

## **Predicting Modulus of Elasticity of Short Length New Zealand Radiata Pine Finger Joint Shooks using Flexural Vibration Method**

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### **Abstract**

Predicting static bending stiffness of timber using stress wave methods has been well established especially with longitudinal stress wave. The elementary concept of longitudinal wave propagation is based on the rod theory. Length-to-depth ratio (L/D) of 120:1.6 has been reported in testing small beams (Ilic, 2003). There are very few studies on specimens with L/D ratio less than as stated.

This research aimed to obtain a mathematical function for the static MOE of short length shooks used for finger-jointing via testing dynamic stiffness using a resonance tool. The function will be incorporated into a computer simulation system to optimise the arrangement of shooks before finger profiling and jointing.

In this study, a flexural wave is chosen to measure the dynamic elasticity with low L/D ratio. It is based upon Kirchhoff's theory which requires test specimens to be compliant with the appropriate slenderness ratio. Test specimens with an initial L/D ratio of 8:1 (depth =36mm) were initially dynamically tested and later trimmed to 17:1 (depth = 15mm) for static bending. The  $R^2$  value for the linear regression of MOE static vs MOE dynamic for specimens at 15mm depth is considered acceptable ( $R^2=0.65$ ), taking into account there will be a sizable random mixture of timber shook quality and stiffness affecting the strength property of wood in a mass production environment. When the results are grouped, two different sets of correlations are observed; the first fared very well ( $R^2=0.95$ ) while the latter reasonably well ( $R^2=0.70$ ).

In conclusion, the discrepancy found in correlations can be used as a calibration tool for flexural dynamic stiffness test and it is practical to be incorporated within finger-jointing production.

**Keywords** Finger-jointing, dynamic stiffness, static stiffness, Radiata pine, flexural wave

## **Introduction**

Variability of properties within a tree is not uncommon especially for New Zealand Radiata Pine. Such occurrence is due to several factors including geo-topography, genetics and harvesting of juvenile crops. Reports on variability have been on-going for decades; as such has brought much undesirable impact in the downstream productions, mainly affecting the product quality and performance.

Machine Stress Grading (MSG) has been traditionally used in measurement of elastic modulus of lumber. The bending and tensile strength properties and other design properties are often inferred by referring to established correlations (Hernandez & Moody, 1996).

Recently the established correlations are found to be no longer reliable due to greater variability in physical and mechanical properties in Radiata Pine timber. The relationship in predicting strength and stiffness using machine strength grading (MSG) operation is found to have deteriorated (Gaunt, 1999). In the original MSG grading system, the minimum Modulus of Elasticity (E) is required for timber design purposes so that timber designers would know the lowest E value that could be expected from a certain grade. The minimum MOE is used as means to assign a grade for the overall piece. In regards to the aforementioned issue, it was nonetheless found that the minimum E point from the actual MSG processing operation has often been outside the test span zone. Issues on the relevance in predicting the structural properties became the main concern (Gaunt, 1999).

### ***Why Elasticity is important?***

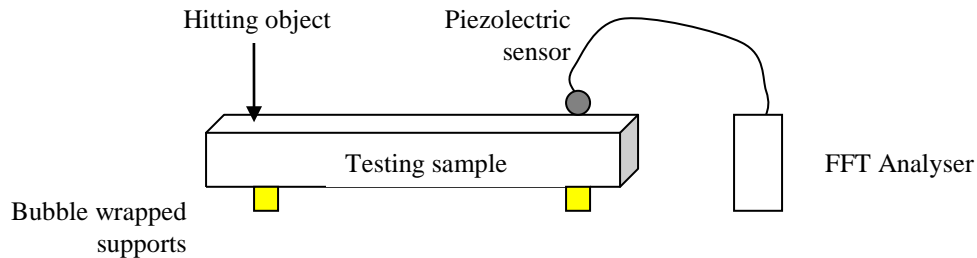
Elasticity in wood contributes to the damping effect thus giving a wooden structure ability to absorb impact and cyclic loading. While strength refers to the ability of a wood piece to resist stress under load, stiffness is another important measure particularly in structural design. In designing longer spans structures often confined more by deflection limits than the beam strength (Anon, 1999). Quantifying stiffness or elasticity of wood accurately and effectively would help in better grade recovery and therefore benefits to the industries.

### ***Background on dynamic MOE***

Predicting Modulus of Elasticity (E) using resonance tools is one of the non-destructive techniques (NDT) in determining the elasticity of timber test samples. There are various NDT technologies including tomography, near infrared scanning, acousto-ultrasonic, stress wave, laser and ultrasound. Generating vibrations by means of mechanical excitation methods (hammer or other hitting tools) are commonly used and are commercially available. The mechanism of the operation includes a hammer or other means to excite resonance waves and the magnitude of frequencies will be picked up by an accelerometer (e.g. piezoelectric transducer). The spectrum of frequencies is then analysed by a Fast Fourier Transform (FFT) spectrum analyser (Fig. 1) and calculates the dynamic elasticity value of the testing sample.

Application of NDT in timber has not been uncommon in research and manufacturing. It has been used as an inspection tool for on-site tree defect evaluation, assessment of the mechanical resonance of a building for earthquake hazards, as an in-service testing tool for infrastructures such as lumber pole and wooden bridges (Zombori, 2001) & (Ross, Pellerin, Volny, Salsig, & Falk,

1999), determination of the strength performance of lumber (Chauhan, Entwistle, & Walker, 2005), (Rajeshwar, Bender, Bray, & McDonald, 1997) and wood composites.



*Fig. 1: Resonance test setup with a FFT analyser measuring flexural frequencies.*

In this study, it was proposed to employ a resonance tool to measure the dynamic elasticity (E-dynamic) of each short-length defect free wood sections known as a shook, prior to finger profiling. The idea is to utilize the E-dynamic data of each shook and find the optimum elasticity arrangement function for a finger-jointed piece. As mentioned earlier, due to variability of properties within a tree, it is anticipated the variance in elasticity between shooks could be fairly wide. Hence, being able to capture the E-dynamic of each shook piece would be useful for optimization of further processing.

### **Bridging the Gap**

E-dynamic value can be equated as a function based on frequency-domain measurement (i.e. frequency), or time-domain measurement from pulse response of a system (e.g. ultrasonic pulses). The models used in deriving E-dynamic were essentially the Elementary Rod Theory, and Bernoulli-Euler Beam Theory, for longitudinal and flexural waves respectively. These theories assumed a long slender members and neglected any shear deformation (Doyle, 1997).

It is known in a finger-jointing processing environment that shook dimensions are processed to be short and thick after defect removal. In this paper the aim is investigate how shook dimensions affect the overall correlations between E-dynamic and E-static. The paper will present the effect of a short length testing sample and how it would affect the correlations between static and dynamic MOE. A correction factor to take into account the shear effect may be needed, and suggestions to fill the gap will be discussed.

## Literature Review

### Background

There are essentially two types of wave motions measurable in a solid medium, the longitudinal and flexural waves. The classification of wave motions is based on the direction of vibration of the medium relative to the direction in which the wave is moving (Speaks, 2005).

Longitudinal wave are compressed (high density) and rarefractioned (low density) along the same plane as the direction of wave propagation. Flexural wave moves in the direction of vibration of the medium at right angles to the direction of the wave that is propagated through the medium (Speaks, 2005). From the wave point of view, the differences between wave propagation in a beam/plate and in a rod are significant.

The fundamental in acoustic science defines the elasticity of an object in the following equation:

$$E = \rho v^2 \dots\dots\dots \text{Eq. 1}$$

where                    E = Elasticity or stiffness of object (Pa)  
                               $\rho$  = density of object (kg/m<sup>3</sup>)  
                              v = velocity of sound (m/s)

However, Eq. 1.0 is only valid for longitudinal waves in one dimension such as in a rod; hence, the Rod Theory is often related. The model developed by Euler-Bernoilli Theory is often related to a beam while the *Kirchhoff theory* is for plates, and they are interchangeably used.

Flexural waves (also known as bending waves) are more likely to resemble static flexural bending tests. Moreover, it is easier to excite in a transverse manner than side ways for a longitudinal wave. It is easier to obtain the stiffness in a transverse plane and thus more practical in a processing environment (Donohue & Chauhan, 2010).

Since comparing between E-dynamic and E-static values, using the static bending test would be of prime concern, and flexural frequency is opted for use in determining E-dynamic. The dynamic MOE using the flexural vibration frequency can be estimated using Eq. 2.

$$E_{dyn} = \frac{0.946L^4 f^2 \rho}{d^2} \dots\dots\dots \text{Eq. 2}$$

where                    L = sample length (m)  
                              f = flexural frequency (Hz)  
                               $\rho$  = Density of sample (kg/m<sup>3</sup>)  
                              d = depth of the sample in the plane of bending (m)

## **Methods and Materials**

### **An Overview of Sample Preparation**

Comparisons between E-dynamic and E-static flexural test were made in two phases. Wood samples at original shoo dimension (nominal size at 120x36x290mm) were dynamically tested. Later, the depth of the same piece was trimmed to nominal depth,  $d = 15$  mm. E-dynamic tests were conducted on the trimmed samples again as were static flexural tests. In order to compare the effect of slenderness upon correlation between static and dynamic E, some samples were tested without trimming to the smaller depth. The reason for reducing the depth of samples is to obviate shear effect in static tests. The minimum length-depth ratio can be referenced from standards.

### *Sample Size*

All samples were originally cut to nominal size at 120x36x290mm.

There were total of 10 samples dedicated for test without trimming. Another 16 samples were trimmed to  $d = 15$ mm after the first run of dynamic test. Hence, a total of 26 samples were tested.

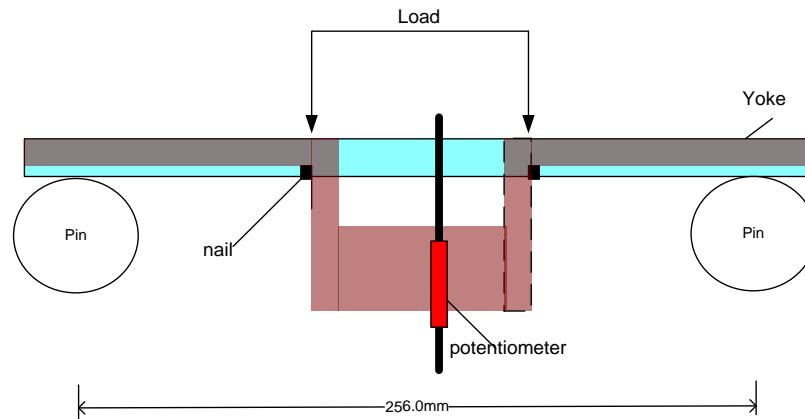
### *Dynamic Test Setup*

The experiment was carried out using a commercial handheld Fast Fourier Transform (FFT) analyser – Bruel & Kjaer 2260 Investigator. The first mode fundamental frequencies were measured and the dynamic E for each sample was estimated. The analyser was set at frequency span 5kHz and speed of vibration  $3.112\text{m/s}^2$ . The FFT analyser is connected to a PCB piezoelectric sensor as receiver.

The wood samples were supported by bubble-wrapped supports. The idea was to create air-supports to simulate a “free-free” boundary condition. The illustration of test setup is as Fig. 1. Each time when samples were tested, a hammer-like plastic strip was used to lightly knock on the plane surface. The fundamental vibration frequencies were recorded from the FFT analyser.

### *Static Flexural Test*

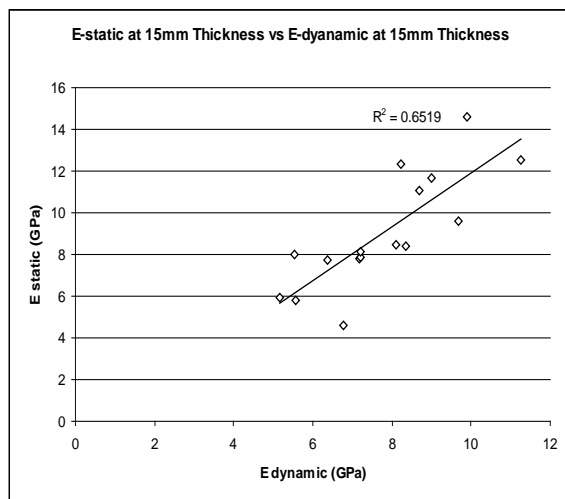
Four-point flexure bending was carried out to measure the static E. The test setup for flexural bending is shown in Fig. 2. Testing procedures from ASTM D198-5a (ASTM, 2005) were followed and tests were conducted on an Instron UTM Model A212-201 with a load cell Type 2511-308. The maximum load for a nominal 125x15x256span mm samples were calculated to be 1kN. The loading speed was set at 1.0mm/min. Two 8mm potentiometers were used to measure the displacements on each side of the wood samples. The potentiometers were attached on a “U”-shaped yoke hanging on either side of the specimens during load application. The average of displacements was computed and the static MOE and MOR estimated based on the average displacement.



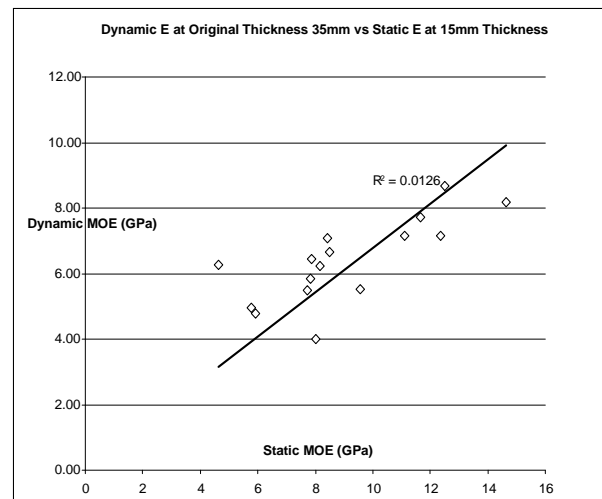
*Fig. 2: Four-point static bending setup*

### Results and Discussion

The correlation coefficient ( $R^2$ ) between E-dynamic at 35mm depth and E-static at 15mm depth were very low ( $R^2=0.0126$ ) (Fig. 4). The correlation relationship improved tremendously for E-dynamic measured at 15mm with E-static at 15mm ( $r^2=0.65$ ). This indicates the ratio for length-to-depth has a significant impact upon the reliability of correlations between static and dynamic elasticity. Goodness-of-fits tests were conducted to investigate the effect of density and moisture content of samples upon the correlation; nonetheless the results showed they were not the main contributors for the discrepancy. The most possible influence could be the shear effect taken placed during measurement of dynamic elasticity at low length-depth ratio (35mm depth).

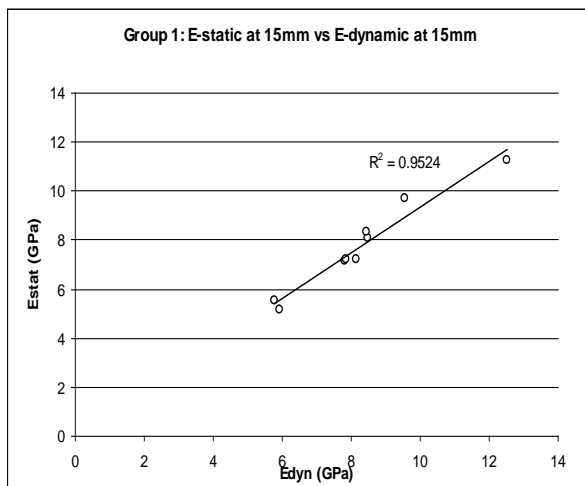


*Fig.3: Correlation between E-static measured at 15mm depth and E-dynamic at 15mm depth.*

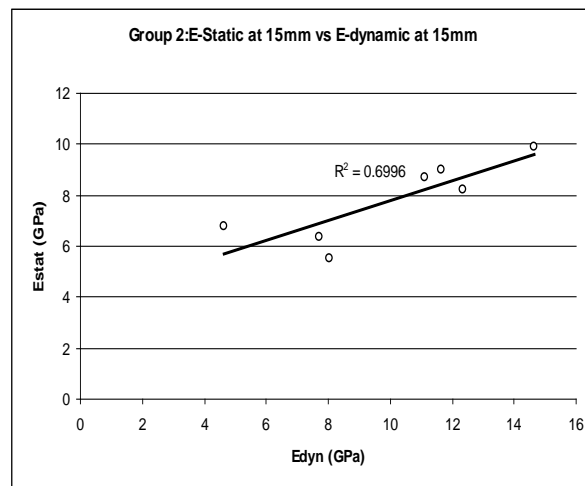


*Fig.4: Correlation between E-dynamic measured at 35mm depth and E-static measured at 15mm depth.*

During the analysis of the bending tests, it was noticed some of the dynamic and static elasticity showed very strong correlations while the others were poorly related. The results were later classified into a distinct division between the stronger and poorer correlations. Fig. 5 shows the result for samples showing a better correlation (Group 1); Fig.6 consists of the weaker group denoted as Group 2. In the process of classification, it was observed the growth ring orientation plays a vital role in determining the group. To simplify the explanation on growth ring orientation, they are categorized to be Flatsawn or Quartersawn ,or the in between. Approximately 55.6 percent of the samples in Group 1 belong to Full Quartersawn, with the remaining mixture of Full Flatsawn and Semi-flatsawn. None of the Full Quartersawn belongs to Group 2. About half of the samples in Group 2 were Semi-flatsawn and the other half consists of Full Flatsawn.



*Fig.5: Classified samples for Group 1 correlation between E-static and E-dynamic measured at 15mm thickness.*



*Fig.6: Classified samples for Group 2 correlation between E-static and E-dynamic measured at 15mm thickness.*

## Conclusion

The correlation between E-dynamic measured at 35mm depth and E-static at 15mm depth did not fare well; however, the correlation improved for E-dynamic measured at 15mm depth. Shear effect is suspected to be the main contributor and thus the reliability of prediction of static elasticity has to be overcome by available means. When these results were classified, the distinction between groups due to growth ring orientation was significant. Further exploration on the effect of growth ring orientation should be conducted and could be used as a means to correct the low reliability of correlations between E-dynamic and E-static for a reasonable yet acceptable low length-depth ratio shooks.

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