**Final Report – NPS Grant Agreement P13AP00080**

# Preserving Timber Structures with Non-destructive Evaluation of Critical Joinery

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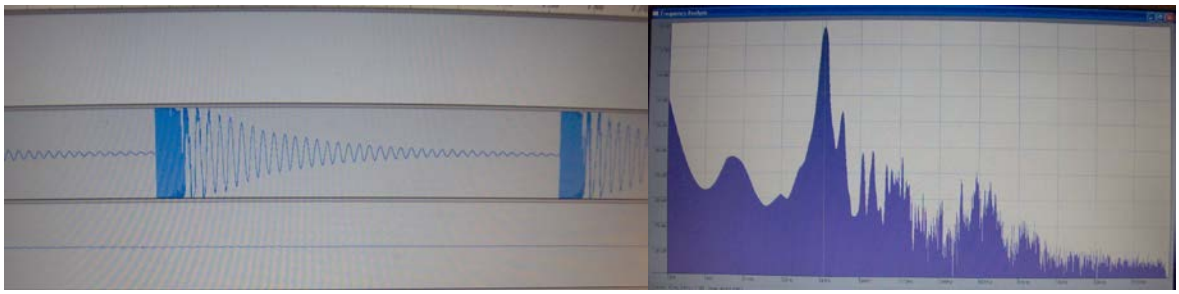

March 30, 2015

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## Executive Summary

The restoration and preservation of historic timber structures depends on the integrity of the structural members. Structural properties need to be assessed for the individual members and for the connections between those members. An array of methods has been developed to non-destructively determine mechanical properties of wood in-situ. However there is no widely accepted method for non-destructively determining the structural properties of connections in timber structures.

This research work field tested a rapid method that had been developed and validated in laboratory work. The work is based on the theory that the natural frequency of vibration of the beam depends on the stiffness of the beam and the stiffness of the connections at the end of the beam. Just as changing the tension in a guitar string changes its frequency, so does change the degree of rotational restraint at the end of the beam. The frequency of vibration of the beam can determine how rigid (stiff) or pinned (loose) the joints in a building are, indicating connection differences between repetitive members and providing the essential steps in performing a structural analysis of the building.

Six buildings of varying age, size, archetype, and connection type were studied. In each of these buildings, critical members were identified that had a clear span that allowed them to vibrate freely. For each of these members, the basic geometric properties were measured, and the Modulus of Elasticity was estimated based on species and grade identification. The member was then instrumented with an accelerometer and allowed to vibrate freely. The time history of the vibration was recorded using a laptop computer. The corresponding frequency spectrum was analyzed, and the fundamental frequency identified. Based on a closed form solution, the frequency and other measured properties could be used to determine the rotational stiffness of the supports.

The results from field testing provided a number of significant findings. First, the wide-spread assumption that timber joints have insignificant rotational stiffness ($\alpha < 1$)is not valid. 70% of the 20 joints tested had stiffness values that classified them as semi-rigid ($1 < \alpha < 100$). Second, the finding from lab work was confirmed: the ability to accurately predict the stiffness improves as the joint stiffness increases from pinned to semi-rigid (Percent error of 84% for $\alpha<1$, and 41% for $1< \alpha <100$). Finally, the method showed anecdotal evidence that joints with lower measured stiffness had visual defects evident upon inspection.

## Introduction

Successful conservation, restoration, and rehabilitation of historic timber buildings will depend on the ability to determine their structural condition. To perform a structural analysis of an existing timber frame, the member properties (strength, stiffness, and dimensions) of the timber elements must be known, as well as the boundary conditions (strength and stiffness of joints) for each member. While extensive research has been performed to non-destructively evaluate the timber properties (e.g. Ross et al, 2004, Kasal et al, 2009), the literature on in-situ determination of the joint properties is by comparison very limited. 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, identified the first need for further work as "Detection of fastener deterioration and deformation". Dave Fischetti in 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."

Anthony has found x-ray techniques effective to reveal in-situ joint geometry and advanced decay. However this is not sufficient to define joint properties. Morlier, Bos, and Castéra (2006) used modal analysis to predict wood joint stiffness in a small scale wood portal frame under laboratory conditions. However this method is not appropriate for in-place evaluation of structural assemblies.

A non-destructive method for determining the rotational stiffness of timber joints using the natural frequency of vibration of the beam has been developed (Crovella and Kyanka, 2011).
In a typical timber-frame building, double pegged mortise and tenon joints tend to be the most common joints (Brungraber, 1985) Excessive tension in these joints is the most common mode of failure (Fischetti, 2009) For many traditional timber structures the "critical" tension joinery is located at the ends of a tie beam at the base of a roof structure. This beam is responsible for resisting the outward thrust of the walls from a roof load (snow, wind, or seismic), and both joints are in tension. Being able to assess the strength of these joints is critical to determining the load bearing capacity of the building. The method that was developed allows the rotational stiffness of these joints to be determined in a non-destructive manner.

The method is based on using the natural frequency of vibration of a beam to determine the rotational stiffness of these joints. As the rotational stiffness of joints at each end of a beam decreases, the natural frequency of vibration decreases as well. By measuring properties of the wooden beam, the frequency of vibration can be correlated to a numeric value of rotational stiffness Laboratory testing found that this method could predict joint stiffness of both hardwood (within 17%) and softwood (within 16%) beams when restrained in a metal fixture. A beam tested in a metal fixture with sequentially weakened joints showed that the stiffness decreased with a matching decrease in frequency. Two softwood frames with all timber joinery, one with stiff, and one with loose joints, were tested. Results showed that tight wood joinery can produce significant joint stiffness that will affect the structural analysis. The stiffness values based on this method ranged from 2-31% of the values measured by deflection. This method needs further field

applications to present as case studies for design professionals looking for clear examples of the utility of the method. The method is based on determining propertied of the structure in the field, and the utilization of the method will need to be supported by specific field studies.

## Method

*Theory* The fundamental frequency for a uniform beam is governed by the beam's geometry, material properties, and the joint stiffness (Eq. 1). If the geometry, material properties, and natural frequency can be determined non-destructively, the stiffness of the joints can be determined. This equation is derived by combining expressions for the displacement of beam with the equation of motion of a harmonic oscillator. The solution of this combined equation results in the general form sine, cosine, and hyperbolic sine and cosine. The exact shape is found by applying boundary conditions to the solution. This solution can then be expressed in terms of the frequency that matches the boundary conditions. For a uniform beam, the resulting equation is:

$$f_n = \frac{K_n (EI/w)^{1/2}}{2\pi l^2} \qquad (1)$$

Where $f_n$ = Natural frequency of mode $n$ (cycles per second), $K_n$ = Constant dependent on the boundary conditions and mode, $w$= uniform mass per unit length (including beam mass), $E$ = modulus of elasticity, $I$ = second moment of area, $l$= length of beam

The value of $K_n$ for the first mode of vibration is 9.87 for a simply supported beam, and 22.4 for a beam fixed at each end. (Figure 1)

A useful expression for describing the joint stiffness between the two extreme values is the "normalized frequency" which represents a linear variation between 0 for a simply supported beam, and 1.0 for a fixed-fixed beam.

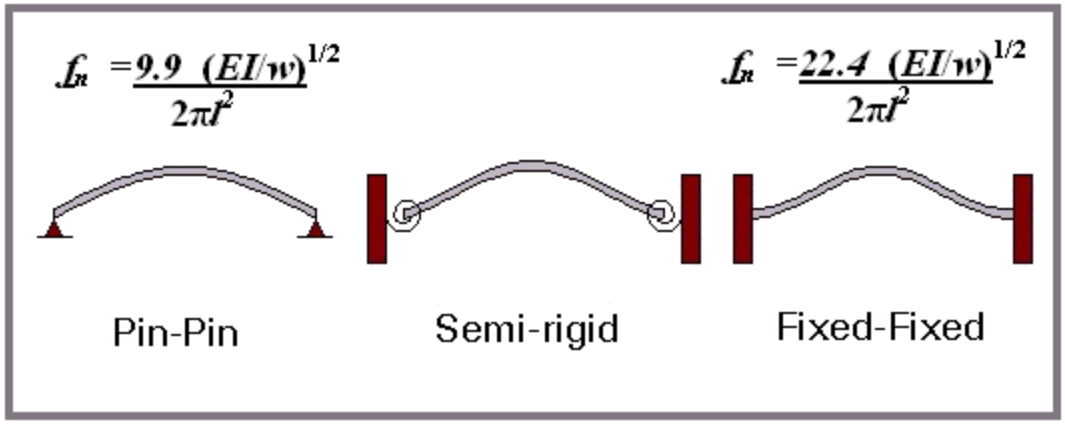



**Figure 1** –Fundamental Frequency of a beam depending on boundary conditions (adapted from McGuire, 1995)

If the beam properties and fundamental frequency are determined, the constant $K_n$ can be calculated as shown in Equation 2

$$K_n = \frac{f_n \, 2\pi l^2}{(EI/w)^{1/2}} \qquad (2)$$

The value of $K_n$ is not the value of the rotational stiffness of the joint, but rather a value that can be correlated to the rotational stiffness of the joint. An important point arises here: When considering a beam with semi-rigid joints, whether the joint stiffness will be significant in the analysis depends on the ratio of the joint stiffness to the bending stiffness of the beam. As shown in Figure 2, when the beam flexural or the joint rotational stiffness is large in relation to the other, the effect of changing joint stiffness has a minimal effect on frequency. When the joint stiffness is between 1 and 100 times that of the flexural stiffness, a change in joint stiffness produces a relatively large change in frequency. A helpful distinction when analyzing the rotational stiffness of beam supports is to consider the relative ratio of joint stiffness (k) to the bending stiffness of the beam (EI/L). When joint stiffness is low relative to the bending stiffness, the beam acts as though the supports were pinned. When the joint stiffness is high, the beam acts as though the supports were fixed. The ratio of k/EI/L is defined as $\alpha$. When $\alpha < 1$, the beam can be considered pinned. When $100 < \alpha$, the beam can be considered to be fixed at each end. When $1 < \alpha < 100$, the beam is said to have semi-rigid supports, and the analysis of the stress in the beam should include the actual rotational stiffness of the joints to accurately reflect the behaviour.

To accurately understand how the frequency maps to determine the value of $\alpha$, a graphical representation can be used. On the Y axis a normalized value for the frequency is determined as follows:

$$\text{Normalized frequency} = \frac{\text{freq. measured} - \text{freq pinned}}{\text{Freq. fixed} - \text{freq. pinned}}$$

Now plotting the frequency as a function of alpha, the blue line in the graphs below shows that there is low discrimination for the method when $\alpha < 1$ or $>100$. However in the intermediate semi-rigid range, a smaller change in alpha will produce a larger change in the measured frequency. This leads to the observation that the method is most accurate for the semi-rigid range.

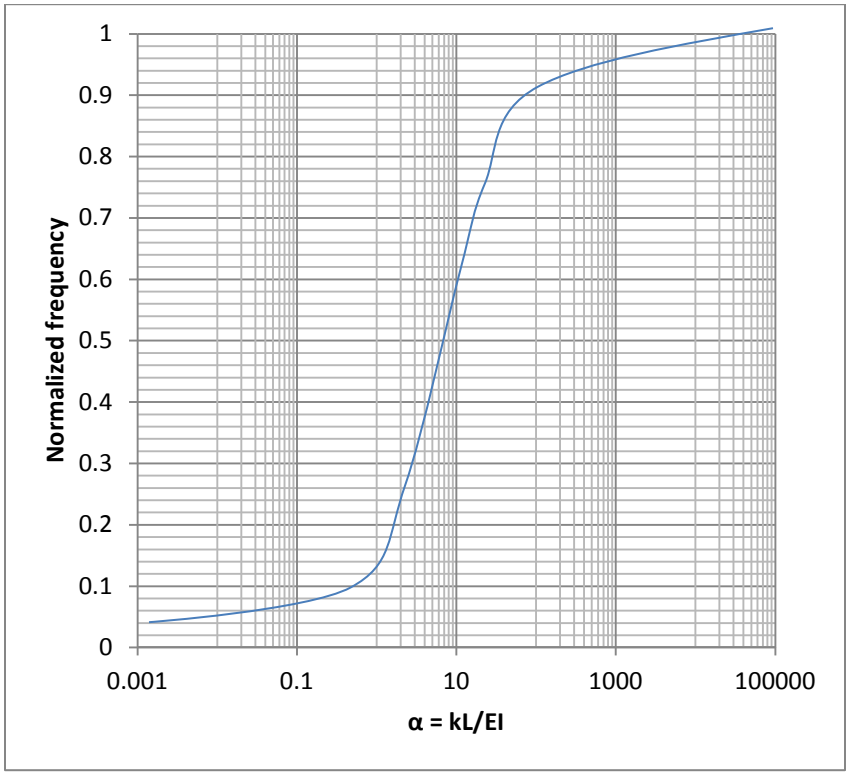



**Figure 2** – Effect on natural frequency of varying rotational joint stiffness relative to beam stiffness

*Experimental Apparatus*

The frequency was determined using an accelerometer placed on the beam to produce an electrical signal due to the free vibration of the member. The accelerometer was a quartz shear type single-axis accelerometer (500 mV/g). The accelerometer was attached through a 9 m (30 ft) foot cable to a USB powered signal conditioner. This signal conditioner is powered through the USB port of the computer, and provides a constant current input to the accelerometer. The voltage at which this current flows is measured by the signal conditioner, and then amplified and output to the computer via a stereo jack.

The sound card of a personal computer accepted the stereo jack signal as an input. A digital audio editor "Audacity 1.2.6" was used to capture, edit, and save the signal as a wav format file. The signal was then processed using a Fast Fourier Transform (FFT), with code based on an applet from Evan Mroz. The resulting frequency response spectrum output file was imported to Excel® to identify the maximum spectral component for the first mode natural frequency.

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).

## SELECTION OF STRUCTURES FOR EVALUATION

The method developed was tested on six different structures, selected for their unique typologies. The buildings selected represent a wide variety of sizes, uses, and connection types typically evaluated for structural capacity.

For each of these buildings a deflection method was also used to determine the joint stiffness. A load was applied at the mid-point of the beam, and the deflection at the mid-point measured. This deflection was used with a closed form solution to determine the reference joint stiffness.

### *1. Agricultural - c. 1900 English frame 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 3.

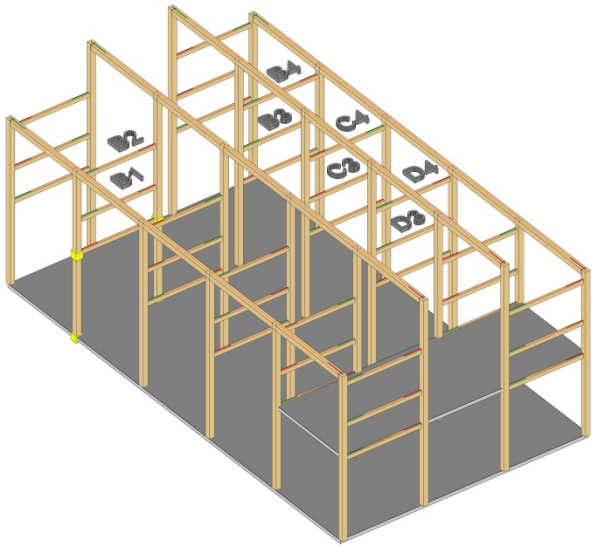



***Figure 3:*** *Agricultural Structure c.1900*

### *2. Civic - 1936 log frame visitor center*

The 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 as shown in Figure 4.

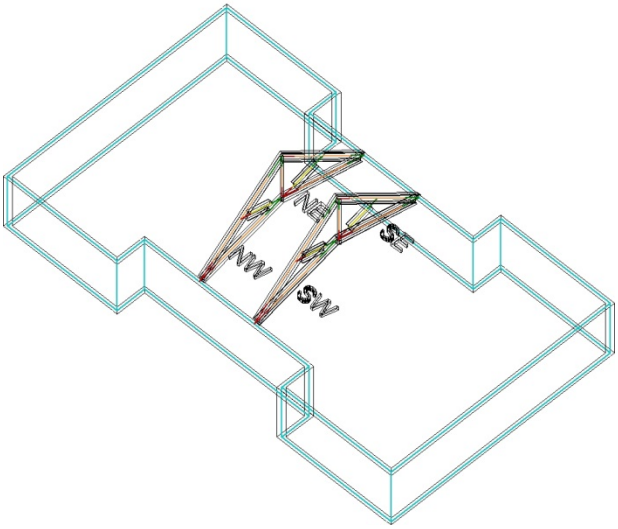



***Figure 4:*** *Civic Structure c.1936*

*3. Civic – 1980 French frame post and beam carpenter's shop*

This structure is a recreation of a French Fort building from 1684. It was built using the materials and methods appropriate to that era by the Timber Framers Guild of North America. The dimensions of the structure are 20'x40'x20'. The two members that were tested are the wall ties shown in Figure 5. The French framing technique used secured the joints with a dovetail connection mortised into the top plate of the wall. The joint stiffness was tested in the horizontal plane. The members were made from Eastern Hemlock (*Tsuga Canadensis)* and were approximately 6" x 6" x 20' in dimension. The moisture content averaged 13.7% and ranged from 13.6-13.7%.

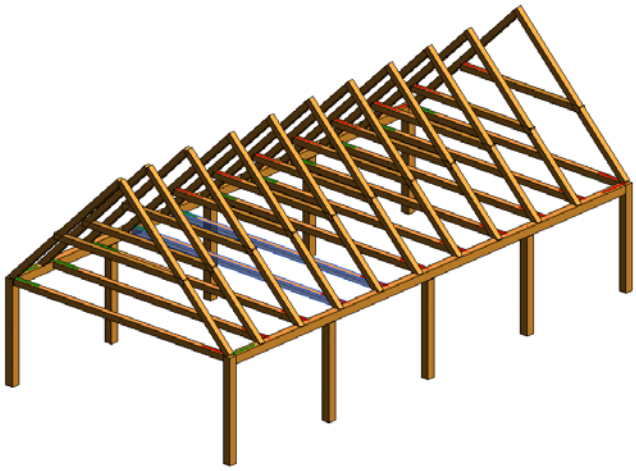


***Figure 5:*** *Historical Recreation – c.1980*

*4. Civic – 1980 French frame post and beam refectory*

This structure is also part of the recreation of a French Fort building from 1684. The dimensions of the structure are also 20'x40'x20'. The two members that were tested are the wall ties shown in Figure 6. These have a similar French framing dovetail connection. The joint stiffness was also tested in the horizontal plane. The members were made from Eastern Hemlock (*Tsuga Canadensis)* and were approximately 6" x 6" x 20' in dimension. The moisture content averaged 13.5% and ranged from 13.4-13.5%.

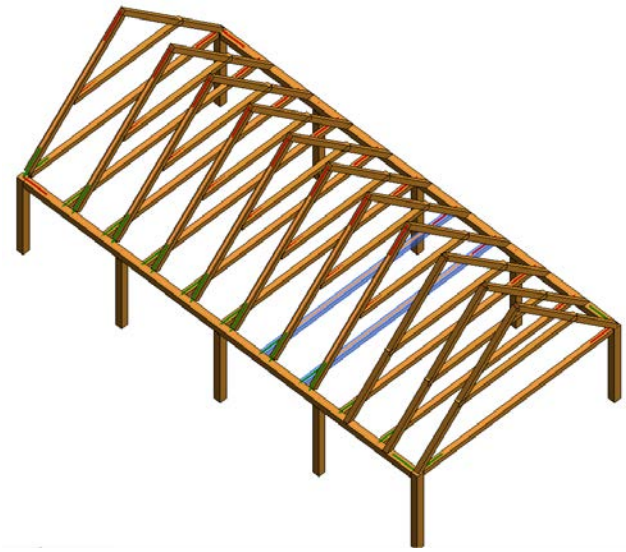


***Figure 6:*** *Historical Recreation c.1980*

*5. Academic – 1889 – Hybrid Timber-Iron construction*

Crouse College, on the Syracuse University campus, is a Romanesque Revival style academic building used for fine arts. The structure has a footprint of approximately 162' x 190', and the main roof 48' x 120'. The main timbers of the roof are approximately 10" x 12" in cross section. The members that were tested were three 5"x8" secondary members (knee braces) as shown in Figures 7 and 8. The members were made from Eastern Hemlock (*Tsuga Canadensis).*

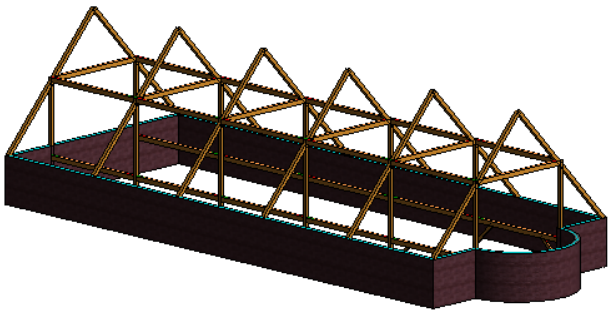


***Figure 7:*** *Academic hybrid timber-iron construction c.1889*

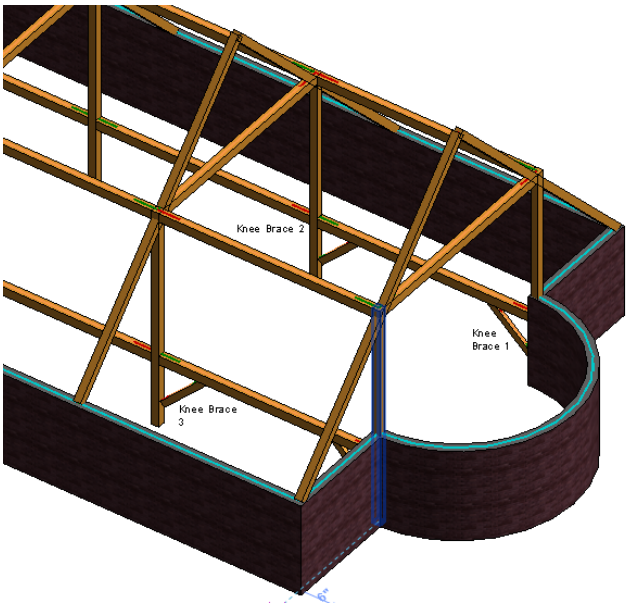



***Figure 8:*** *Close up of knee brace location*

*6. Residential – c. 1870 – Hand hewn tiebeam construction*

The Platt Barn is modified English tithing barn style structure. It is 25'x 50' x 25', and the tested tiebeam was made from White Ash (*Fraxinus Americana*). The tiebeam shown in Figure 9 had been reinforced with a cable parallel to the beam, and connected to the posts just below the timber connections. Reinforcement ties had also been placed at the top of the other interior posts, parallel to the tiebeam.

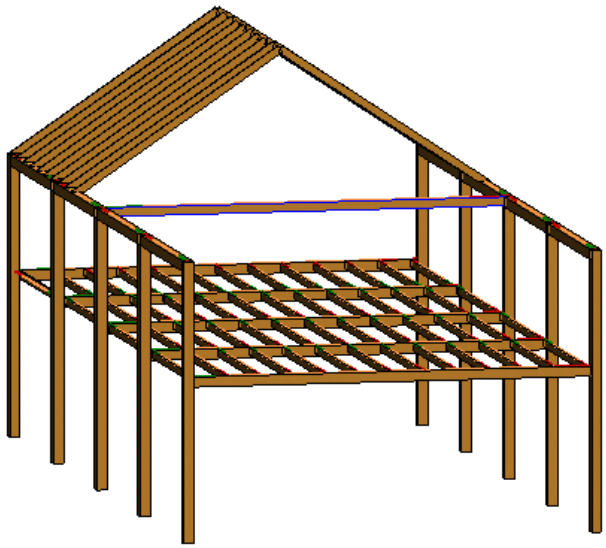


***Figure 9:*** *Residential structure with tiebeam*

## RESULTS

**Summary of joint stiffness comparison.** The stiffness of the joints was measured using vibration method and using the deflection method. The results are compiled in Table 1.

***Table 1:*** *Joint Stiffnesses by deflection and vibration*

| Structure<br>Structure ID for beams | Stiffness – deflection (lb-in)/rad | Stiffness-vibration (lb-in)/rad |
|---|---|---|
| 1 | 2,200,000 | 1,000,000 |
| | 1,330,000 | 1,100,000 |
| | 130,000 | 100,000 |
| | 25,000 | 60,000 |
| | 1,000,000 | 700,000 |
| | 600,000 | 600,000 |
| | 850,000 | 400,000 |
| | 25,000 | 0 |
| .2 | 12,000,000 | 2,500,000 |
| | 6,000,000 | 9,000,000 |
| | 700,000 | 1,400,000 |
| | 28,000,000 | 21,000,000 |
| 3 | 1,950,000 | 1,450,000 |
| | 2,150,000 | 1,550,000 |
| 4 | 3,100,000 | 2,000,000 |
| | 4,250,000 | 2,000,000 |
| | 1,000,000 | 100,000 |
| 5 | 3,300,000 | 2,100,000 |
| | 1,800,000 | 2,500,000 |

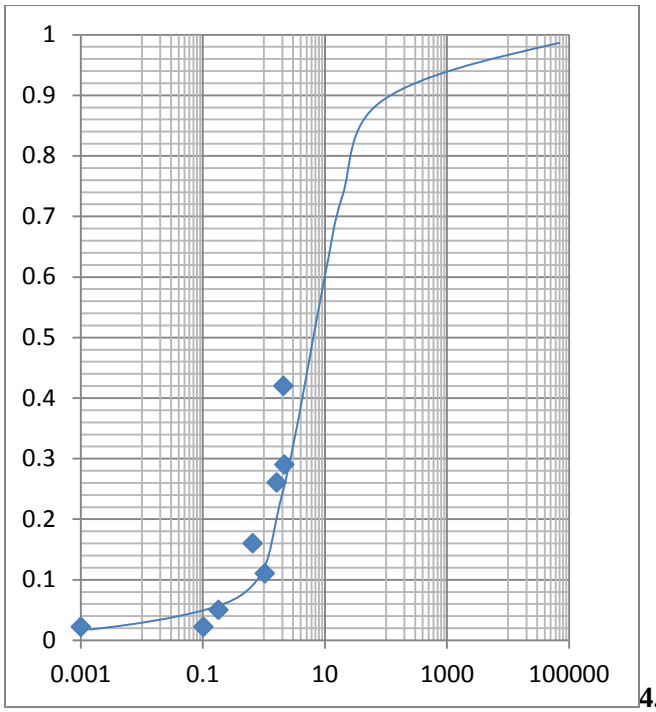
| | | | |
|---|---|---|---|
| 6 | | 500,000 | 1,000,000 |

]

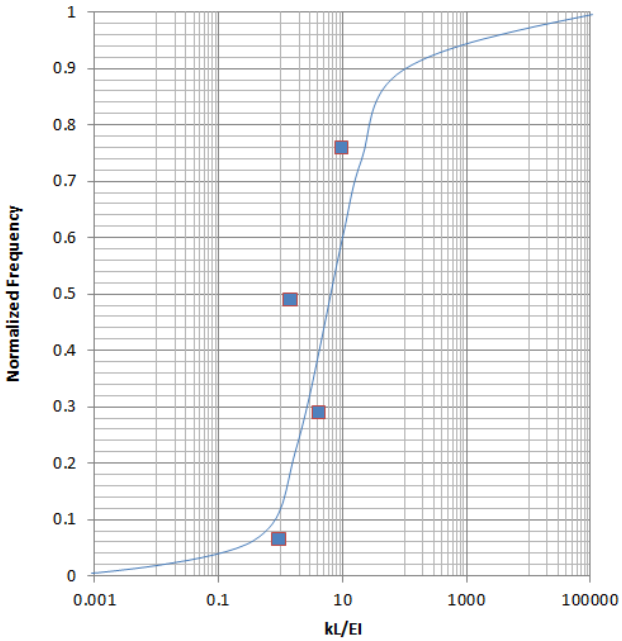
The result of this analysis was that the average percent error for all values was 54%. The beams having an 1 < α had an average percent error of 41%, and the beams having α <1 were found to have an average percent error of 84%.

In these tests, 70% of the beams were found to have 1 < α, indicating that semi-rigid behavior is common.

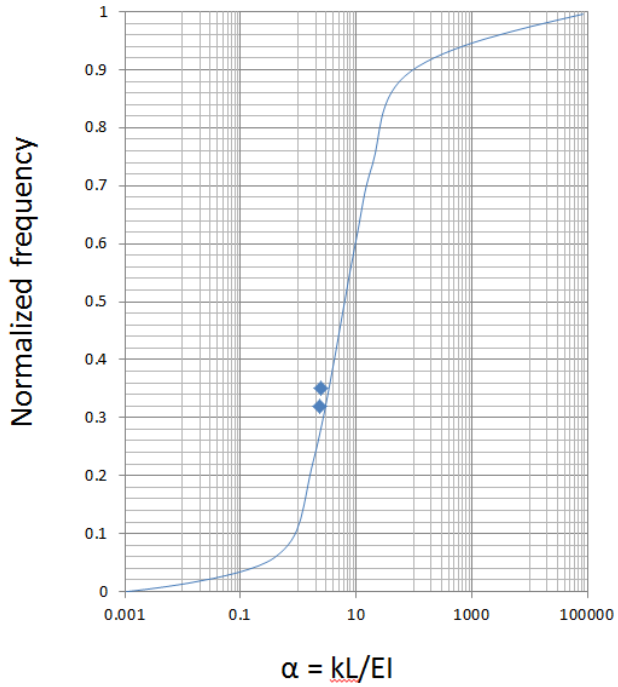
### 1.1. Agricultural - c. 1900 English frame post and beam barn



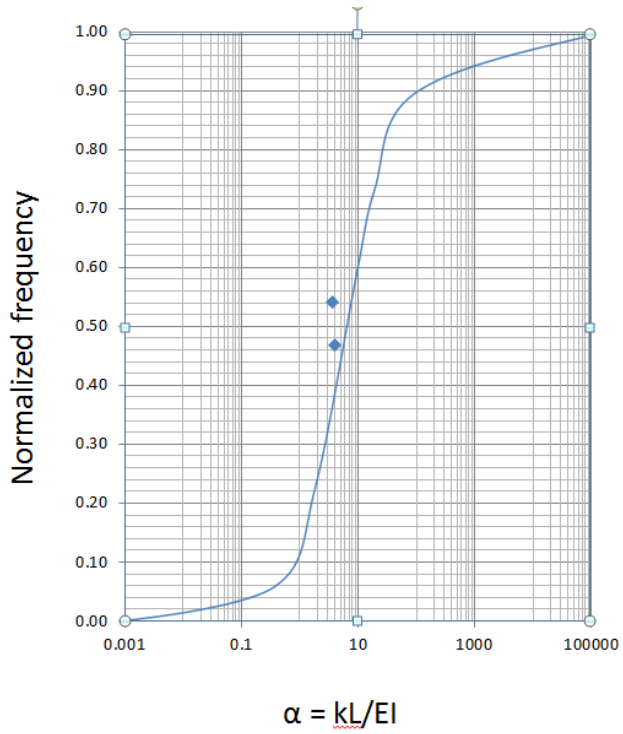

### 4.2 Visitors Center



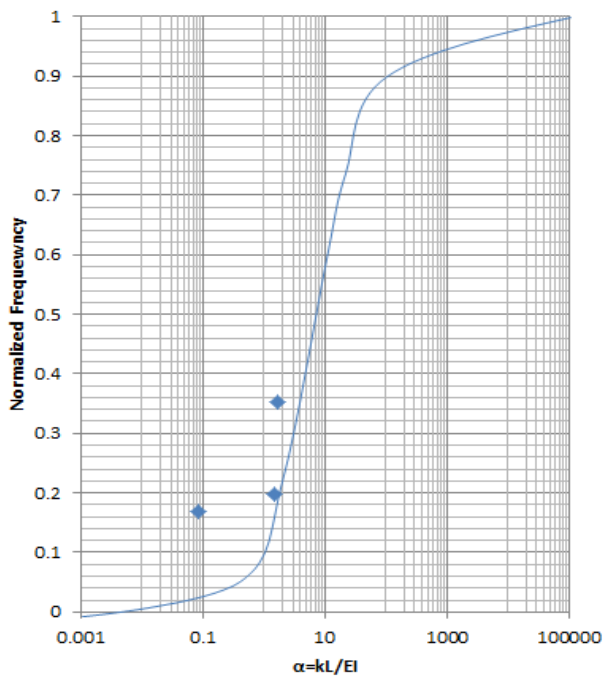

### 4.3 Museum – Building 1



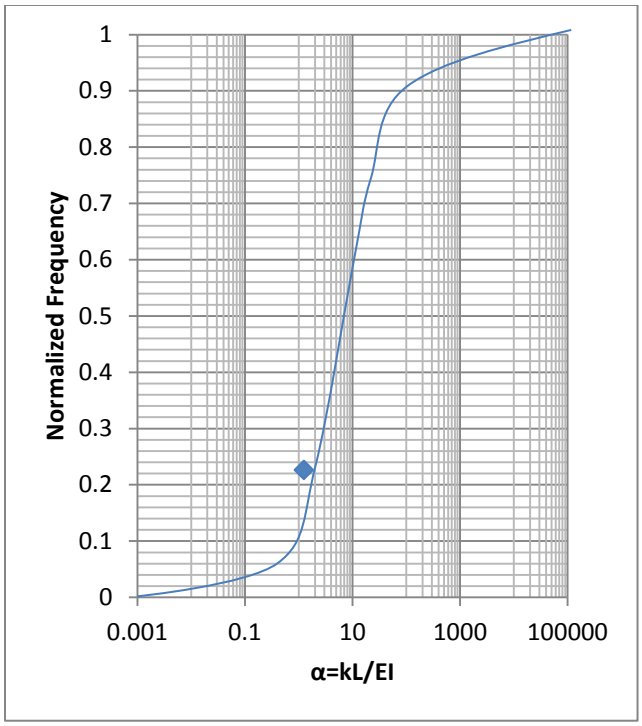

### 4.4 Museum – Building 2




**4.5 Academic Building**




**Residential Building**




***Testing assumptions of MOE and density***

For the agricultural structure studied, he 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) | 1750000 | 1300000 | 26 |

and density (31.3 pcf)

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Finally, for the group of eight beams tested from the agricultural structure, the beam with the lowest joint stiffness value was visually inspected. In figure 3 below, one of the joints is shown to have a broken housing below the peg that was driven through, indicating damage to mortise housing (the pipe shown was removed during testing).

## Conclusions

The results from field testing provided a number of significant findings. First, the wide-spread assumption that timber joints have insignificant rotational stiffness ($\alpha < 1$)is not valid. 70% of the 20 joints tested had stiffness values that classified them as semi-rigid ($1 < \alpha < 100$). Second, the finding from lab work was confirmed: the ability to accurately predict the stiffness improves as the joint stiffness increases from pinned to semi-rigid (Percent error of 84% for $\alpha<1$, and 41% for $1< \alpha <100$). Furthermore, for the agricultural structure tested, the beam from the $1 < \alpha$ group with the greatest percent error (55%), testing a sample of the beam to reduce error in the assumed values for MOE and density allowed the error to be reduced to 26%. Finally, the method showed anecdotal evidence that joints with lower measured stiffness had visual defects evident upon inspection.

**Acknowledgements** This publication (and the associated website) were developed under a grant from the National Center for Preservation Technology and Training, a unit of the National Park Service. The contents are solely the responsibility of the author(s), and do not necessarily represent the official position or policies of the National Park Service or the National Center for Preservation Technology and Training.

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