Advantage

Restricted to FERIC Members and Partners Vol. 5 No. 42 November 2004

Contents

Bending strength and stiffness of log stringers for bridges on forest roads: tests of second-growth Douglas-fir and western hemlock logs

Abstract

In order to provide bridge designers with better information, International Forest Products Limited (Interfor) asked the Forest Engineering Research Institute of Canada (FERIC) to evaluate the bending strength and stiffness of log stringers used for constructing bridges on forest roads in coastal British Columbia. Given the lack of definitive standards for testing this material, FERIC developed a field-based test procedure and designed a test facility for destructive testing of full-size, whole-log stringers obtained from second-growth stands. Sixteen coastal Douglas-fir and twelve western hemlock logs were tested in 2003. This report describes the test procedure and methods of analysis, presents the log bending strength and stiffness results, and makes recommendations regarding future testing.

Keywords

Bridge design, Log stringers, Bending strength, Stiffness, Modulus of rupture, Modulus of elasticity, Test procedure, Second-growth logs, Douglas-fir, Western hemlock, Coastal British Columbia.

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Introduction

Bridges constructed of logs are proven structures for water crossings on forest roads. Many forest operations in western Canada see log bridges as an inexpensive, effective, and practical alternative to installing steel or concrete structures at temporary stream crossings.

In a log bridge, several whole logs, known as stringers, are placed side-by-side to span a stream. Decks for these bridges typically consist of wood cross-ties and planks, or of a layer of gravel applied directly on top of the stringers. The stringers are the load-carrying component of the bridge superstructure; loads on log bridges often include heavy logging trucks with gross weights up to 150 tonnes.

Traditionally, engineers used a working stress approach to design log bridges. However, engineering design codes and government regulations have evolved such that Limit States Design procedures have now been adopted globally for most structures, including bridges.[3] For example, in British Columbia, forest practices legislation

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[3] A working, or allowable, stress approach uses factored design stresses for materials. For timber, these stresses may be based on tests of small, clear wood specimens where the relationship to full-size materials is not known. The load effects are the vehicle and dead loads when designing a bridge under this approach. With Limit States Design, the design properties should be based on the actual material properties for the type and size of structural member. The load effects are factored loads.

specifies that bridge design and fabrication must meet the standards set out in the Canadian Highway Bridge Design Code (Canadian Standards Association 2000) which is based on the Limit States Design philosophy. Using the Code is problematic for designers of log bridges because little is known about the mechanical properties of the logs commonly used in such bridges. To date, only one other study of log stringer strength has been completed (Tuomi et al. 1979); it involved destructive testing of old-growth Sitka spruce and western hemlock logs in Alaska.

Another concern about log stringer properties relates to the age of the source trees. As harvesting of second-growth stands increases, the use of second-growth logs for bridge stringers is also increasing. Because the pith-to-bark gradient in wood density varies with tree species and age (Jozsa and Middleton 1994), log bridge designers have questions about how the strength values for second-growth and old-growth logs may differ.

The need for information about full-size logs is reminiscent of the progress made in developing structural properties for sawn lumber. Lumber properties were originally derived from tests of small, clear specimens of wood with the results adjusted to account for product dimensions, grade, and other factors. Extensive work in the 1970s and 1980s (summarized in Madsen 1992) showed that "in-grade" testing of full-size wood products was a superior approach to estimating structural properties. Research showed that small, clear specimens of wood and full-size lumber products have different failure modes and structural behaviour, which effectively makes them different material types. As a result, the Canadian Wood Council (CWC) undertook a comprehensive program to derive properties for full-size lumber based on "in-grade" testing (Barrett and Lau 1994). This approach is now the basis of the design properties used in Canada's national standard for Engineering Design in Wood (Canadian Standards Association 2001a).

Objectives

In order to provide bridge designers with better information, International Forest Products Limited (Interfor) asked FERIC to evaluate the bending strength and stiffness of log stringers used for constructing bridges on forest roads in coastal British Columbia. Given the lack of definitive standards for testing this material, FERIC developed a field-based test procedure and designed a test facility for destructive testing of full-size, whole-log stringers.

The objectives of the study were to:

- Design a methodology and field facility for testing log stringers.
- Determine bending strength and stiffness of a sample of coastal second-growth Douglas-fir and western hemlock log stringers.

This report describes the test procedure and methods of analysis, presents the log bending strength and stiffness results, and makes recommendations regarding future testing.

Description of the test facility and test procedure

The facility was constructed at one of Interfor's contract logging operations on the east coast of Vancouver Island, approximately 80 km northwest of Campbell River, British Columbia (Figure 1), and testing was completed in 2003. The test facility was built adjacent to a log sortyard to take advantage of nearby

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ISSN 1493-3381

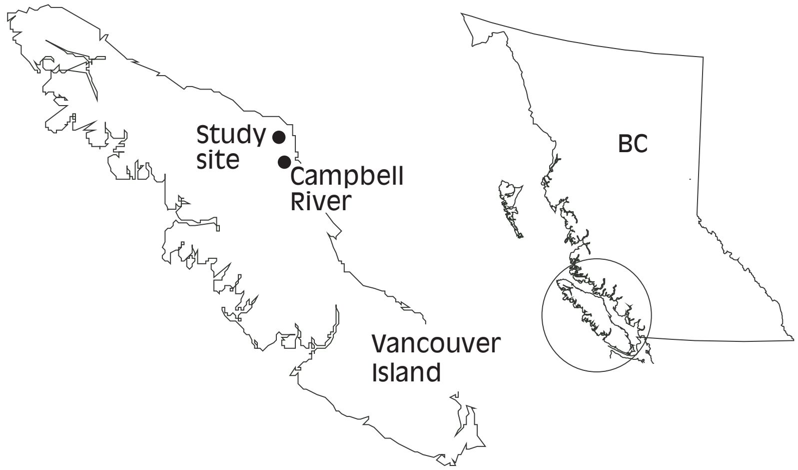


Figure 1. Location of study site.

equipment, supplies, and log storage areas. To control costs, FERIC incorporated local logging equipment and rigging supplies in the test procedure.

It was important that the test procedure and facility simulate the end-use conditions of the logs as closely as possible, and therefore the facility was designed to test each log as a simply supported beam. The logs were elevated on two concrete-block pillars that were spaced at 15 m from center to center (Figures 2 and 3). Three 25x25-cm Douglas-fir timbers were bolted to the top of each concrete pillar, and a steel support saddle, fabricated by FERIC, was secured to each set of timbers. The test log rested in the support saddles. One saddle rotated in a fixed position during testing and the other was free to rotate and slide longitudinally.

While the 15-m spacing of the pillars was selected in order to accommodate Interfor's longest preferred log length of 16.7 m, a few of the test logs were longer. The longer logs were placed in the saddles with the top end overhanging.

Before being placed in the support saddles, the logs were weighed by means of two portable weigh scales spaced 15 m apart (Figure 4). Each log was positioned on the scales such that the marked reaction points were aligned with the scale centers.

Figure 2. Log stringer in position at test facility.

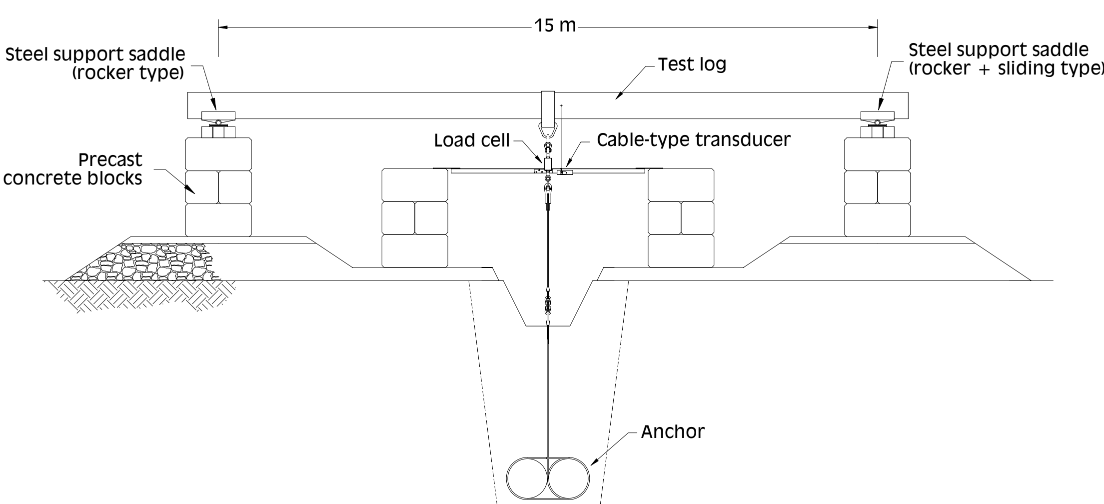


Figure 3. Design of facility for testing log stringers.

Figure 4. Placing log on weigh scales.

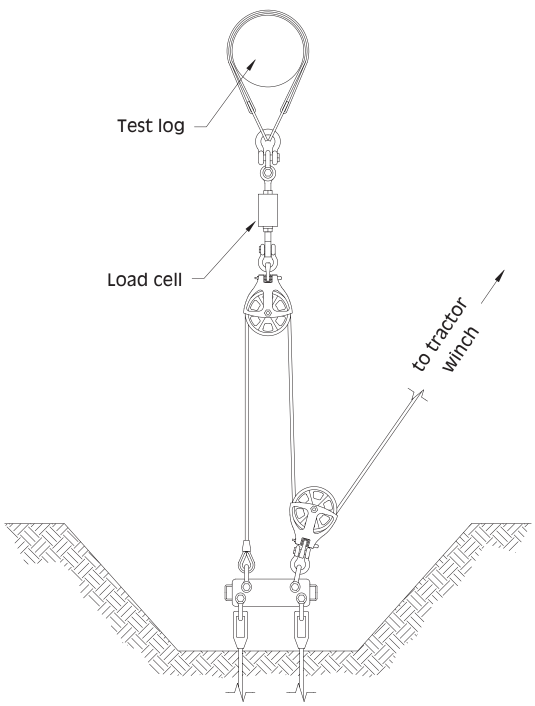


Figure 5. Block and tackle arrangement.

Figure 6. Connecting transducer draw-wire to log.

After the log was placed in the saddles, a concentrated load was applied to the log at midspan by means of a 30-cm-wide nylon web sling. The sling was draped over the log and connected to a block and tackle arrangement that provided a 2:1 mechanical advantage (Figure 5). The rigging was secured to a deadman anchor buried beneath the test facility at the midspan point. A crawler-tractor winch provided system power. The force applied to the log was measured by a load cell positioned between the sling and the upper block. A 222-kN load cell was used for the first 25 test logs but it was replaced with a 445-kN load cell for the final three logs, which were larger than average.

Log deflection was measured with a cable-type displacement transducer. This instrument was mounted on a steel beam that spanned two other, lower concrete-block pillars located between the two main pillars. These secondary pillars also prevented the broken log segments and equipment from falling to the ground at the end of each test. The transducer's draw-wire was connected to a nail driven into the log at its neutral axis (Figure 6). The nail was offset 0.3 m from midspan, toward the top end of the log, to accommodate the width of the nylon strap.

Inclinometers were attached to the support saddles to measure change in slope at the support reactions. All instruments were linked to a datalogger housed in a nearby van, and monitored continuously at 20 Hz.

After each log had been tested, a wheel loader retrieved the broken log sections and moved them to a nearby area where the failure zone of the log could be examined and documented. Then the broken segments were returned to the logyard inventory for subsequent processing.

Description of the logs

The physical characteristics of the test logs are summarized in Table 1. Physical characteristics for individual log stringers are listed in Appendix I. Linear regression analysis was used to investigate relationships between bending strength and potential variables, including basic relative density, proportion of juvenile wood, and knot frequency and size.

Log selection

The Douglas-fir and western hemlock test logs came from several second-growth harvesting units within Interfor's local operating area. As logs arrived at the operation's sortyard during the course of regular harvesting activity, the scaling crew identified potential log stringers according to guidelines provided by the forest engineer. They were separated from the current log inventory and stored in the sortyard for up to several months until testing began.

The main criteria for selecting the test stringers were that the logs be 16.7-m long (one of Interfor's longest preferred lengths), and be free from obvious defects due to handling. However, relatively few Douglas-fir logs were available in this length. Therefore, of the twenty-eight logs tested, twenty-three were 16.7-m long and five logs, all Douglas-fir, were 20.7-m long. All the test logs were cut from the lower portion of the tree bole.

The logs were graded according to the Schedule of Coast Timber Grades, part of the Scaling Regulation under British Columbia's Forest Act.[4] The western hemlock test logs were classified as either Grade H or I,[5] while all of the Douglas-fir test logs were Grade H. These grades describe logs suitable for the manufacture of lumber; frequent small-to-medium sized knots were permitted (BCMOF 2003). All logs were sound, although two hemlock logs had small, inconsequential amounts of butt rot. The bark remained intact on all test logs.

Table 1. Physical characteristics of test logs

	Douglas-fir	Western hemlock
Moisture content (%)		
Mean	50	97
Standard deviation	8	7
Minimum	34	85
Maximum	64	115
Basic relative density		
Mean	0.48	0.43
Standard deviation	0.06	0.04
Minimum	0.34	0.38
Maximum	0.58	0.49
Cambial age (y)		
Median	88	122
Minimum	61	95
Maximum	330	290
Inside-bark diameter at midspan (cm)		
Mean	52	47
Standard deviation	5	4
Minimum	45	43
Maximum	61	57
Span-to-depth ratio		
Mean	29	32
Standard deviation	3	2
Minimum	25	26
Maximum	34	35
Log taper (%)		
Mean	1.1	1.0
Standard deviation	0.3	0.3
Minimum	0.4	0.7
Maximum	1.6	1.9
Juvenile-wood basal area (%)		
Mean	15.1	8.0
Standard deviation	10.4	4.8
Minimum	1.5	1.6
Maximum	37.0	15.7
Knot frequency (no./m)		
Mean	1.4	1.0
Standard deviation	1.1	0.5
Minimum	0.0	0.2
Maximum	3.6	1.5
Knot size/log (cm)		
Mean	3.8	2.7
Standard deviation	1.3	1.6
Minimum	1.7	1.3
Maximum	6.7	7.0

4 Grade rules can be found in the B.C. Ministry of Forest's *Scaling Manual* (BCMOF 2003). The grade rules are based on log dimensions, the proportion of the log that will produce end products, and the quality of the potential end products. These rules include specifications for characteristics such as sweep, rot, spiral grain, knots, and grain density.

5 Grade H = No. 2 Sawlog. Grade I = No. 3 Sawlog.

Log measurements

Prior to being tested, the logs were spread out on the sortyard surface so that several measurements could be taken. The logs were marked with paint at the points specified for the butt support reaction (0.7 m), top support reaction (15.7 m), and the midpoint (8.2 m) as measured from the butt end of the log.

Diameter. Outside-bark diameter was measured at 1-m intervals along the log and at the ends. Outside-bark diameter was also taken at the reaction points and at the midpoint. If the logs had elliptical stem sections, dimensions of the major and minor axes were measured. Inside-bark diameter was measured at the log ends and estimated at intervals along the log under the assumption that bark thickness varied linearly between each end. Bark thickness measurements were also taken at any points where bark sloughing had occurred. Log taper was calculated as the difference between the inside-bark diameter at the butt and top end reactions divided by the span.

Inside-bark diameter at midspan ranged from 45 to 61 cm for Douglas-fir and 43 to 57 cm for western hemlock. Outside-bark diameter at midspan ranged from 48 to 64 cm for Douglas-fir and 45 to 60 cm for western hemlock. One-half of the Douglas-fir logs had outside-bark diameters greater than or equal to 70 cm at the butt end, i.e., 0.7 m from the butt reaction. The largest log was 75 cm on the butt end.

Age. Cambial age was determined by counting the annual rings at the butt end. The median cambial age at the butt end was 88 years for Douglas-fir and 122 years for western hemlock. Two logs within each species group were greater than 240 years old and were classified as old-growth veterans.

Knots. The size and frequency of knots were determined by diagramming all knots visible on the bark surface.

Moisture content. After being tested to the point of failure, the moisture content of each log was measured with an instrument according to the principles of time domain reflectometry described in Ewart (2003). Probes were inserted into a series of holes drilled in log sections near the fracture zone. Moisture content readings were averaged over the log section.

All test logs were in the green condition; that is, the moisture content was above the fibre saturation point.

The moisture content of test specimens is important because it can influence the mechanical properties of wood. At moisture contents slightly below the fibre saturation point, wood becomes stronger and stiffer in bending. For small, clear specimens, the threshold moisture content values below which these changes occur are 24% for Douglas-fir and 28% for western hemlock. When wood is in the green condition, properties such as bending strength and elasticity are assumed to remain constant.

Basic relative density. Basic relative density is an important wood characteristic known to be a predictor of strength and stiffness. Disks were cut from the broken logs and transported to FERIC's lab in Vancouver for density analysis. Three cores, 1.9 cm in diameter and 5 cm long, were cut from the outer 5 to 6 cm of each disk. Basic relative density was determined from the core's oven-dry weight and green volume.

Basic relative density averaged 0.48 for Douglas-fir and 0.43 for western hemlock. These measurements represent the mean density for *mature* wood in the stem section because sample cores were taken from the outer portion of the log.

Juvenile wood. The proportion of juvenile wood relative to mature wood is a characteristic that distinguishes second-growth timber from old-growth. Juvenile wood, also known as crown wood, was defined as the wood encircled by the first twenty annual rings emanating from the stem pith. The diameter of the juvenile-wood core was assumed to vary linearly between the log ends. The diameter of the juvenile wood core was measured at the ends in order to determine the proportion of juvenile wood at midspan. The proportion of juvenile wood was the area of the juvenile core divided by the inside-bark basal area at midspan.

On average, the Douglas-fir test logs contained a larger proportion of juvenile wood. Average juvenile wood basal area was estimated at 15.1% for Douglas-fir and 8.0% for western hemlock.

It was important to measure the proportion of juvenile wood because second-growth trees usually have a greater proportion of juvenile wood than do old-growth trees, and, for the species in this study, juvenile wood is less dense and weaker than mature wood.

Determining bending strength and stiffness

Bending strength

Bending strength and stiffness calculations were based on inside-bark dimensions. Log bending strength is represented by the modulus of rupture (MOR). MOR was defined as the computed maximum bending stress, at extreme fibre, at the time of failure. Bending stress at extreme fibre was calculated by dividing the total bending moment by the section modulus. Most logs had circular sections but if elliptical sections were encountered, the section modulus was calculated accordingly.

Total bending moment resulted from a concentrated load applied at midspan and from a distributed load due to the log's weight, known as the dead load. The dead load was divided into two parts for the moment calculations. First, a uniformly distributed load was assigned to the cylindrical portion of log volume. The diameter of this cylinder was considered to be the log's minimum diameter, found at or near the top end. Second, a load distribution profile, representing the portion of log volume situated outside the cylinder, was plotted for each log. This load was attributed to log taper. Two load models, one that decreased linearly from the butt to the top and one in the form of a parabolic spandrel, were superimposed over each plot and then the appropriate model was selected to represent log taper. Moment equations were derived for the various loading conditions resulting from the differences in log length and taper. Logs were classified into one of four beam and loading configurations to determine total bending moment (see Appendix II).

Unit weights, used in the dead load calculations, were derived for individual logs from the weigh scale data. Log volume, which was also required for these calculations, was the sum of successive conical frusta with end diameters taken from the diameter measurements.

Log stiffness

In this report, log stiffness in bending is represented by an *apparent* modulus of elasticity (MOE). To determine the apparent MOE, the following assumptions were made:

- Logs were composed of isotropic, homogeneous material.
- Logs were simply supported with a concentrated load applied at midspan.
- The effects of shear deformation on log deflection were considered to be negligible because span-to-depth[6] ratios were large, ranging from 25:1 to 35:1.

MOE was calculated using the moment-area method. The moment-area method uses the geometric properties of the elastic curve to determine beam deflection and slope, and is a recognized approach for analyzing beams of variable cross-section (Beer et al. 2002; Wolfe and Moseley 2000; American Society for Testing and Materials 1999). With this method log taper could be accounted for, that is, all diameter measurements taken at intervals along the log were used to determine MOE. This is important because tapered circular beams do not deflect symmetrically; rather, they have a point of maximum deflection between midspan and the top end. With this method the location of deflection

[6] Depth is the inside-bark diameter at midspan.

measurement—0.3 m away from midspan toward the top end—could also be accounted for in the analysis.

The load and deflection values used to calculate MOE were taken from the linear-elastic portion of the load-deflection curves (see Appendix III). Linear regression analysis was conducted using the data points lying between 20 and 40% of the ultimate load.[7] This procedure provided the load and deflection increments used in the calculations.

The inclinometer data—i.e., records of change in slope at the support reactions—were compared to predicted slope changes. The predictions were derived using the moment-area method. Although slope information can also be used to determine MOE, the deflection data were retained as the basis for reporting in this study.

Characteristic structural properties

Characteristic strength values for wood products are typically derived from the lower 5th percentile property estimates for a test sample[8] (Canadian Standards Association 2001b). Adjustment factors are applied to the characteristic values to produce the specified strengths used in engineering design. Assignment of specified strengths for engineering design purposes falls under the jurisdiction of technical committees for applicable design codes and standards.

This report presents characteristic values for bending strength and stiffness of log stringers based on small samples of logs taken from one geographic region. Tests for normality showed that the data could be modeled using the normal distribution. The 5th percentiles are parametric estimates derived from the normal distribution. The tolerance limits are one-sided lower tolerance limits for a normal distribution, calculated according to the procedures described in Natrella (1963).

The MOR summary includes the means, and parametric estimates of the 5th percentile, and of the 75% tolerance limit on the 5th percentile. For MOE, the means, and parametric estimates of the 5th percentile and 75% tolerance limit on the median are presented.

Results and discussion

Bending strength

Sixteen Douglas-fir and twelve western hemlock logs were tested to failure. The average time to failure was approximately 1.7 min. Average bending strength, shown as mean MOR in Table 2, was 51.67 MPa for Douglas-fir and 49.86 MPa for western hemlock. The difference in MOR between the two species was not significant ($p<0.05$). The lower tolerance limits were 32.79 and 32.13 MPa for Douglas-fir and western hemlock, respectively.

The range of MOR values was similar for the two species. Minimum MOR was 32.43 and 35.55 MPa, and maximum MOR was 65.24 and 63.73 MPa, for the Douglas-fir and hemlock, respectively. The coefficient of variation was 18.5% for Douglas-fir and

Table 2. Modulus of rupture (MOR)

	Douglas-fir	Western hemlock
Logs tested (no.)	16	12
Mean MOR (MPa)	51.67	49.86
Minimum MOR (MPa)	32.43	35.55
Maximum MOR (MPa)	65.24	63.73
Coefficient of variation (%)	18.5	17.4
5th percentile (MPa)	35.96	35.62
Lower tolerance limit (MPa)	32.79	32.13

7 This approach has been adopted by Forintek Canada Corp. in its wood products testing (Conroy Lum, Research Scientist, Forintek Canada Corp., Vancouver, B.C.; personal communication, September 2003).

8 For structural sawn lumber, design strength properties are typically derived from the 5th percentile with 75% confidence. Design stiffness properties are typically based on the median with 75% confidence. These are known as lower tolerance limits.

17.4% for western hemlock. Although sample sizes in this study were small relative to test programs for most wood products, the coefficients of variation compared reasonably well to the averages found in bending tests of small, clear specimens of wood. For example, for clear wood grown in Canada, mean coefficients of variation reported by Jessome (1977) were 13.8 and 12.1 for Douglas-fir and hemlock, respectively. And, in its summary of MOR data, the American Society for Testing and Materials used an overall average coefficient of variation of 16% for commercial species (American Society for Testing and Materials 1998).

The MOR values found in this study were similar to those published for unseasoned, clear wood. For woods grown in Canada, average MOR has been reported at 52.0 and 48.0 MPa for Douglas-fir and western hemlock, respectively (Jessome 1977). Compared to in-grade test results for sawn lumber, the mean and characteristic bending strength estimates for the test logs exceed the values published for many grades of lumber. Note that the effect of moisture content needs to be considered in such comparisons. For example, strength properties for logs are based on them being in the green condition while lumber is reported at 15% moisture content.

The consistency of the bending strength results for the test logs can likely be attributed to the physical characteristics of this material type. Unlike lumber, the wood grain in a whole log is uninterrupted by saw cuts. With the grain intact throughout its length, a log may perform better than lumber in bending because the likelihood of cross-grain tension failure—a common mode of failure in sawn lumber—is perhaps reduced. Further, it has been shown that the bending strength of a thick beam is superior to the strength of a 38-mm-wide piece of lumber of the same depth (Madsen 1992). The bending strength of the thick beam is superior because it is unlikely that a defect, such as a knot, would pass through the entire tension zone of the wider beam and thus weaken the member. It is also unlikely that a knot will pass through the entire tension zone of a large log, therefore helping to explain the relatively consistent test results obtained in this study.

Log stiffness

Modulus of elasticity results are summarized in Table 3. Mean MOE was 11 753 for Douglas-fir and 11 456 MPa for western hemlock, while the lower tolerance limits were 11 369 and 11 074 MPa, respectively. The mean MOE values determined in this study were slightly higher than the published averages for clear wood, at 11 100 for Douglas-fir and 10 200 MPa for western hemlock (Jessome 1977).

The coefficients of variation, at 19.1% for Douglas-fir and 17.1% for western hemlock, were comparable to the averages found for this property in tests of clear wood. For example, Jessome (1977) reported coefficients of variation of 17.7% for Douglas-fir and 13.4% for western hemlock. And the American Society for Testing and Materials assumed an overall average of 22% when reporting MOE values for commercial species (American Society for Testing and Materials 1998).

Some aspects of test equipment have the potential to influence deflection measurement and MOE values, and this warrants discussion. For example, possible deformation of the beam support structure during loading, and local crushing of the wood at the supports and

Table 3. Modulus of elasticity (MOE)

	Douglas-fir	Western hemlock
Logs tested (no.)	16	12
Mean MOE (MPa)	11 753	11 456
Minimum MOE (MPa)	6 898	8 231
Maximum MOE (MPa)	16 436	13 774
Coefficient of variation (%)	19.1	17.1
5th percentile (MPa)	8 065	8 234
Lower tolerance limit (MPa)	11 369	11 074

load point, must be considered. In this study, these issues were addressed in the following ways. First, the base for each support pillar was carefully constructed and compacted using well-graded angular rock in order to prevent settlement. Second, the heavy steel base plates on which the support saddles rested were monitored using an automatic level. No movement of the base plates—and therefore the supporting structure—could be detected during test loading. Third, local crushing of the wood fibres at the load point was likely negligible because a wide nylon sling was used to apply the load.

A fourth consideration, potential local crushing of wood fibres at the contact zone between the log and saddles, was not measured in this study. However, visual observations by researchers did not produce evidence of any local crushing at the supports. Further, the method of selecting the deflection increment used in the analysis may have limited the influence of this factor. The increment began when 20% of the ultimate load was reached, and ended at 40%. The logs appeared to be stable and well-seated on the saddles during this period.

Relationship between bending strength and stiffness

It is useful to examine the relationship between bending strength and stiffness. For structural lumber, strength properties are related to the bending modulus of elasticity and this relationship forms the basis for machine stress grading. For log bridges, performance depends on load sharing between the stringers, and the load-sharing effect depends on the correlation between MOR and MOE.

Simple linear regression analysis conducted on the log stringer data revealed significant relationships between MOR and MOE for both species. The coefficients of determination (r^2) were 0.45 and 0.42 for the Douglas-fir and western hemlock data, respectively. Scatterplots and the results of the analysis are presented in Appendix IV.

Physical characteristics of the logs

Knots

Data from the survey of visible knots are summarized in Table 1 under two variables: average number of knots per metre over the length of each log, and average knot diameter per log. The statistics do not account for any dead branch stubs—which were likely more prevalent on the lower portion of the bole—that were covered by layers of wood during the course of natural pruning and tree growth. Regression analysis showed a trend toward reduced MOR as average knot size increased. A weak relationship between knot frequency and MOR was found only for the Douglas-fir logs.

Basic relative density

The average basic relative densities of 0.48 for Douglas-fir and 0.43 for western hemlock concur with the values for mature wood, for both species, as shown in Jozsa and Middleton (1994). Mature-wood density is the pertinent density value in this study because it is the strength at extreme fibre that is of interest in bending tests. The coefficients of variation for the density measurements were 13.6 and 8.2% for the Douglas-fir and hemlock samples, respectively. These compare well to the average coefficients of variation of 11.4 and 9.4%, respectively, for large sample sizes of small, clear specimens of wood (Jessome 1977).

In this study, simple linear regression analysis showed a weak relationship ($p<0.05$) between relative density and MOR for both species combined. The coefficient of determination (r^2) found in this analysis was 0.15.

Juvenile wood

Juvenile wood content ranged from 1.5 to 37.0% for the Douglas-fir logs and 1.6 to 15.7% for the western hemlock logs. No relationship was found between the amount of juvenile wood and bending strength. This finding can be explained by the relative positions of juvenile and mature wood within a log section. Because juvenile wood is found at the center of a stem, it is analogous to the web in an I-beam (Jozsa and Middleton 1994). It is the outer layer of mature wood, comparable to the flanges in the beam, which resists tension and compression during bending. Juvenile wood content is perhaps a more important issue for lumber production and sawing patterns than for structural applications of whole logs in bending. Further, the proportion of juvenile wood relative to mature wood diminishes as trees grow. Therefore, any influence on bending strength is likely to be minimal in the larger second-growth logs usually selected as bridge stringers.

Figure 7. Failed western hemlock log in bending test.

Figure 8. Failed Douglas-fir log in bending test.

Description of log failure

All logs had load-deflection curves that exhibited a linear-elastic zone, a period of plastic behaviour, and an obvious failure point (see Appendix III for examples). Usually a series of cracks and internal wood fibre failures would develop in the log as loading increased toward the ultimate. Initial cracking was clearly audible but not always visible from a distance. A saw-tooth pattern on the load-deflection curve was evidence of cracking having occurred prior to total failure.

The failure zone had a similar appearance for most logs of both species. The under side of the log usually had a fibrous or splintering-type tension failure. The upper side, which was subject to compression, had a brash or narrow, vertical failure plane. Figures 7 and 8 show examples of the predominant failure type. Most logs failed approximately 0.3 to 0.8 m away from midspan toward the top end. Although the intact bark made it difficult to assess failure mode, it appeared that failure of many logs was initiated in compression. This was manifested by buckling of bark and wood fibres on the top side of the log near the point of maximum deflection. It was also evident that the point of maximum deflection was away from midspan and toward the top end.

Only a few logs had a brash, well-defined vertical break through the entire log section. Upon inspection, this sort of failure was the obvious result of a concentration, or whorl, of knots, which were not always apparent on the surface of the bark. Some of the knots were overgrown dead branch stubs. In a few other logs, horizontal shear failures and cross-grain tension failures appeared to be contributing factors.

All twelve of the hemlock logs and nine of the sixteen Douglas-fir logs were loaded until a complete break occurred and the segments came to rest on the innermost concrete pillars (Figure 9). The remaining Douglas-fir logs had distinct failure zones but some of the fibrous splinters on the tension side remained connected in these logs.

Figure 9. Completed test.

Conclusions

In 2003 FERIC conducted a study of the structural properties of coastal Douglas-fir and western hemlock log stringers used for bridges on forest roads. The field-based test procedure developed by FERIC proved to be a practical method for determining the bending strength and stiffness of full-size, whole logs.

Bending strength and stiffness test results showed the whole logs to be a strong and consistent material type. The mean modulus of rupture (MOR) found for each species was similar to known values for small, clear specimens of unseasoned wood. Mean moduli of elasticity (MOE) were slightly higher than known values for small, clear specimens of wood. Coefficients of variation derived from the tests, and observations of the mode and location of failure, support the notion of consistent performance for the whole log material type.

Some bridge designers have questioned the strength of second-growth log stringers compared to stringers originating from old-growth stands. Although sample sizes in this study were small, the data nevertheless suggest that Douglas-fir and western hemlock logs, in sizes commonly used as bridge stringers, do not have reduced bending strength when they originate from second-growth stands.

Characteristic strength and stiffness values are included in this report. These types of property estimates are used in the development of specified strengths for engineering design purposes. The results of this study provide some insight and context for engineers involved in log bridge design and for those considering a Limit States Design approach. Further, log bridge designers can use the property estimates provided by this study to evaluate their existing working stress models.

Implementation

Evaluating log stringer strength and stiffness is consistent with the goal of maintaining a cost-effective wood supply for Canada's forest industry. As engineering design methods and government regulations evolve, and increased accountability is placed on forest industry professionals, a log-testing program will provide the data needed to ensure that practical, economical, and safe bridge-construction options are available. Specifically, testing of full-size logs is required if engineers are to apply Limit States Design principles to log bridges.

The difference in costs between types of forest road bridges is an important factor motivating this research. Depending on site conditions, the installed cost for a typical gravel-decked log bridge, in single spans of 6 to 12 m, is often in the range of $500 to $1000/lineal metre. A steel bridge under similar conditions may range in price from $4000 to $5000/lineal metre. In many cases only a temporary bridge is needed. Further, forest road bridges are often located in isolated areas where use of on-site materials can reduce costs substantially. These factors favour log bridges.

Notwithstanding the monetary aspects, safety considerations are paramount for bridge design. Using appropriate information about structural properties and reducing the uncertainty around decisions in the design and evaluation of log bridges are important issues. These issues have been driving forces behind the need to test full-size log stringers.

Testing various species of logs, including logs from second-growth stands, has the potential to expand the pool of potential bridge stringer material. This is because the likelihood of finding stringers in the vicinity of a bridge site will increase if a variety of log types are shown to be suitable. In this project, Douglas-fir, a long-accepted species for bridge construction, and western hemlock, the most common tree species found on coastal British Columbia, were examined and similar strength properties were found. However, even though the bending strength of western hemlock makes it suitable for bridge construction, this species is known to deteriorate more rapidly in the field than Douglas-fir. This must be accounted for in the bridge design process.

Ultimately, new information on the structural properties of full-size logs needs to be incorporated into engineering design codes to fully meet the forest industry's needs for bridges on forest roads. This study and potential future projects can provide data for evaluation by code technical committees. Recommendations for future work to advance the understanding of log structural properties and their application to log bridge design include:

- Supplement the results of this study with data from other geographic regions.
- Include other appropriate species, for example western red cedar, in a test program.
- Test decommissioned log stringers to evaluate the rate and extent of deterioration.
- Investigate load-sharing factors and mechanisms to promote load sharing among log bridge members.

References

American Society for Testing and Materials. 1998. Standard test methods for establishing clear wood strength values. West Conshohocken, Pa. ASTM D2555-98.

American Society for Testing and Materials. 1999. Standard test methods of static tests of wood poles. West Conshohocken, Pa. ASTM D1036-99.

Barrett, J.D. and Lau, W. 1994. Canadian lumber properties. Canadian Wood Council, Ottawa, Ont. 346 pp.

Beer, F.; Johnston, E.R.; and DeWolf, J.T. 2002. Mechanics of materials. Third edition. McGraw-Hill, N.Y.

British Columbia Ministry of Forests. 2003. Scaling manual. Revenue Branch, Victoria, B.C.

Canadian Standards Association. 2000. Canadian Highway Bridge Design Code, a national standard of Canada, CAN/CSA-S6-00. Toronto, Ont. December 2000.

Canadian Standards Association. 2001a. Engineering design in wood, a national standard of Canada, CAN/CSA-O86-01. Toronto, Ont. Approved January 2003.

Canadian Standards Association. 2001b. Standard practice relating specified strengths of structural members to characteristic structural properties. Revised April 2001. Canadian Standards Association, Toronto, Ont.

Ewart, J. 2003. Determining log moisture using time domain reflectometry: Case study results. FERIC, Vancouver, B.C. Advantage Report, Vol. 4, No. 12.

Jessome, A.P. 1977. Strength and related properties of woods grown in Canada. Eastern Forest Products Laboratory, Fisheries and Environment Canada, Ottawa, Ont. Forestry Technical Report 21.

Jozsa, L.A. and Middleton, G.R. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corp., Vancouver, B.C. Special Publication No. SP-34.

Madsen, B. 1992. Structural behaviour of timber. Timber Engineering Ltd., North Vancouver, B.C. 405 pp.

Natrella, M.G. 1963. Experimental statistics. National Bureau of Standards, U.S. Department of Commerce, Washington, DC. National Bureau of Standards Handbook 91.

Tuomi, R.L.; Wolfe, R.W.; Moody, R.C.; and Muchmore, F.W. 1979. Bending strength of Alaskan Sitka spruce and western hemlock log bridge stringers. USDA Forest Service, Forest Products Laboratory, Madison, Wis. Research Paper FPL 341.

Wolfe, R. and Moseley, C. 2000. Small-diameter log evaluation for value-added structural applications. Forest Products Journal 50(10):48–58.

Acknowledgements

The authors acknowledge the support of Interfor's Campbell River Operation and the cooperation of personnel at Palmer Bay Logging Ltd. Assistance with the field work by Interfor employees, Lyle Unwin and Brooks Yancey, is also appreciated.

This report benefited from the suggestions put forward by several reviewers, including:

- Dr. J. David Barrett, Department of Wood Science, Faculty of Forestry, University of British Columbia;
- Dr. Robert G. Sexsmith, Department of Civil Engineering, Faculty of Applied Science, University of British Columbia;
- Conroy Lum, Forintek Canada Corp.;
- Dr. C. Kevin Lyons, Department of Forest Resources Management, Faculty of Forestry, University of British Columbia;
- Ron Wolfe, USDA Forest Service, Forest Products Laboratory;
- Dale Harrison, Associated Engineering (B.C.) Ltd.;
- Ally Gibson, Weyerhaeuser Company Limited;
- Gino Fournier, Hayes Forest Services Limited;
- G. Glen Beaton, Stonecroft Project Engineering Ltd.; and
- Ron Sawatzky, RKS Consulting.

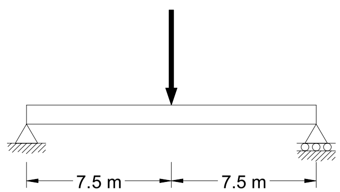
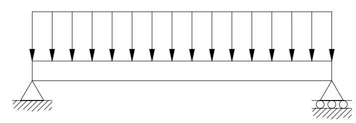
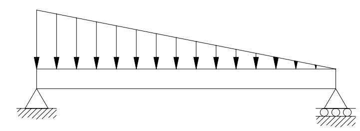
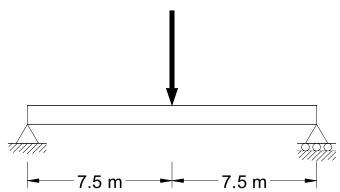
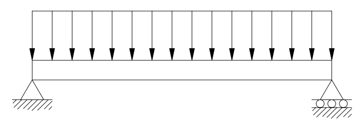
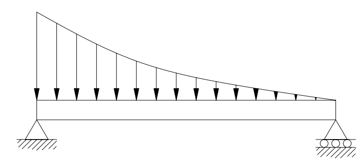
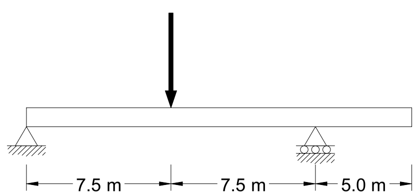
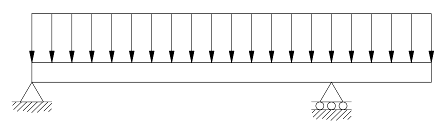
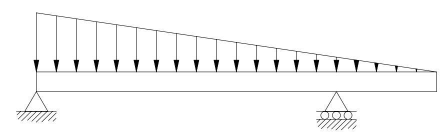
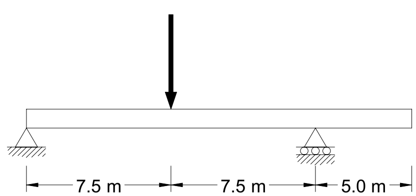
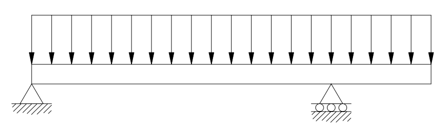
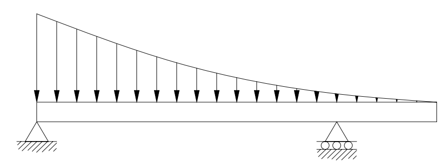
Appendix I

Bending strength and related properties for individual log stringers

Species	Log	Cambial age (y)	Basic relative density	Moisture content (%)	Outside-bark diameter at: Butt reaction (cm)	Outside-bark diameter at: Midspan (cm)	Outside-bark diameter at: Top reaction (cm)	Inside-bark diameter at: Butt reaction (cm)	Inside-bark diameter at: Midspan (cm)	Inside-bark diameter at: Top reaction (cm)	Juvenile-wood basal area (%)	MOR (MPa)	MOE (MPa)
Fd	1	105	0.46	53	70	51	47	63	49	45	12.5	50.04	10 857
Fd	2	85	0.49	60	63	58	49	59	55	46	16.9	58.40	14 278
Fd	3	62	0.50	49	58	49	42	55	47	40	25.7	45.37	7 849
Fd	4	86	0.53	50	69	52	44	63	48	41	25.5	64.61	16 436
Fd	5	119	0.51	51	72	50	45	66	46	43	9.1	65.24	10 955
Fd	6	74	0.44	46	71	58	49	63	53	46	15.2	47.72	12 635
Fd	7	254	0.34	64	70	62	51	63	58	49	1.5	32.43	6 898
Fd	8	330	0.56	52	70	56	51	62	50	47	2.0	60.24	12 661
Fd	9	84	0.58	45	70	56	53	64	51	49	22.3	40.32	11 376
Fd	10	63	0.49	53	66	53	46	60	49	44	25.0	58.41	12 652
Fd	11	186	0.35	51	61	62	52	56	57	47	2.1	46.22	11 535
Fd	12	61	0.43	47	65	53	46	60	50	44	22.8	42.88	11 717
Fd	13	61	0.45	35	61	48	44	56	45	42	37.0	60.47	12 843
Fd	14	89	0.48	56	67	64	60	63	61	57	6.9	56.30	10 757
Fd	15	98	0.49	51	71	56	51	65	52	48	9.0	55.23	13 161
Fd	16	111	0.52	34	74	63	56	68	58	52	8.3	42.90	11 440
Hw	1	220	0.49	98	51	45	40	49	43	38	2.0	55.82	13 774
Hw	2	115	0.38	85	61	52	46	58	50	44	8.0	63.73	13 713
Hw	3	155	0.43	101	55	45	43	53	43	41	6.3	57.10	10 180
Hw	4	102	0.45	98	58	48	40	56	46	38	9.3	50.18	11 211
Hw	5	290	0.40	90	56	50	43	54	48	41	1.6	43.15	8 662
Hw	6	95	0.49	93	62	50	46	60	48	44	12.0	60.86	13 296
Hw	7	na	0.42	91	56	49	43	54	47	41	15.7	49.92	11 897
Hw	8	100	0.45	98	61	46	42	59	44	40	8.8	51.65	10 732
Hw	9	102	0.39	98	53	47	42	50	45	40	15.4	48.28	12 945
Hw	10	na	0.43	100	58	48	43	56	46	41	8.4	43.41	13 076
Hw	11	128	0.39	100	64	60	52	61	57	49	7.1	38.67	8 231
Hw	12	260	0.44	115	71	50	41	68	48	39	1.6	35.55	9 754

Appendix II

Beam and loading configurations used to determine bending moment

Beam and loading classification	Concentrated load applied at midspan	Uniformly distributed portion of deadload	Linear or parabolic portion of deadload
Type A (5 Douglas-fir and 6 western hemlock logs)			
Type B (6 Douglas-fir and 6 western hemlock logs)			
Type C (3 Douglas-fir logs)			
Type D (2 Douglas-fir logs)			

Appendix III

Examples of load-deflection curves for log stringers

Figure III-1. Load-deflection curve for a Douglas-fir log stringer.

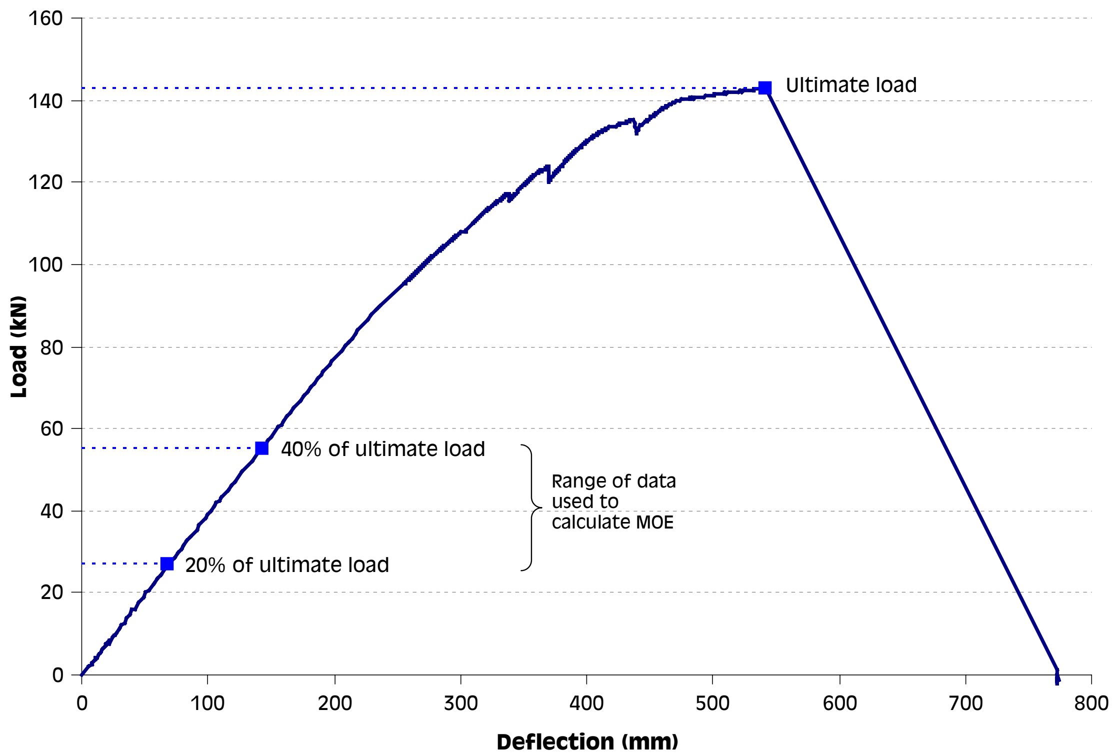
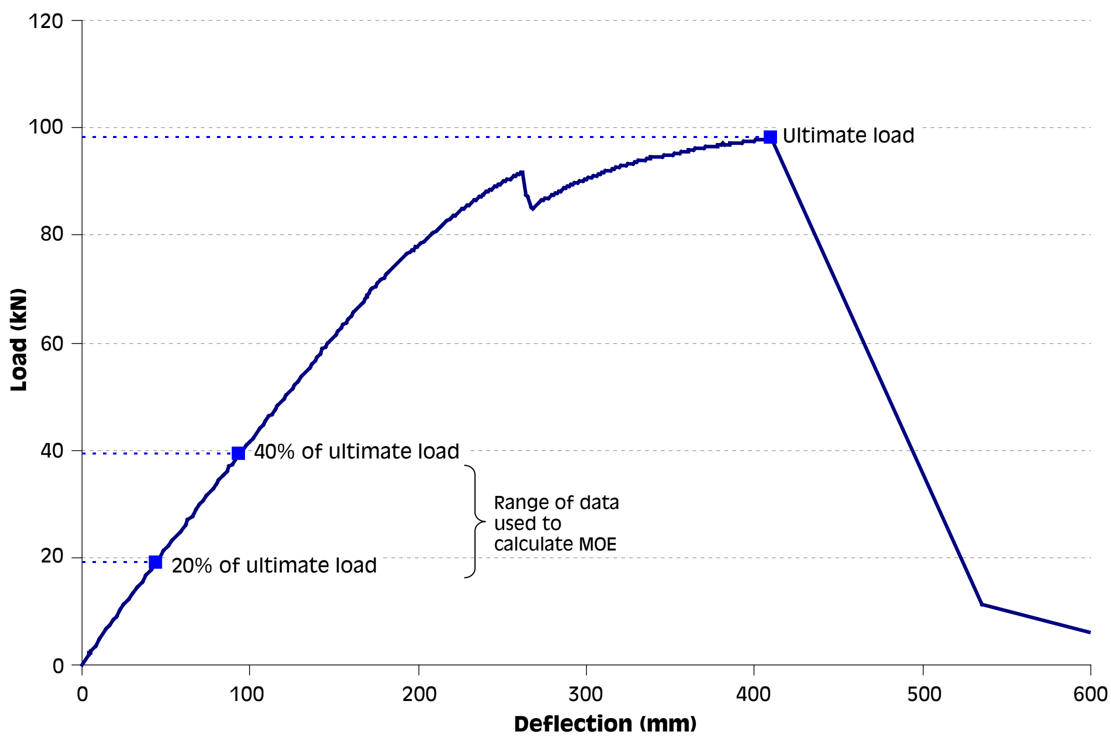


Figure III-2. Load-deflection curve for a western hemlock log stringer.



Appendix IV

Relationship between bending strength and stiffness for log stringers

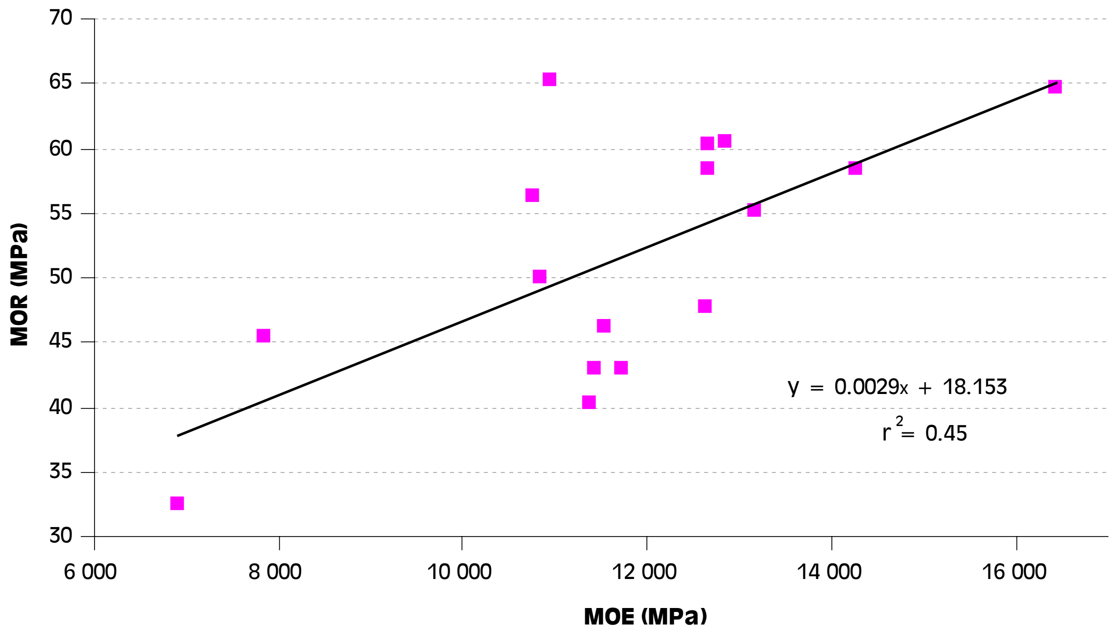


Figure IV-1. MOR vs. MOE for the Douglas-fir log stringers.

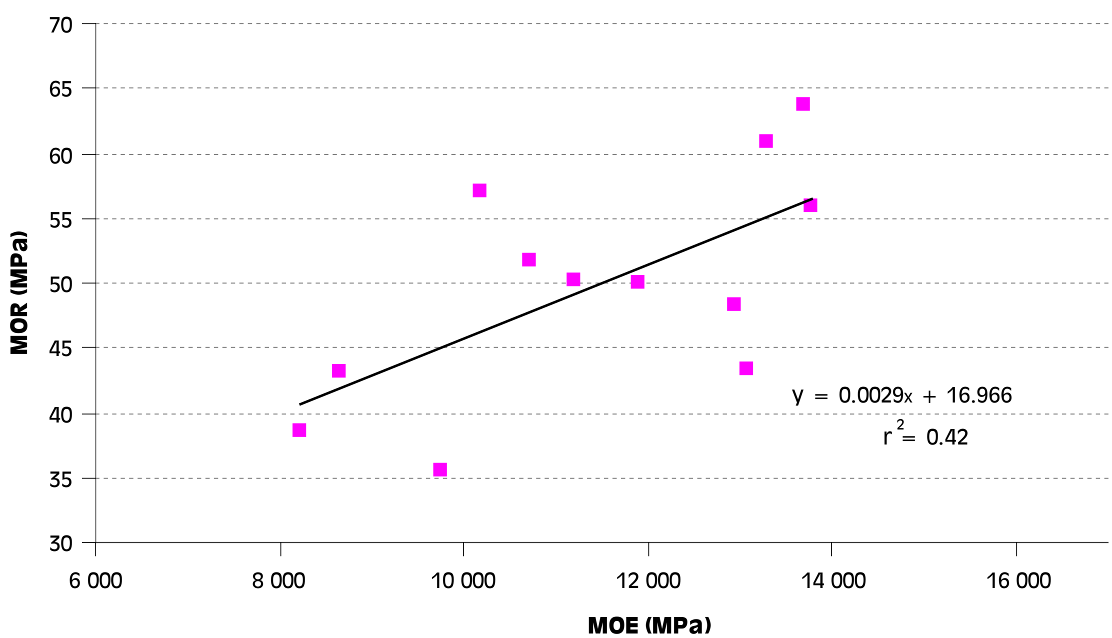


Figure IV-2. MOR vs. MOE for the western hemlock log stringers.