

Preserving timber structures with non-destructive evaluation of critical joinery

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Abstract

A non-destructive method of evaluating the rotational stiffness of timber joints was applied to two historic timber structures. Results from the testing showed that more than half the members had joint stiffness values of $\alpha > 1$. For the first structure tested, the average percent error for members with $\alpha > 1$ was 31%. When values of wood density and Modulus of Elasticity were determined in the lab rather than estimating, the percent error for one member was reduced from 55% to 26%. For the second structure tested, the method provided lower percent error for joints with $\alpha > 1$ than for joints with $\alpha > 1$. The second structure had larger percent error in the measurements than the first structure. This is believed to be due to the non-geometric (natural) shape of the members used in the construction. Further research is needed to properly validate the method across different structure types and sizes.

Keywords: Timber Frame joint, non-destructive evaluation, rotational stiffness

Introduction

Overview

In structural rehabilitation of timber-framed bridges, churches, mill buildings, homes, and barns, an engineering analysis is often necessary to determine the load bearing capacity. To perform this analysis the properties of the wood and the properties of the connections must be determined (Brungraber, 1985). There are a number of accepted non-destructive methods for determining in-situ mechanical properties of wood (Ross et al., 2004, Kasal et al., 2009). However, there are no commonly accepted methods for non-destructively determining the strength and stiffness of timber connections (Anthony, 2008). This paper presents results on the use of a frequency-based method to non-destructively determine the initial rotational stiffness of timber joints in two timber structures.

Literature Review

In identifying critical research needs for the American Society of Civil Engineers Structural Engineering Institute, Ron Anthony wrote "Under design loads, seldom do wood members fail in a structure unless they are severely deteriorated. Failures generally occur at connections. Yet we have a wealth of knowledge about wood properties, but not the behavior of connections. Unfortunately, connections are critical in structure performance, . . . , and yet we do not have a reliable means to assess their condition or capacity." (Anthony, 2008) Bo Kasal (Kasal, 2011) in summarizing state-of-the-art in in-situ lumber evaluation for the 2011 Structural Health Assessment of Timber Structures Conference, identified the first

need for further work as “Detection of fastener deterioration and deformation”. Determination of all strength and stiffness properties of timber joinery is ultimately necessary. This paper presents results on determination of just one of those properties, in-plane rotational stiffness. This property may be an indicator for overall joint quality for rehabilitation (Brungraber, 1985). Alternately, it may be the value of critical interest for the structural analysis. Dave Fischetti (Fischetti, 2009) in the book Structural Investigation of Historic Buildings states that “Structural Engineers are aware that it is very difficult to produce a true hinge or a true fixed joint in the actual structure. Joints in timber trusses may act somewhere between those two, causing a very different distribution of forces than produced by the analysis.”

A non-destructive method for determining the rotational stiffness of timber joints using the natural frequency of vibration of the beam has been developed and tested in the laboratory (Crovella and Kyanka, 2011). This paper presents results from applying this method in two timber structures.

Method

Structures for Testing

Circa 1900 post and beam barn

Eight secondary structural members in a 56' x 30' x 20' barn shown were evaluated. The principal structural members were solid sawn 8" x 8" members, and the secondary members were 4" x 6", both Eastern Hemlock (*Tsuga Canadensis*). Moisture content of the members averaged 11.1% with a range from 10.3 to 11.9%. The secondary members were mortised into the principal members and secured with a single peg (wood dowel). The eight members tested (B1,B2,B3,B4,C3,C4,D3,D4) are indicated in Figure 1.

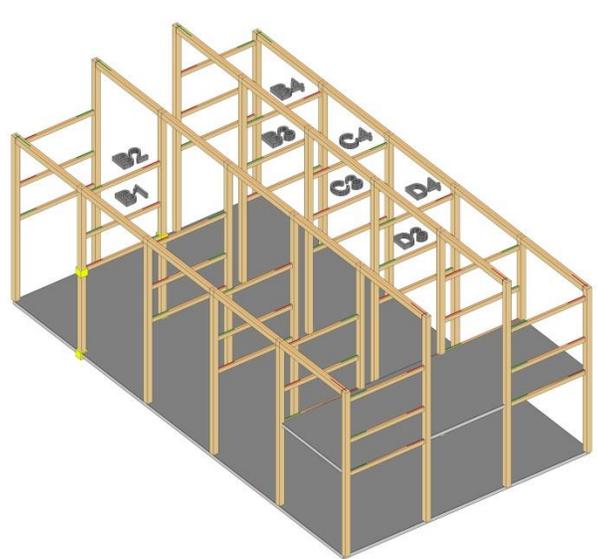


Figure 1—Elements of circa 1900 barn that were tested

For each of these elements, a single axis accelerometer was attached to the top center of the member, and then the member was struck with a soft-faced mallet to excite vibration in the elastic range. The free vibration time history was recorded on a portable computer (Audacity, 2011), and then custom software was used to perform a Fast Fourier Transform. The fundamental natural frequency of vibration was identified from the frequency plot, and used with the beam properties to determine input values for an analysis using the finite element method. Ansys® finite element software was used to produce a dynamic

analysis and the rotational stiffness of the member joints (in the vertical plane) was varied until the natural frequency matched the recorded values.

Next, each member was loaded with a series of weights to produce an elastic deflection less than $L/1000$, and the midpoint deflection was measured.

Using the frequency and deflection measurements, as well as mechanical properties of the member, a comparison was made between joint stiffness as determined by vibration, and by closed-form solution using deflection. For more details on the method, refer to the description from Crovella and Kyanka (Crovella and Kyanka, 2011).

For this building, the species was visually identified and graded (No 3 Eastern Hemlock) and assigned values for Modulus of Elasticity (MOE) (based on the National Design Specifications for Wood Structures) and density (based on the Wood Handbook) at an assumed 12% MC. Further, a sample of material was removed from one of the members (B1) to determine density and MOE with laboratory tests.

1936 Pack Lodge Visitor Center

The second building tested had light frame wall construction, with a log truss roof structure. Two 24' log trusses spanned the main hall. These scissor trusses were constructed from ~8" diameter Eastern Spruce (*Picea glauca*, *Picea rubens*, *Picea mariana*) with the bottom chords intersecting at a center post. The average moisture content was 12.6% with a range from 11.7 to 13.6. The joints appeared to be a combination of wooden joinery and steel fasteners. The four sections of the truss bottom chords were evaluated to determine their rotational stiffness using both the frequency and deflection methods (as described above).

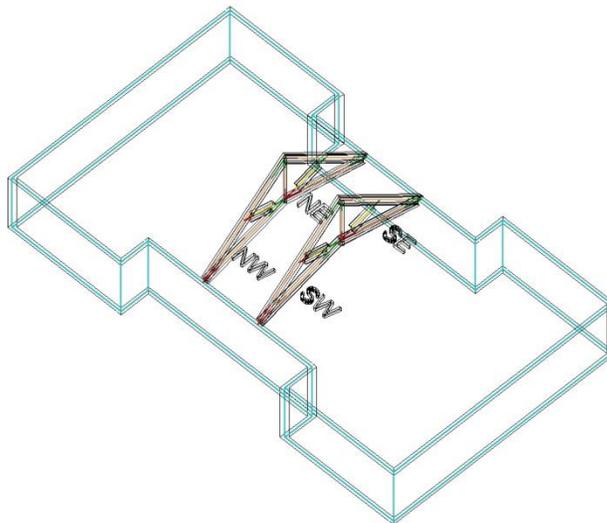


Figure 2 – Bottom chord members of Pack Lodge that were tested

Results

Testing of the circa 1900 barn provided a total of eight similar members with stiffness results for both deflection and frequency.

Table 1 - Circa 1900 Barn Joint Stiffnesses

Member	Joint stiffness (lb-in/rad) based on deflection	Joint stiffness (lb-in/rad) based on frequency
B1	2,200,000	1,000,000
B2	1,300,000	1,100,000
B3	130,000	100,000
B4	25,000	60,000
C3	1,000,000	700,000
C4	600,000	600,000
D3	850,000	400,000
D4	25,000	0

Testing of Pack Lodge provided four similar members (truss bottom chords) with stiffness results for both deflection and frequency.

Table 2 - Pack Lodge Truss Joint Stiffnesses

Member	Joint stiffness (lb-in/rad) based on deflection	Joint stiffness (lb-in/rad) based on frequency
NE	12,000,000	2,500,000
NW	6,000,000	9,000,000
SE	700,000	1,400,000
SW	51,000,000	21,000,000

Discussion

Circa 1900 Barn

Analysis of joints by relative stiffness

The results from testing of the circa 1900 barn showed a general correspondence between larger and smaller values with the two methods. The percent error in the frequency measurement varied from 140% for B4 to 0% for C4. The average percent error was 52%. The method showed which joints have higher rotational stiffness relative to the bending stiffness of the member. This stiffness can be classified by the ratio of the rotational stiffness of the joint (k) to the bending stiffness of the member (EI/L). When separated by those members with kL/EI ratios greater than 1 (5 members), the percent error of the method is reduced to 31%, for members with kL/EI ratios less than 1 (3 members), the error increases to 88%. This separation at kL/EI of 1 is useful for the purpose of analysis, generally for kL/EI values less than 1, joint stiffness can be considered to be negligible. Thus the method provides more precision in the range where it most impacts structural behavior. Graphical representation of these ranges can be found in Figure 3. This figure shows that 0.1 change in normalized frequency corresponds to changes in orders of magnitude of rotational stiffness for kL/EI less than 1. For kL/EI values greater than 1, a 0.1 change in normalized frequency corresponds to less than one order of magnitude change.

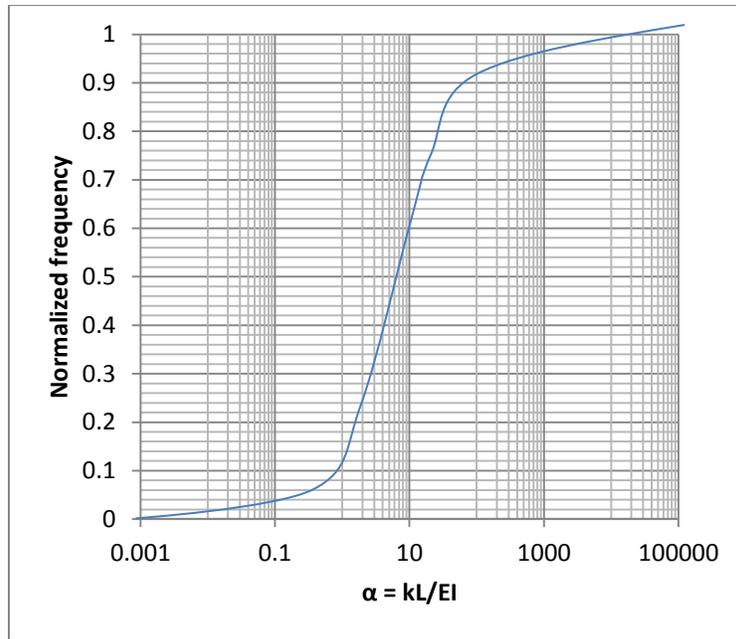


Figure 3 – Effect on natural frequency of increasing rotational joint stiffness (normalized frequency is the ratio of the frequency measured minus the frequency of a pinned member to the frequency of rigid member minus the frequency of a pinned member).

Testing assumptions of MOE and density

The greatest percent error (55%) in the members with kL/EI ratios greater than 1 was found in B1. Two assumptions that introduce inaccuracy in the method are the values for MOE and density. In order to better understand the potential precision of the method, a wood sample was removed from member B1, and tested according to ASTM D143 to determine the MOE. A sample was also removed to determine density using the oven-dry method. Using these measured values of MOE and density, the calculations for joint stiffness due to deflection and frequency can be corrected. As a result, the joint stiffness for deflection was reduced, and the joint stiffness for frequency was increased, reducing the percent error from 55% to 26% (Table 3)

Table 3 – Joint stiffness calculations based on assumed and tested values

Values used for calculations	Joint stiffness (lb-in/rad) based on deflection	Joint stiffness (lb-in/rad) based on frequency	% Error
Assumed values of MOE (900,000 psi) and density (26.2 pcf)	2200000	1000000	55
Measured values of MOE (1,010,000 psi) and density (31.3 pcf)	1750000	1300000	26

Pack Lodge

The results from testing the Pack Lodge visitors center produced results with greater variability than the circa 1900 barn. The percent error varied from 100% to 50%. The average percent error was 72%. Three of the four members had stiffness ratios of kL/EI greater than 1. The largest percent error (100%)

was in the member with the kL/EI value less than 1. The average percent error in members with kL/EI greater than 1 was 63%.

A number of difficulties arose in applying the method to this structure. The non-geometric forms of the members made accurate determination of member properties difficult. These peeled logs were neither straight, nor uniform in their cross section or taper. The dimensions of the members were determined by measuring the circumference at each end and in the middle. These three values were averaged, and then the average circumference was used to calculate an equivalent circular diameter. The cross section varied along the length, with significant shape defects due to the natural form. Values of the Moment of Inertia calculated for these members varied by 45% for members that appeared nearly equal in size. The crook (variation from a straight line) along the length of the member made determination of length a more difficult operation. Finally, the shape of the joints made the definition of the end point more difficult, further complicating the process (Figure 4).



Figure 4 – Pack Lodge bottom chords showing the boundary conditions

Conclusions

The use of a frequency technique to determine the rotational stiffness of joints in a timber structure may be two-fold. First, for a structural analysis of a building, it may be necessary to determine which members should be modeled as pin connected, and which members should be modeled as semi-rigid with a specific value for rotational stiffness. For the two buildings tested, the frequency method showed an overall correlation to deflection, and was able to determine joints of greater and lesser stiffness. The precise stiffness value of joints is of interest when the kL/EI ratio is greater than 1. The frequency method has improved precision in this range, and averaged 32% for solid sawn members. This percent error was able to be reduced by approximately half by measuring, rather than assuming, values for MOE and density.

The method has greater difficulty determining stiffness values for irregularly shaped members, whose overall lengths, etc. are harder to define.

A second use for this method is to determine which joints may be particularly weak and in need of closer inspection and repair. Work done by Brungraber (Brungraber, 1985) and Yue (Yue, 2011) have shown a correlation between lower rotational stiffness and lower ultimate rotational strength. Using this frequency method may allow for rapid location members of lower rotational strength for focused attention in

restoring timber structures. However further research is needed in this area before proposing an acceptable technique.

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