System Stiffness for Stress-Laminated Timber Bridge Decks

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Abstract
Both stress-laminated (stresslam) lumber and glulam timber bridge decks are usually modeled as thin orthotropic plates, neglecting the out-of-plane shear deformations and Poisson's effects. This analysis approach requires three "system" elastic properties: $E_1$, $E_2$, and $G_{12}$. In this study, we present experimental/analytical methods to evaluate "system" elastic moduli for stress-laminated systems consisting of lumber and also vertically-laminated glulam sections, both built with No. 2 Yellow-poplar material of 3.3 cm x 10.16 cm x 3.05 m (1.3" x 4" x 10') finished dimensions. The following properties are evaluated: (1) bending modulus of lumber, (2) bending and shear moduli of vertically-laminated glulam beams, and (3) longitudinal and transverse bending moduli and in-plane and out-of-plane shear moduli of stress-laminated decks consisting of lumber and also glulam sections. We describe an efficient method to compute shear moduli from torsion tests, which permit the evaluation of in-plane ($G_{12}$) and longitudinal out-of-plane ($G_{13}$) moduli. Explicit linear formulas are provided to compute the "system" moduli as functions of the transverse prestress level applied by the bars. The results of this study for $E_2$ and $G_{12}$ obtained for stresslam lumber decks compare favorably with existing formulations, particularly at a prestress level of 344.5 kPa (50 psi), which is commonly used in design.

Keywords: Bridges, Stress-laminated timber, Beading/shear moduli, Orthotropic modeling, Torsion.

Introduction
Stress-laminating technology has proved to be a viable alternative for constructing new timber bridges and rehabilitating old ones (Taylor et al. 1983, Ritter et al. 1990, Davalos et al. 1993). In 1983, the Ontario Highway Bridge Design Code incorporated design procedures for stress-laminated (stresslam) timber bridge decks. Similarly, considerable research in this topic has been undertaken in the United States, resulting in the development of design, construction, and inspection guidelines for stresslam timber bridge decks (Ritter 1990, AASHTO 1991, Davalos and Petro 1993).

Due to the arrangement of the lumber components, a stresslam deck can be analyzed as an orthotropic plate with distinct properties in the longitudinal and transverse directions. The orthotropic modeling of a stresslam deck requires accurate estimates of the "system" moduli, particularly the longitudinal modulus $E_1$, transverse modulus $E_2$, and in-plane shear modulus $G_{12}$. A number of researchers (e.g., Taylor et al. 1983; Davalos, Kish, and Wolcott 1993) have concluded that for decks without butt joints, the system longitudinal modulus can be represented by the mean elastic modulus of the lumber components. To account for the presence of butt joints, reduction factors are applied to the lumber modulus. Limited information exists on the transverse and in-plane moduli for stresslam decks. Taylor et al. (1983) and Oliva et al. (1990) have used nearly identical plate-twisting tests (Tsai 1966) to provide formulations for $E_2$ and $G_{12}$ as functions of the transverse prestress. However, there is considerable difference between their reported results, particularly for $G_{12}$. Recently, Davalos and Brokaw (1992) have proposed an innovative torsion test method to determine in-plane and out-of-plane shear moduli for stresslam decks. Through a parametric study, these investigators have concluded that the Poisson’s ratios ($V_{13}$ and $V_{23}$) and the transverse out-of-plane shear modulus ($G_{23}$) can be neglected in practice, and as a consequence, a stresslam deck behaves as an integrated plate in the longitudinal direction and as an articulated plate or a membrane in the transverse direction, and therefore, the
primary system elastic properties of interest are $E_1$, $E_2$, and $G_{12}$.

In addition to stresslam, glulam deck systems are used extensively in bridge applications (AITC, Ritter 1990, Manbeck et al. 1991). In general, glulam bridge decks are easy to construct, provide efficient load-distribution response, and can provide cost-savings, because of the relatively few number of components used to build a glulam bridge in contrast to the larger number of components used in a stresslam lumber system. Similar to stresslam lumber, horizontally-laminated glulam beams placed side-by-side and transversely prestressed have been used for bridge construction (e.g., Ritter et al. 1993). An alternative approach is to use vertically-laminated glulam panels of discrete widths [0.61 to 1.22 m (1' to 2')], which can be prestressed in the transverse direction to create bridge deck and deck-and-stringer systems. With this potential application in mind, we evaluate in this study elastic moduli for transversely prestressed vertically-laminated glulam sections.

**Objective**

The objective of this study is to evaluate primarily the bending and shear moduli for vertically-laminated multiple members of No.2 Yellow-poplar lumber for use in stress-laminated (stresslam) timber bridge decks consisting of lumber or glued-laminated (glulam) sections. Specifically, the following properties are evaluated: (1) bending modulus ($E_1$) of lumber; (2) bending modulus ($E_1$) and shear modulus ($G$) of vertically-laminated glulam beams; and (3) bending ($E_1$ and $E_2$) and shear ($G_{12}$ and $G_{13}$) moduli of stress-laminated lumber and stress-laminated glulam sections.

**Test Samples**

The material used for this study was visually-graded No. 2 Yellow-poplar lumber, kiln-dried to a 12% equilibrium moisture content. The lumber nominal thickness was 5.1 cm (2"). For the manufacturing of glulam samples, random lumber lengths were used, and the bending moduli of all of the samples were evaluated by a transverse vibration technique (E-rated) (Ross et al. 1991). Similarly, some representative portion of the No.2 material required for the stresslam lumber decks was tested, and the average modulus was used as a representative value in the analysis.

**Manufacturing of laminated samples**

**Glulam** - Following guidelines for Yellow-poplar lumber by Moody et al. (1993), eight vertically-laminated glulam panels 1.22 m x 3.05 m (4 ft x 10 ft) were manufactured at a glulam plant. The end-jointed lumber was cut to 3.05-m (10-ft) lengths and stacked to form the panels with no prescribed requirements on the placement of finger joints. Then, the location of each piece of lumber within the stacking sequence of each glulam panel was recorded. The mapping of the lumber components was needed to relate the lumber properties to the performance of the panels. The end-jointed pieces were face-planed to a uniform thickness of 3.3 cm (1.3") and laminated into panels, which were edge-planed to a uniform thickness of 10.2 cm (4”). Subsequently, holes were drilled at the mid-depth of the 10.2-cm (4") thickness and through the 1.22-m (4') width of each panel. The holes were 2.54 cm (1") in diameter and spaced 61 cm (2') apart, beginning 30.5 cm (1') from the edge of the panel. The holes were used later to construct and test stresslam decks consisting of glulam sections cut from the 1.22 m (4’) panels.

**Lumber** - The lumber used for single-member evaluation and also for the construction of stresslam decks was planed to 3.3 cm (1.3") thickness and 10.2 cm (4") width to match the dimensions of the glulam panels; consistent dimensions were used for the lumber and glulam materials to provide appropriate correlations and discussions of results. Holes of 2.54 cm (1") in diameter and spaced 61 cm (2’) on centers were also drilled through the lumber components to assemble the stresslam test samples. Both lumber and glulam samples were prestressed with high-strength steel bars of 1.58 cm (5/8") diameter and varying lengths to accommodate the specific width requirements of the samples.

**Elastic moduli Evaluations**

The stiffness properties evaluated include the longitudinal modulus $E_1$ and transverse modulus $E_2$ obtained from bending tests, and the shear moduli $G_{12}$ and $G_{13}$ obtained from torsion tests, as discussed next.

**Longitudinal Modulus El**

**Materials and Method** - The longitudinal modulus $E_1$ was obtained for the following samples: 30 lumber pieces; ten 30.5 cm (1’) wide stresslam lumber decks; and ten 61 cm (2’) wide glulam decks, which were obtained by cutting the 1.22-m (4’) panels.

The longitudinal moduli $E_1$ of the lumber samples were determined by the standard procedures of ASTM D198
Thirty lumber samples 3.3 cm by 10.16 cm by 3.05 m (1.3” x 4” x 10’) were tested under four-point bending, with a support-span of 2.44 m (8’) and a load-span of 0.81 m (2.67’). The longitudinal modulus was obtained from a linear regression of the load-deflection data. The lumber material contained predrilled holes of 2.54 cm (1”) diameter to facilitate the subsequent construction of stress-laminated samples.

Then, 10 stresslam lumber decks of 30.5 cm (1’) width, consisting of nine laminae, were transversely prestressed with five high strength steel bars of 1.59 cm (5/8”) in diameter; discrete steel bearing plates were used to anchor the bars against the outer lumber components. The stresslam lumber decks were tested under four-point bending, with the same support-span and load-span as the lumber samples. Similarly, ten 30.5-cm (1’) wide vertically-laminated glulam samples were also tested in four-point bending, with the same spans as the previous samples.

**Results and Discussion**

The edgewise bending test results for lumber, stresslam lumber, and glulam were used to evaluate their corresponding bending moduli, $E_1$, as: 10.75 GPa (COV = 4.5%) [1.56 x 10^6 psi], 11.3 GPa (COV = 12.8%) [1.64 x 10^6 psi], and 11.5 GPa (COV = 6.4%) [1.67 x 10^6 psi]. As expected, the mean modulus for the lumber samples correlates closely (within 5% to 7%) with the values for the deck samples.

**Transverse Modulus $E_2$**

This section discusses the evaluation of $E_2$ for stresslam lumber and glulam decks obtained from bending tests at four prestressed levels. Expressions for the transverse modulus as a function of the prestress level are established.

**Materials and Method**

The materials used included lumber samples and also glulam panels of three widths: 1.22 m (4’), 61 cm (2’), and 30.5 cm (1’). For each of these materials, a test-deck of 3.05 m (10’) wide by 3.66 m long (12’) was stress-laminated and tested in transverse bending (Fig. 1). Since stress-laminated decks exhibit a very low transverse stiffness, the test-deck geometry consisted of a simply-supported span of 2.06 m (6.75’) with overhangs of 0.80 m (2.63’) on each side (Fig. 1), which were designed to counteract the initial dead load deflection of the sample. The testing procedure was based on ASTM D-198 standards. The samples were placed on roller-supports along the 3.05-m (10-ft) width, as shown in Fig. 1. The samples assembled with 1.22 m (4’) and 61 cm (2’) wide glulam panels and also with lumber were tested with a load-span of 69 cm (2.25’), whereas the sample built with 30.05 cm (1’) wide glulam panels was tested with a load-span of 92 cm (3’) to avoid loading directly over the joints. Two symmetric line loads were applied using spreader beams and loading beams. Each loading-beam was independently loaded by a hydraulic jack, but both jacks were operated simultaneously by a single pump. The midspan deflections along the width were measured with LVDT’s. Each of the four types of deck samples was tested at four transverse prestress levels: 172.3, 344.5, 516.8, and 689.0 kPa (25, 50, 75, and 100 psi). Each deck was subjected to a total load of 4.45 kN (1000 lb), and each test was repeated three times. The transverse modulus, $E_2$, was computed from classical beam-bending formulas.

**Results and Discussion**

A linear regression fit to the data results in the following expressions for $E_2$ in kPa, as a function of the average transverse prestress, $F_p$, given in kPa:

- **Panels of 1.22-m (4-ft):** $E_2 = 289F_p + 361098$
- **Panels of 61-cm (2-ft):** $E_2 = 434F_p + 71766$
- **Panels of 30.5-cm (1-ft):** $E_2 = 414F_p + 38715$
- **Lumber:** $E_2 = 406F_p + 31189$ \hspace{1cm} (1)

As observed from Eq. (1), the transverse modulus increases as the prestress level increases; a consistent result with previous studies. Also, as the width of the components of
the deck increases, from lumber to 1.22 m (4') glulam panels, the transverse modulus also increases. The differences in $E_2$ obtained for the decks built with lumber and 30.05 cm (1') wide glulam panels are negligible, particularly for stress levels between 344.5 and 689.0 kPa (50 and 100 psi). Similarly for the same range of prestress level, the decks built with 61 cm (2') glulam panels exhibit an average increase in modulus of approximately 25% with respect to the lumber decks; in contrast, the decks built with 1.22 m (4') panels show an average modulus increase of 125% in relation to the lumber decks. For a 344.5 kPa (50 psi) transverse prestress, which is typically recommended in design, the results of the present study for lumber compare favorably with those reported previously for similar lumber samples; present study: 171.1 MPa (24828 psi); Taylor et al. (1983): 168.8 MPa (24504 psi); and Oliva et al. (1990): 157.2 MPa (22810 psi).

Shear Modulus $G$

In this study, a torsion solution developed by Lekhnitskii (1963) and applied to wood (Davalos et al. 1991) and stress-laminated samples (Davalos and Brokaw 1992) is used to obtain the shear moduli $G_{12}$ and $G_{13}$ from torsion tests.

Materials and Methods - Shear moduli for stress-laminated and glued-laminated samples were obtained from torsion tests in the linear range. Nine 30.5 cm (12") wide (containing nine laminae) and nine 53.34 cm (21") wide (16 laminae) stress-laminated lumber samples were tested. The following nine glulam samples were also tested in torsion: three 30.5 cm (1') glulam beams; three 61 cm (2') glulam beams; and three 61 cm (2') wide prestressed glulam sections, each section assembled by prestressing two 30.5 cm (1') glulam beams. Figure 2 shows typical stresslam and glulam samples.

As Shown in Fig. 3, a torsion machine was used to obtain the experimental torque vs. angle of twist, called torsional stiffness ($K = \frac{T}{\theta}$), of the samples (see Davalos and Brokaw 1992). The angle of twist of the samples was measured over a gage-length of 1.83 m (6'), with each gage point located 61 cm (2') away from the grip. To verify the accuracy of the experimental torsion program, a 6061-T6 aluminum bar, 15.24 cm x 2.54 cm x 3.05 m (6" x 1" x 10'), was tested in torsion, and a good correlation was obtained between the experimental results and the predicted values.

For the stresslam and glulam samples, the test results were used in conjunction with Lekhnitskii's orthotropic solution to obtain the in-plane, $G_{1\alpha}$, and out-of-plane, $G_{\alpha\beta}$, shear moduli. The material coordinates are as defined in Fig. 2. In addition, St. Venant’s isotropic torsion solution was used to determine the shear modulus $G$ of the solid glulam samples, since these samples can be modeled as transversely isotropic (Davalos et al. 1991); this simplification permits computing the shear modulus of a sample from a single torsion test and isotropic torsion solution for elastic rectangular bars. In contrast to the isotropic solution, Lekhnitskii's orthotropic torsion solution requires that two samples of different widths be tested in torsion to determine their torsional stiffnesses $K$ and $K_\alpha$ and the resulting system of two equations is then solved by a method of successive substitutions (Davalos et al. 1991) to obtain $G_{1\alpha}$ and $G_{\alpha\beta}$. The torsion results are presented separately for stresslam lumber and glulam samples.

Results and Discussion for Stresslam Lumber - The stress-laminated lumber samples of two widths were tested at four prestress levels of 172.3, 344.5, 516.8, and 689 kPa (25, 50,75, and 100 psi), and for each sample, its torsional stiffness $T/\theta$ was measured. The test results and corresponding linear regressions are shown in Fig. 4. By pairing each of the nine 30.5 cm (12") specimens with each of the nine 53.34 cm (21") specimens, a total of 81 sets of values for $G_{1\alpha}$ and $G_{\alpha\beta}$ were obtained for each of the four prestress levels, and these values were used to develop linear
regression relations for $G_{12}$ and $G_{13}$ as functions of the transverse prestress level, $F_p$. An alternate approach, termed "average-stiffness" was to plot the mean stiffness values vs. transverse prestress levels (Fig. 4), and using a linear fit to the data, the sample-pairing solution was evaluated only four times, one for each prestress level. In addition, an approximate "average" shear modulus, $G$, for the stresslam samples was computed from isotropic theory, using the linear regression values from Fig. 3 and Saint Venant’s torsion solution. The resulting linearfunctions for the three methods used are:

Sample-pairing:  
\[
G_{12} = 373F_p + 229506 \\
G_{13} = 499F_p + 270908 
\]

Average stiffness:  
\[
G_{12} = 602F_p + 213163 \\
G_{13} = 537F_p + 228638 
\]

Isotropic solution:  
\[
G = 560F_p + 225455 \tag{2}
\]

where, both the shear moduli and prestress are in kPa. The difference between the values by the sample-pairing and average-stiffness methods is about 15%, and therefore, the average stiffness method can be used to obtain sufficiently accurate design values. Moreover, the isotropic solution also provides reasonably acceptable values. The results of the present study for $G_{12}$ compare favorably with those obtained for lumber by Taylor et al. (1983); for $F_p = 344.5$ kPa (50 psi), the values predicted by the present "sample-pairing" method and Taylor's solution are, respectively, 358 MPa (51960 psi) and 343.8 MPa (49886 psi).

Results and Discussion for Glulam Samples - The torsional stiffnesses ($T/\theta$) for three 30.5 cm (1') and three 61 cm (2') glulam samples were measured, and based on transverse isotropy (Davalos et al. 1991), which is particularly valid for glulam samples of the same material-grade, the shear modulus of each glulam sample was computed from isotropic torsion solution. In addition, each of the three 30.5 cm (1')samples was paired with each of the three 61 cm (2') samples to obtain $G_{12}$ and $G_{13}$ by the sample-pairing method and orthotropic solution. The mean value of $G$ from isotropic solution was 751.0 MPa ($1.09\times10^6$ kPa).
psi), and the mean values of $G_{12}$ and $G_{13}$ were respectively 833.7 MPa ($1.21 \times 10^5$ psi) and 815.0 MPa ($1.18 \times 10^5$ psi). It is signified that $G_{12}$ is approximately equal to $G_{13}$; a result that further reinforces the transverse isotropy assumption for glulam.

To study the prestressing effect on the shear modulus for stresslam glulam samples, three 61 cm (2') wide samples, each consisting of two 30.5 cm (1') wide glulam samples, were transversely prestressed in a similar way as the lumber samples. The samples were tested in torsion at four prestress levels, and their shear moduli were computed from isotropic solution. Based on the favorable results obtained from isotropic solution for stresslam lumber samples, the use of isotropic approximation for stresslam glulam samples is justifiable, and the linearized response is given by the following equation (kPa):

$$G = 206F_p + 545771$$  \hspace{1cm} (3)

The results for the prestressed glulam samples indicate that the shear modulus is not significantly influenced by the prestress level, particularly for a range between 344.5 and 689 kPa (50 and 100 psi). Also, the shear modulus of prestressed glulam samples (Eq. 3) approached the modulus of the material itself, approximately 758 MPa ($1.1 \times 10^5$ psi), for a prestress level around 1034 kPa (150 psi).

From the results for the stresslam lumber and stresslam glulam samples, it can be observed that the prestress level has a more significant effect on the shear modulus of the stresslam lumber samples than of the glulam samples. For the stresslam lumber samples, when the prestress level increases from 172.3 kPa (25 psi) to 689 kPa (100 psi), the shear modulus increases by 98% (sample-pairing method). Whereas, for the stresslam glulam samples, for a similar increase in prestress level, the modulus increases by only 18%. At a low prestress level of 172.3 kPa (25 psi), the shear modulus for stresslam glulam samples is 83% higher than for stresslam lumber samples (sample-pairing); but as the prestress level increases, the differences in shear moduli reduce to as low as 9.5% at 689 kPa (100 psi) prestress.

**Conclusions**

The following properties were evaluated: (1) bending modulus of lumber, (2) bending and shear moduli of vertically-laminated glulam beams, (3)
longitudinal/transverse bending moduli and in-plane/out-of-plane shear moduli of stress-laminated (stresslam) lumber and also stresslam glulam sections. The following conclusions are presented:

1. The longitudinal modulus of stresslam lumber and vertically-laminated glulam beams can be estimated from the mean modulus of the corresponding lumber components.

2. The transverse modulus of stresslam lumber and stresslam glulam assemblies can be computed from bending tests as described in this study. Since the transverse stiffness of these systems is quite low, particularly of stresslam lumber, a test-deck with overhanging sections (see Fig. 1) can be used to overcome the self-weight of the sample and eliminate potential errors. Similar to previous studies, our results indicate that the transverse moduli of these systems can be represented as linear functions of the applied pressure provided by the stressing bars. The results of the present study for stresslam lumber compare favorably with those reported previously by Taylor et al. (1983), particularly for a prestress of 344.5 kPa (50 psi), which is commonly assumed in design.

3. The in-plane and longitudinal out-of-plane shear moduli ($G_{12}$ and $G_{13}$) of laminated timber assemblies can be efficiently obtained using the torsion method discussed in this study. In contrast, the plate-twisting tests used by previous researchers cannot be used to compute $G_{13}$. The proposed simplified approach based on average torsional stiffness (torque divided by angle of twist) can be used to evaluate shear moduli with sufficient accuracy. The expressions for $G_{12}$ obtained in this study for the stresslam lumber system compare closely with that given by Taylor et al. (1983).

The results of the present study can be applied to the analysis and design of stresslam bridge decks consisting of lumber and vertically laminated glulam sections. The vertically-laminated glulam panels considered in this study can be efficiently used in timber bridge construction, particularly in modular designs of decks and deck-and-stringer stress-laminated systems, but because of the difficulty of drilling holes through a 1.22 m (4') wide panel, 61-cm (2-ft) sections can be used to develop innovative systems.

References


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