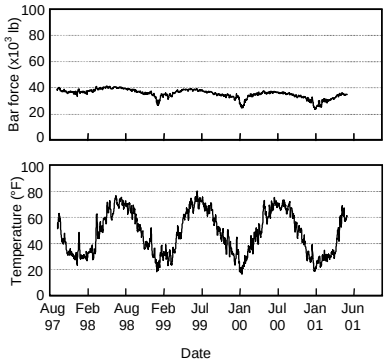

Figure 10. Bar-force and internal deck temperatures from the Birch Creek bridge in Sullivan County, Pennsylvania.

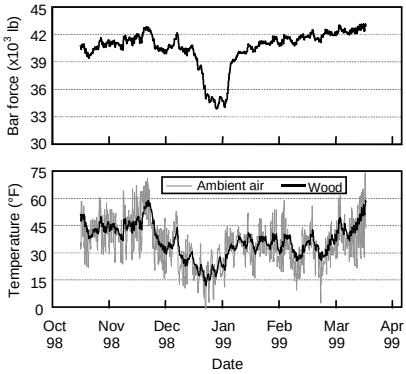

Figure 11. Typical plot of cold-temperature induced bar-force losses from the Laurel Run Bridge in Huntingdon County, Pennsylvania.

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DESIGN IMPLICATIONS

Although laboratory studies detected significant percentages of bar-force loss when moisture content was near or above fiber saturation and test temperatures dropped below 0°F (–18°C), numerous field-monitoring studies throughout the United States did not detect any significant bar-force losses during the cold winter seasons. Therefore, we have not recommended thermal-related design considerations to the American Association of State Highway and Transportation Officials (AASHTO) specifically for stress-laminated decks. The current AASHTO-LFRD (Load and Resistance Factor Design) Bridge Design Specifications (AASHTO 2007) includes design considerations for thermal expansion of timber decks (reference 9.9.3.4), but requires only consideration of longitudinal movements of continuous stress-laminated or glued-laminated timber decks longer than 400 ft. Bridge owners and designers should be made aware that stress-laminated decks with elevated moisture contents are susceptible to significant bar-force losses under extreme cold temperatures. There should also be renewed emphasis placed on the importance of specifying, verifying, and installing dry sawn lumber (maximum moisture content of 19 percent) for stress-laminated decks.

SUMMARY

Stress-laminated deck highway bridges are more common since being introduced in the United States in the late 1980s. Their structural integrity is predicated on adequate bar-force, or deck pre-stress, and being maintained above the long-term threshold of 40 lb/in.^{2} interlaminar stress. Field reports of a stress-laminated bridge deck in northern Minnesota losing significant amounts of deck pre-stress (well below 40 lb/in.^{2} interlaminar stress) during the cold winter season triggered further investigations of this phenomenon. Two laboratory studies were conducted to study the effects of wood species, preservative, moisture content, and temperature variations as they affect pre-stressing bar forces (critical factor) in stress-laminated decks. Field performance of several stress-laminated timber bridges were monitored within the Nationwide Timber Bridge Monitoring Program, a cooperative effort by the Forest Products Laboratory and Federal Highway Administration. Bar-force and temperature data from a subset of bridges was continuously monitored for a period of 2 to 5 years with remote data acquisition systems. The field study concluded that the magnitude of cold-temperature induced bar-force losses is not significant enough to warrant special considerations in the U.S. bridge design code. However, it may warrant special design considerations in cold weather regions like interior Alaska and other countries, wherever deck lamination moisture contents exceeding 20 percent are combined with ambient temperatures remaining below 0°F (–18°C) for extended periods of time.

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FUTURE WORK

Further monitoring efforts should investigate stress-laminated decks in severely cold climates and with average moisture content ranges above 20 percent to determine the severity of temperature-induced bar-force losses.

ACKNOWLEDGEMENTS

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