United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

Research
Note
FPL–RN–0308

Cantilever-Beam Dynamic Modulus for Wood Composite Products: Part 1 Apparatus

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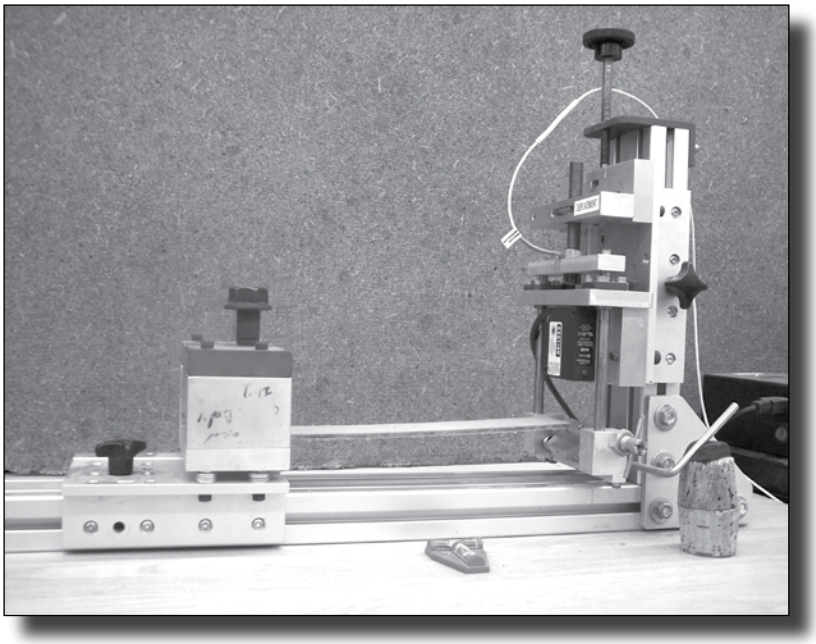

Abstract

A cantilever-beam vibration-testing apparatus has been developed to provide a means of dynamic and non-destructive evaluation of modulus of elasticity for small samples of wood or wood-composite material. The apparatus applies a known displacement to a cantilever beam and then releases the beam into its natural first-mode vibration and records displacement as a function of time. That frequency and amplitude attenuation is then used to calculate the dynamic material properties of the cantilever beam. The dynamic testing is quick and calculates the dynamic modulus and loss-tangent damping coefficient.

Keywords: wood composites, cantilever-beam vibration, dynamic modulus, storage modulus of elasticity, loss modulus of elasticity

April 2008

Turk, Chris; Hunt, John F.; Marr, David J. 2008. Cantilever-beam dynamic modulus for wood composite products: part 1 apparatus. Research Note FPL-RN-0308. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

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Cantilever-Beam Dynamic Modulus for Wood Composite Products: Part 1 Apparatus

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Introduction

Evaluation of wood and wood composites properties through vibrational methods have been used with good success for several decades (Ilic 2003, Moslemi 1967, Ross and Pellerin 1994). They have shown that non-destructive vibrational properties correlate well with bending or tensile moduli and can be used to obtain damping coefficients and creep response. As new composite products with increasing demands on performance continue to be developed, we need to have better analysis tools to differentiate products or to describe enhanced performance characteristics. The Forest Products Laboratory (FPL) has conducted numerous research studies on the use of vibrational methods to determine structural material properties on wood. Most if not all the studies have focused on solid, large wood pieces using either longitudinal stress-wave or simply supported transverse-beam vibration techniques (Murphy 1997; Ross and others 1991, 2005; Schad and others 1995). For large pieces of wood, it is easy to use a simply supported beam method with transverse vibration. However, as specimen size is reduced, it becomes more difficult to simply support a small light-weight beam and measure vibration. Therefore, as specimen size is reduced, the cantilever beam becomes the preferred method for obtaining vibrational characteristics. This is seen in other industries where cantilever beams are used to test material properties of small flat beams (Weihs and others 1988, Yam and others 2004).

We developed a dynamic cantilever transverse-beam vibration (CBV) apparatus to continue work on testing thin to moderately thick wood-fiber composite materials. Though much vibration theory treats the static and dynamic moduli as equivalent (Harris 2002), differences have been observed in the comparison of static bending and dynamic vibration data for simply supported beams (Ross and others 1991). The goal of the research is to provide a means to measure transverse vibrational properties of cantilever beams both qualitatively and quantitatively to better understand fundamental wood-composite material properties and their relationship with processing conditions. This development process has included design of an apparatus, development of software, and evolution of a test method.

Theory of Operation

The frequency of the first mode of free vibration of a cantilever beam is given by (Harris 2002)

$$\omega_{n1} = 2\pi f = \left(\frac{1.875^2}{l^2}\right)\sqrt{\frac{EI}{m_u}} \tag{1}$$

Where

ω_{n1}	is	frequency of the first natural mode of vibration (rad/s),
f		detected frequency of the first natural mode of vibration (Hz),
l		unclamped or "free" length of the cantilever beam (m),
E		bulk modulus of elasticity (N/m^2),
I		area moment of inertia of the beam cross section (m^4), and
m_u		mass per unit length (kg/m).

The definition of a cantilever beam is one in which displacement and angular deflection at the supported end remains zero, whereas the other end is free to translate. Equation (1) can be rearranged and written in terms of known values to provide the bulk modulus of elasticity:

$$E = \frac{m_u}{I}(2\pi f)^2\left(\frac{l^2}{1.875^2}\right)^2 = \frac{M}{L}\frac{12}{bt^3}(2\pi f)^2\left(\frac{l^2}{1.875^2}\right)^2 \tag{2}$$

Where

M	is	mass of the specimen (kg),
L		complete length of the specimen (m),
b		base width of the specimen (m), and
t		thickness of the specimen (m).

Equation (2) is an idealized equation of vibration that neglects the effects of shear force and rotary motion in the specimen. To determine the relative magnitude of shear force terms to the idealized solution, Timoshenko (Harris 2002) introduced a correction factor defined by the radius of gyration divided by free length:

$$\frac{\text{Radius of gyration}}{\text{Free length}} = \frac{\sqrt{I/\text{Area}}}{l} = \sqrt{\frac{t^2}{12l^2}} \tag{3}$$

From Equation (3), correction depends on the ratio of specimen thickness to specimen length. Timoshenko

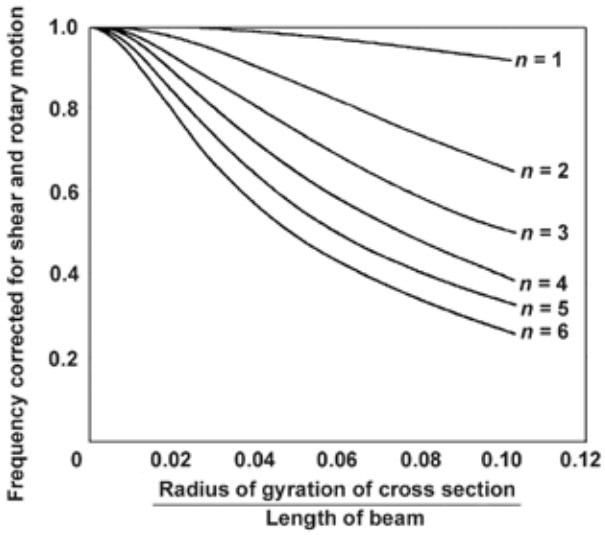

Figure 1—Influence of shear force and rotary motion on natural frequencies of uniform cantilever beams. The curves relate to the corrected frequency of that given by equation (2) in Harris (2002).

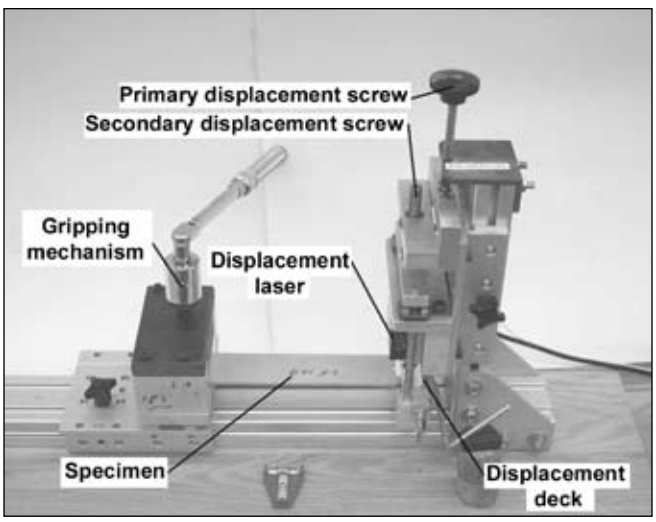

Figure 2—Cantilever beam vibration tester shown with a specimen in position.

(Harris 2002) presented a set of curves (Fig. 1) to determine the correction factor (where *n* represents mode of vibration). Therefore, if care is taken to control the ratio of thickness and length such that the radius of gyration divided by free length (Equation (3)) is <0.005 (dimensionless), the frequency correction factor approaches 1.0 such that shear and rotary effects are negligible. To obtain negligible effects, the *l/t* ratio needs to be >58.

Experimental Apparatus

The CBV hardware (Fig. 2) consists of a slider assembly that can be positioned and locked in place along an extruded aluminum bar to accommodate different sample lengths. Whereas a larger apparatus can later be built, maximum specimen size the current apparatus can accommodate is 7.5 cm (3 in.) wide by 50 cm (20 in.) long. For this length, maximum panel thickness based on Timoshenko's theory would be 8.6 mm (0.33 in.). The specimen is clamped to the slider through a plate-and-screw assembly. A torque wrench is used to apply a consistent force through a ¾-in., 16-threaded bolt to the plate that covers 5.08 cm (2 in.) of one end of the specimen. On the other end of the specimen, an adjustable height laser-displacement measuring assembly is mounted perpendicular to the specimen to adjust the input signal from the laser, apply a pre-load or displacement to the end of the specimen, and serve as a mount for the triggering mechanism. A primary displacement screw is first used to position the height of the laser and triggering mechanism relative to the neutral specimen position (no-load). A secondary displacement screw applies an initial displacement relative to the specimen's initial no-load neutral position. Displacement in this position minus the neutral displacement is recorded as the initial deflection. Displacement is applied by the triggering mechanism, which is engaged by a spring pin. When the operator retracts the spring pin, a torsion spring causes the trigger to rapidly rotate away from the specimen, allowing the beam to enter free vibration. The result is vibration in only the first mode. Some damping occurs during the release of the trigger during the first cycle of vibration, resulting in lower amplitude than the initial deflection. The laser measures displacement of the beam tip as a function of time.

The CBV software controls sampling rate and total sample count and can be adjusted during each calibration. This allows the operator to adjust the collection parameters for each sample and when necessary to readjust the settings based on initial results. If, for example, the specimen dampens quickly within the total sample count, then the count should be reduced to eliminate non-free vibration data that may then result in an erroneous calculated frequency. The sampling rate is in counts per second, so the total sampling time in seconds can be determined by dividing the total count by the sampling rate. The operator may also choose to increase or decrease the sampling rate based upon the initial detected frequency and the desired number of samples per waveform. Defaults for sampling rate and count are 1,000 and 3,000, respectively. These parameters provide good data for typical fiberboards vibrating at or below 40 hertz, yielding at least 25 sample points per waveform (Fig. 3). Once the triggering routine in the software detects an upward deflection, it assumes the trigger has been released and data acquisition begins.

The next step in the data analysis is determination of the frequency of vibration. The software uses fast Fourier transformation algorithm with input data. A data sampling rate approximately 25 times the vibrational frequency provides sufficient characterization of the vibration for the fast Fourier transformation algorithm to extract a single frequency.

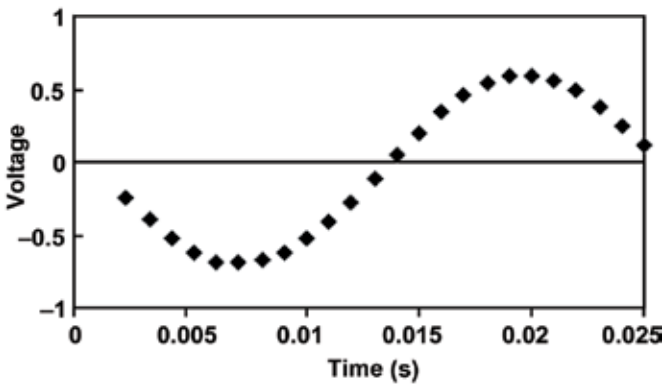

Figure 3—Data acquisition of approximately 25 data points per wave form yields good representation of the vibrational beam response.

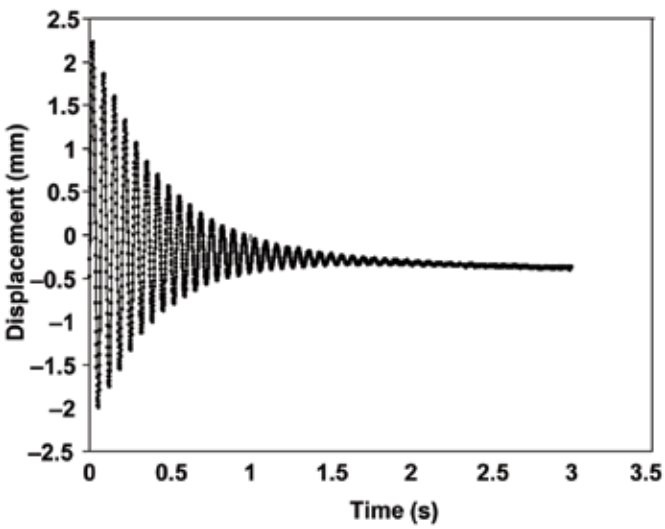

Figure 4—A typical specimen free vibration response.

Noise in the signal should be automatically disregarded, provided it has lower amplitude for the majority of the sampling time. If the operator designates a count and rate that result in a large number of data points beyond the final damping of the specimen vibration, erroneous values can be produced because at lower amplitudes electronic noise can be higher than the "at-rest" amplitude. In these circumstances, the detected frequency is typically around 800 or 900 Hz, well beyond reasonable vibration rates for specimens in the size range associated with the CBV.

After detecting vibration frequency, the program has all the necessary information needed to determine the theoretical bulk modulus of elasticity. Bulk modulus is determined according to the generally accepted theory of prismatic beam vibration, as presented by Timoshenko (Equation (2)).

Testing Procedure

The specimen's mass (M), total length (L), width (b), and thickness (t) are measured and input into the software. The specimen is then inserted 50.8 mm into the grip mechanism and centered with a special plate. The 50.8-mm grip length is subtracted from L to obtain the free-beam length (l). The specimen is next clamped using a torque wrench to obtain no more than 10% compression deflection applied by the clamp screw or a maximum pressure of approximately 689 kPa (100 lb/in^2), whichever is less. The torque for panels of different densities was determined from an initial calibration curve developed from fiberboard panels of different densities.

An example of a typical specimen (2.11 mm (t) × 50.8 mm (b) × 254 mm (L)) response is shown in Figure 4. A displacement of approximately 9 mm was applied to the unsupported specimen edge, and then the specimen was released into free vibration. The resulting displacement over time is recorded. The slight downward drift in the curve is due to a small amount of creep caused by gravity of the thin-cantilevered fiberboard specimen. This small amount of creep does not interfere with frequency determination. For the sample fiberboard shown in Figure 4, collecting data beyond 1.5 to 2.0 s results in the signal-to-noise ratio getting sufficiently small that errors would be introduced in the calculation of frequency. We suggest reprogramming the data acquisition to record only the first 1.5 s.

The CBV software then uses the frequency value in Equation (2) along with the physical characteristics of the specimen (M, L, b, t, l) to determine dynamic modulus of elasticity. Moslemi (1967) showed that dynamic modulus of elasticity corresponds well with static bending modulus of elasticity.

Repeatability

To verify the repeatability and nondestructive nature of the testing procedure, a random specimen was loaded and tested 10 consecutive times without removing it from the specimen grip or re-adjusting the positioning screws. The results show excellent repeatability, with a maximum variation in recorded frequency of 0.01 Hz (Table 1). Similar observations were made with other samples evaluated multiple times. We believe the repeatable response is specifically related to always starting at the same initial displacement before release into the beam's free vibration.

Whereas the device is repeatable within a particular test set-up, variations in dynamic modulus may occur if the beam is slightly curved or warped or has a through-thickness non-symmetrical heterogeneity. These may also include variations in material properties along the length of the specimen. Thus, it is important to test and compare a subset of specimens by flipping specimens over top-to-bottom or, if possible, end-to-end, resulting in four tests per specimen. If the resulting variation in the subset is small, only one direct test would be needed.

Further Work on the CBV Apparatus

Because the CBV apparatus is designed to first apply a known initial static displacement and then measure

Table 1. Repeated testing results for a single specimen without repositioning

Specimen ID	Dynamic MOE (GPa)	Deflection (mm)	Frequency (Hz)
104T2	3.65	9.08	11.24
104T2	3.65	9.19	11.24
104T2	3.65	9.17	11.24
104T2	3.65	9.2	11.24
104T2	3.65	9.23	11.24
104T2	3.64	9.2	11.23
104T2	3.64	9.21	11.23
104T2	3.65	9.22	11.23
104T2	3.65	9.2	11.23
104T2	3.65	9.22	11.23

displacement compared with time of the free vibration and not just vibrations, it is also possible then to determine the following:

1. Log decrement, storage modulus of elasticity, and loss modulus of elasticity. These are related to the decrease in amplitude as the beam vibrates (Cai and others 1997, Moslemi 1967).
2. How to redesign the apparatus slightly so a load cell could be used to measure static load compared with static displacement just prior to release of the beam into free vibration. This could be used to determine static bending modulus of elasticity of a cantilever beam compared with dynamic modulus of elasticity of the same cantilever beam.
3. Strain rate of the beam as a function of frequency and amplitude. Because data collected are direct displacement measurements of the free end of the beam and not just frequency attenuation, it is possible to calculate strain rate based on these displacement data. The dynamic modulus strain rate is significantly faster than traditional static bending tests and does influence bending response.

A transverse vibration test based upon the CBV apparatus could be adapted to fit the quality control needs of fiberboard or wood composite manufacturers or other laboratories. Because of the fast and repeatable dynamic testing on the CBV apparatus, it is well suited for adaptation to manufacturing environments. Extension of the log decrement analysis and coupling to the dynamic modulus information could provide a means to assess and analyze critical performance factors such as the creep behavior and rate of the vibration damping after initial deflection is released. Such test information is not available from traditional tests including static testing. Dynamic testing may also have applications determining performance characteristics for products that are subjected to high load rates, such as packaging, shock absorbers, or impact-resistant products. Further research in this area could use this type of displacement compared with time data information.

In the next paper, *Cantilever-Beam Dynamic Modulus for Wood Composite Products: Part II Dynamic Moduli vs. Bending Moduli*, specific transverse vibrational information will be presented and discussed for thin fiberboard sheet material.

Summary

The cantilever beam vibration apparatus provides a quick non-contact method to measure end displacement of a fiberboard composite beam. The apparatus applies a known displacement to the beam before it is released to free vibration. The testing is non-destructive and highly repeatable in determining dynamic modulus of elasticity. Software has been developed that rapidly and successfully processes the test data.

Further development of this apparatus will provide improved analysis methods for thin composite materials or products that may be subject to high load rates, such as packaging, shock absorbers, or impact-resistant products or may have other performance characteristics that are not characterized by the static bend test.

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