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# Sawtooth Forces in Cutting Tropical Hardwoods Native to South America

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**Iris Vazquez Cooz**

# Abstract

As a result of design, operation, and maintenance, sawblades used in tropical sawmills can cause many problems. Improvements in these areas are needed to reduce the waste associated with sawing of tropical species that are regarded as difficult to cut. In this study, cutting experiments that simulated bandsawing of tropical hardwoods showed the effect of chip thickness, moisture content, and edge condition on the forces acting on the sawtooth. Forces were measured in three directions: parallel, normal, and lateral to the cut.

Peak principal forces were 1.4 to 2.1 times as large as average forces. Doubling the chip thickness typically increased the principal force by a factor of 1.6. No significant difference existed in the forces for dry wood with a 0.010-in. (0.25-mm) chip or wet wood with a chip twice as thick. The normal force can be reduced by cutting wet wood, especially when using teeth that have some defects. The worst case is cutting dry wood with a thin chip. Large, positive normal forces, tending to repel the tooth, can be an indicator of wear or damage and contribute to wear.

Asymmetry in the tooth caused by mounting, grinding, or damage can result in the generation of a lateral force. The highest lateral forces observed were generated by a tooth with a damaged corner, while cutting dry, high density wood, giving an average lateral force equal to nearly 60% of the principal force for a good tooth. This appears to have implications for sawing accuracy.

Keywords: Tropical hardwoods, cutting force, chip thickness, moisture content, sawing, sawblade

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# Sawtooth Forces in Cutting Tropical Hardwoods Native to South America

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## Introduction

Many difficulties experienced by tropical sawmills originate from the design, operation, and maintenance of the sawblade. Improvements in these areas are needed to reduce the waste associated with sawing of tropical species and allow efficient conversion of abundant but lesser used species, regarded as difficult to cut. The high density of the wood and the occurrence of silica contribute to high cutting forces and wear rates on the sawblade.

Numerous efforts to measure cutting forces are reported in the literature for a variety of wood machining processes, including sawing. In a typical case, the cutting edge was newly sharpened; the wood specimens were dry, uniform in grain, and free of defects; only average forces were reported. Some of that research is noted here, sorted by methodology. We omitted work that focused on power consumption in contrast to cutting forces.

Kivimaa (1950) conducted planing-type experiments with a cutting knife mounted on a rotating spindle. His main interests were cutting force, chip formation, surface quality, and tool life for the woodworking industry. Several researchers have used a pendulum dynamometer to measure energy consumed in making a cut. An average value for the principal cutting force is derived by dividing the amount of energy by the cutting length (Reineke 1950, Chardin 1958, Sugihara and Hoguchi 1962, Sugihara and others 1966). Others measured torque or power on a saw arbor and calculated an average force (Andrews 1955, Pahlitzsch and Rose 1964, Nakamura 1967). Some researchers have found a lathe useful in studying principal (and sometimes normal) cutting forces in relation to high cutting speeds or tool wear (McKenzie 1960, Sugiyama and Matsuo 1981, Wan and others 1987, Stewart 1985, 1987, 1988).

Kirbach and Bonac (1979) measured principal and normal cutting forces with a device that resembled a phonograph. Wood blocks were mounted on a platter that was rotated at high speed while the sawtooth traversed it radially. As part of an effort to model cutting forces, Gronlund (1988) measured forces in the principal, feed, and lateral directions, using a rotating arm to move a wood block past a cutting tool in a 39.4-in.- (1-m-) diameter circle. In follow-up work by Axelsson and others (1991) and Axelsson (1994), wood density and force readings were converted to gray scale images to show the effects of wood features and tooth condition on forces.

Low-speed cutting experiments have proved useful for studying cutting force and chip formation. Woodson and Koch (1970) and Amemiya and others (1981) used linear motion of the tool, and McKenzie (1988, 1991) used circular cutting.

The experiments in the study reported herein provide considerable insight into wood machining processes. Our objective was to extend previous work by measuring forces in three dimensions (e.g., *x, y, z* planes) while cutting tropical hardwoods at several chip thicknesses, both wet and dry. Chip thickness (thickness of the wood chip removed by one pass of the sawtooth) is synonymous with bite or feed per tooth.

## Experimental Procedure

The experiment was designed to simulate wide bandsawing, which predominates in the tropics. We took a tooth from a bandsaw and mounted it on a load cell, which was attached to a positioning device. A linear slide then propelled a small block of wood past the sawtooth in a straight line, at a constant speed of 55 in/s (1.4 m/s) (Fig. 1). This is much slower than an actual cutting speed in sawing, but McKenzie (1960) has shown that cutting force changes little with speed over a wide range.

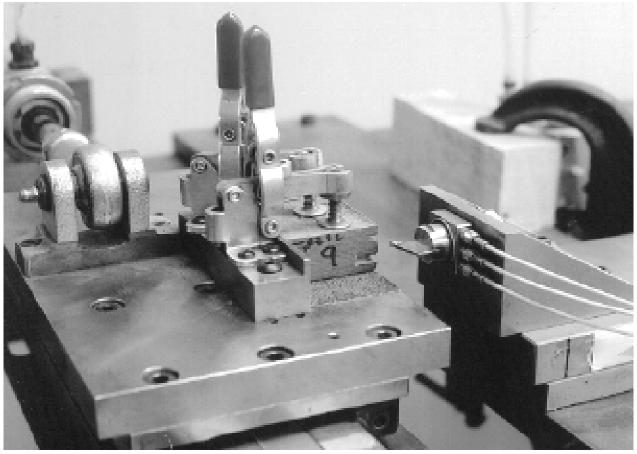

Figure 1—Wood block mounted on linear slide; sawtooth and load cell on the right.

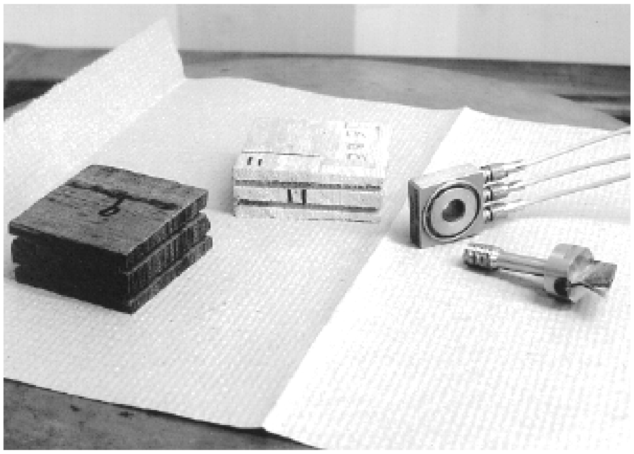

Figure 2—Sawtooth mounted on threaded post; wood blocks showing cutting track.

## Sawteeth

The Universidad Experimental de Guayana, Upata, Venezuela, provided a section of a bandsaw blade with stellite teeth, as described in the following:

5.3-in. (134-mm) band width
0.051-in. (1.30-mm) thickness
1.74-in. (45-mm) pitch
0.55-in. (14-mm) gullet depth
0.1-in. (2.5-mm) tooth width
0.024-in. (0.6-mm) side clearance
22° hook
12° clearance
56° sharpness

Individual teeth were cut off at the bottom of the gullet and mounted in a holder with a threaded stem (Fig. 2). The load cell was clamped underneath the tooth holder and preloaded by tightening the stem to a prescribed torque level. Although the teeth were new, some had broken corners or other damage, presumably from grinding (Fig. 3). This introduced a new experimental variable.

We chose four teeth for our cutting: the two best (teeth 2 and 6) and the two worst (teeth 3 and 7). Our selection was based on a visual and microscopic examination. Dimensions of the defect in tooth 3 (Fig. 3c) were approximately 0.031 in. (0.8 mm) along the top edge (31% of width) and left side, and the defect extended approximately 0.017 in. (0.43 mm) toward the back of the tooth. The chunk missing from tooth 7 measured 0.033 in. (0.84 mm) across the top edge (33% of width) and 0.012 in. (0.30 mm) deep, extending 0.015 in. (0.38 mm) toward the back.

Even the good teeth were somewhat rough along the edge, hence it was difficult to measure edge radius. We estimated approximately 0.0008 to 0.0010 in. (20 to 25 µm) for tooth 6 and 0.0004 to 0.0006 in. (10 to 15 µm) for tooth 2 (Fig. 4). Axelsson (1994) sharpened edges to an 0.0002-in. (5-µm) edge radius and referred to 0.0012 in. (30 µm) as a modest amount of wear. McKenzie and Cowling (1971) referred to a 0.0002-in. (5-µm) radius as blunt, using new edges as sharp as 0.000008 in. (0.2 µm) (tooth material was not specified).

## Test Specimens

We selected 15 species with basic specific gravity (based on ovendry weight and green volume) ranging from 0.48 to 0.91. One species, Chupon, had a silica content of 1%, and the others varied from 0.06% up to 0.56%, based on ash analysis. This analysis converts all siliceous material in the wood to silica ($SiO_2$) and does not report the original form. Some wood specimens were provided by the Institute of Forestry of Latin America (IFLA); others came from the wood collection at the USDA Forest Service, Forest Products Laboratory. For each species, two matching pieces measuring 2 by 2 by 0.75 in. (50.8 by 50.8 by 19 mm) were cut from larger blocks. All wood was initially dry, ranging in moisture content from 6.7% to 9.8% under ambient conditions (Table 1). One piece from each set was cut in this condition, and the matching piece was vacuum soaked and saturated before cutting.

## Data Collection

The light weight and stiffness of our sawtooth/load cell system resulted in a good frequency response. The output was directed to a digital storage oscilloscope, and waveforms could be viewed immediately or copied onto computer floppy diskettes for transfer to a desktop computer. We did not detect any (unwanted) resonance in the load cell response. The number of data points for each direction of measurement approached 1,000/in. (39/mm) over a 2-in. (50.8-mm) length of cut, taken at intervals of 20 µs.

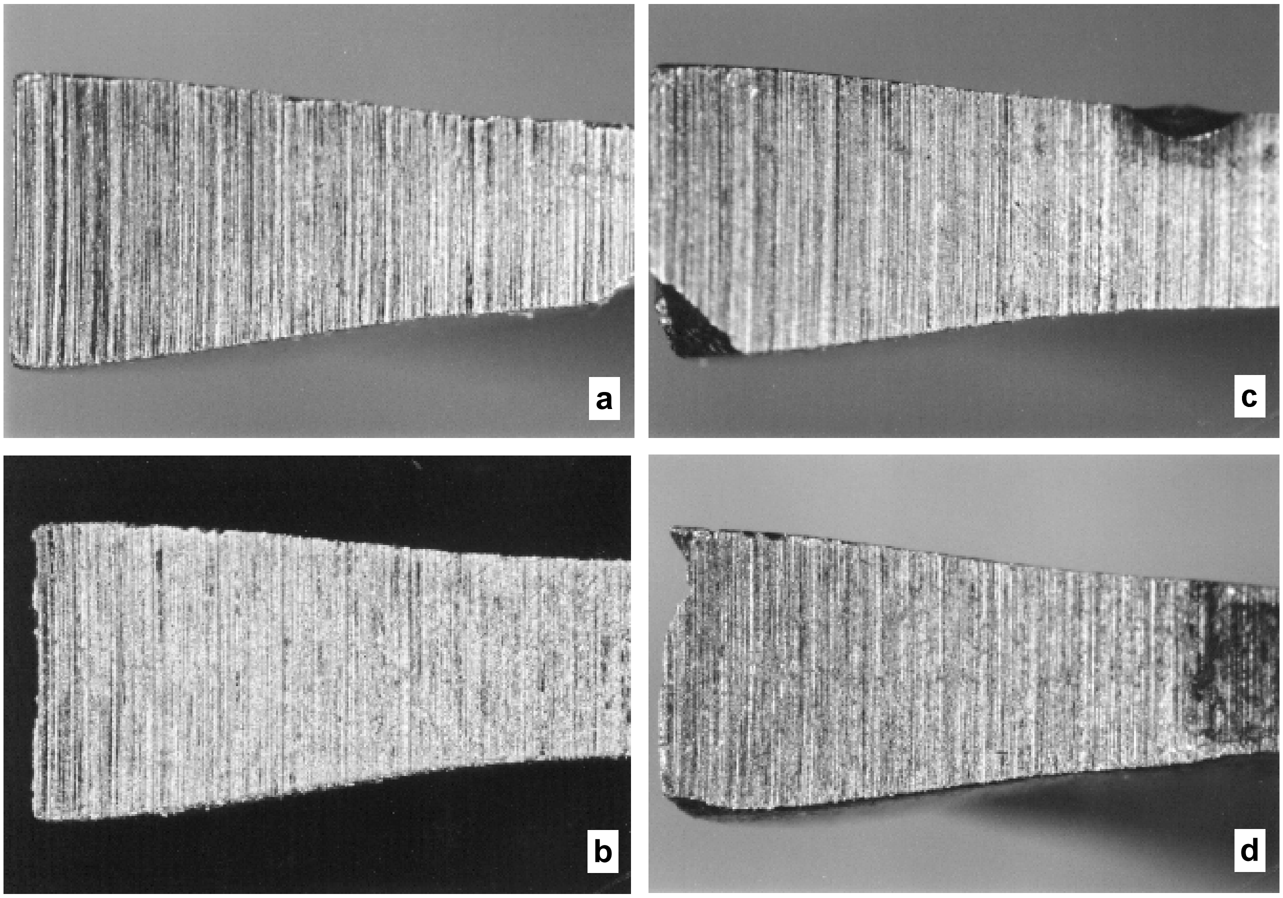

**Figure 3—Four test teeth (30x): (a) Tooth 2 rake face ; (b) Tooth 6 rake face ); (c) Tooth 3 rake face; (d) Tooth 7 rake face.**

Each wood block was cut with the four sawteeth, at each value of chip thickness. We made a minimum of four cuts in the same kerf for a given chip thickness before collecting data. Then, we saved data from a single cut (run) and averaged this with three more successive cuts (avg.); these data provide the basis for much of our discussion.

# Discussion and Results

The power required for sawing is most directly related to the principal cutting force. To many, the term cutting force is synonymous with principal force. It acts parallel to the direction of the tooth and represents the major effort to sever the chip. The normal force measures whether the tooth is being pull into the wood, or repelled by it, and acts parallel to the feed. The lateral force measures if the tooth is being pushed to either side. The normal and lateral forces can offer important insight to the tooth condition and saw operation.

A typical set of force curves generated by a single cut is shown in Figure 5a (tooth 3, Zapatero, wet, 0.010 in. (0.25 mm), run). Each 0.01-s interval is approximately equivalent to 0.50 in. (12.7 mm) length of cut and 500 data points. The principal force is always positive. Each wood species was cut both dry and wet, at chip thicknesses of 0.010 and 0.020 in. (0.25 and 0.50 mm). For tooth 2 only, additional tests were made at a chip thickness of 0.030 in. (0.76 mm).

The overall shape of the waveforms relates to the character of the wood along the length of the cut, while superimposed on it is an irregular, high frequency variation, presumably related to the chip formation process. Previous work has shown that the increase and decrease of the cutting force are related to indentation of the wood and subsequent chip formation (McKenzie 1960, 1971). The average of four successive cuts is presented in Figure 5b.

## Principal Force

### Tooth Effects

In a statistical comparison based on a general linear model, teeth 2 and 3 were always significantly different from each other. When cutting dry wood, the two good teeth (2 and 6)

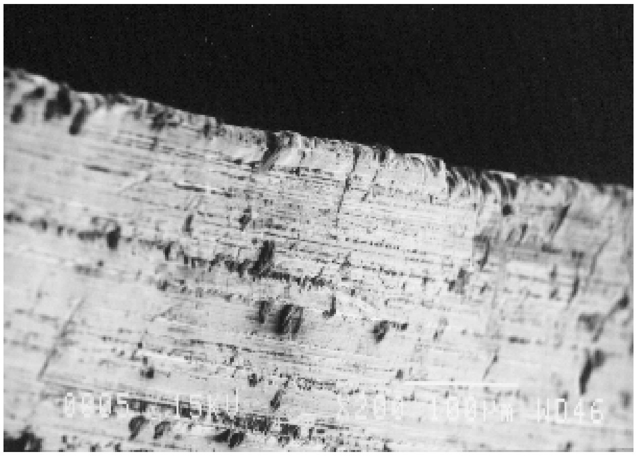

Figure 4—Tooth 2 edge (200x).

Table 1—Moisture and silica content of test specimens

| Species | Basic specific gravity | Dry moisture content (%) | Saturated moisture content (%) | Silica (ash method) (%) |
|---|---|---|---|---|
| Odoum | 0.48 | 7.7 | 108.5 | 0.57 |
| Palapi | 0.50 | 9.1 | 123.5 | 0.06 |
| Jebe | 0.53 | 9.8 | 117.5 | 0.25 |
| Pardillo | 0.57 | 9.2 | 87.0 | — |
| Merecure | 0.63 | 9.5 | 84.7 | 0.43 |
| Chupon | 0.67 | 9.1 | 81.1 | 1.01 |
| Perhuetamo | 0.73 | 9.2 | 67.7 | 0.49 |
| Grapia | 0.75 | 7.2 | 39.1 | 0.53 |
| Zapatero | 0.77 | 8.6 | 75.6 | 0.39 |
| Guacharaco rojo | 0.78 | 9.3 | 47.6 | 0.17 |
| Parajuba | 0.79 | 8.4 | 56.6 | 0.56 |
| Purguuo | 0.82 | 9.2 | 48.1 | 0.31 |
| Mora de Guayana | 0.87 | 8,5 | 35.3 | 0.51 |
| Puy | 0.88 | 7.3 | 34.4 | 0.27 |
| Ipe | 0.91 | 6.7 | 33.7 | 0.34 |

appeared similar, and the same was true of the two bad teeth (3 and 7). However, for saturated (hereafter called wet) wood, all teeth were significantly different.

Tooth 2 was visually our best tooth and most often generated the lowest average principal forces of all four teeth tested. Tooth 3, our worst tooth visually (broken corner), generated the highest average forces, exceeding tooth 2 by an average of 33% to 40%. The forces produced using teeth 6 and 7 were intermediate to these. Figure 6 shows the average force for species tested at four different conditions. Table 2 presents the average principal force levels generated by all four teeth at each test condition.

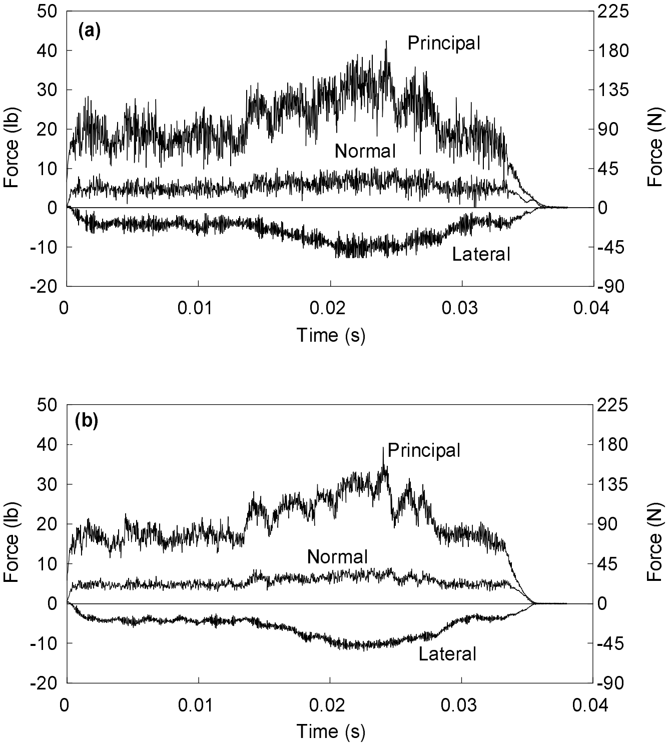

Figure 5—Cutting forces for Zapatero, wet, using tooth 3 and chip thickness of 0.010 in. (0.25 mm): (a) single cut, (b) average of four successive cuts.

## Peak Forces

Chardin (1977) stated that the peak values for the principal cutting force could be five times as large as the average, and peak forces can have significant impact on wear. We estimated peak forces from arbitrary single cuts for each species using teeth 2 and 3. These values are shown in Figure 7 along with the averages for the same cuts, for wet wood at 0.020-in. (0.50-mm) chip. For all test conditions and species, the ratio of peak to average force was within the range of 1.4 to 2.1. Although peak forces were somewhat greater with a bad tooth, the average forces were too, resulting in the ratio remaining similar.

The largest peak principal force observed was approximately 115 lb (512 N), cutting dry Mora de Guayna with tooth 3 and a 0.020-in. (0.50-mm) chip; the average in this case was 57 lb (254 N).

## Basic Specific Gravity

As basic specific gravity increases, the principal force tends to increase from an overall perspective, but there are exceptions on a point-to-point basis. In our study, there was no statistically significant relationship between the two. For the lower density range, the curves were almost flat (Figs. 6 or 7). The effect of mechanical properties, or fiber

**Table 2a—Average principal force in pounds**

| | Average principal force (lb)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.40 | Palapi 0.50 | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perhuetamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guacharaco 0.78 | Parajuba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 8.3 | 16.0 | 14.6 | | 12.9 | 14.5 | 22.2 | 21.2 | 24.2 | 20.9 | 27.4 | 23.0 | 23.4 | 28.2 | 25.6 |
| 3 | 12.4 | 21.1 | 19.6 | 18.5 | 21.2 | 26.4 | 29.6 | 27.5 | 26.1 | 21.6 | 36.9 | 35.6 | 33.1 | 38.8 | 36.5 |
| 6 | 9.9 | 18.3 | 16.2 | 15.2 | 18.3 | | 23.8 | 23.5 | 22.6 | 19.0 | 30.6 | 26.2 | | 29.8 | 28.5 |
| 7 | 9.8 | 20.1 | 18.1 | 14.9 | 25.8 | | 29.7 | 27.4 | 24.2 | 25.7 | 35.6 | 33.0 | | 38.2 | 36.8 |
| **Wet, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 7.7 | 10.7 | 11.8 | | 10.1 | 10.0 | 13.2 | 15.7 | 17.2 | 11.9 | 18.4 | 14.2 | 22.4 | 21.9 | 17.7 |
| 3 | 12.6 | 14.2 | 21.1 | 13.7 | 16.3 | 16.9 | 18.9 | 19.6 | 21.8 | 16.1 | 23.9 | 19.9 | 29.2 | 28.6 | 26.5 |
| 6 | 9.0 | 11.3 | 16.4 | 11.5 | 14.2 | | 14.2 | 17.5 | 16.0 | 12.8 | 19.3 | 15.7 | | 23.6 | 21.6 |
| 7 | 10.5 | 12.6 | 16.2 | 16.9 | 15.5 | | 15.8 | 19.9 | 19.9 | 13.8 | 22.1 | 17.4 | | 27.4 | 25.6 |
| **Dry, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | 13.2 | 26.5 | 19.6 | | 22.7 | 25.5 | 36.4 | 32.8 | 39.3 | 35.0 | 45.8 | 38.3 | 38.9 | 43.9 | 38.0 |
| 3 | 17.8 | 33.0 | 28.6 | 28.4 | 32.7 | 43.3 | 43.9 | 41.1 | 45.2 | 40.1 | 55.5 | 54.5 | 57.6 | 55.6 | 54.6 |
| 6 | 15.1 | 29.2 | 27.8 | 24.4 | 28.0 | | 37.6 | 36.2 | 36.3 | 33.6 | 49.2 | 43.0 | | 42.9 | 41.1 |
| 7 | 18.0 | 29.9 | 29.8 | 21.9 | 33.6 | | 42.5 | 37.8 | 42.8 | 40.4 | 51.4 | 45.5 | | 51.0 | 49.7 |
| **Wet, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | 13.5 | 16.2 | 19.0 | | 16.1 | 16.5 | 20.6 | 26.2 | 25.0 | 18.0 | 28.4 | 23.1 | 39.4 | 34.5 | 30.8 |
| 3 | 18.7 | 21.1 | 27.8 | 20.9 | 24.0 | 24.8 | 28.2 | 30.1 | 34.5 | 23.1 | 36.2 | 31.0 | 43.8 | 42.3 | 41.0 |
| 6 | 14.3 | 17.4 | 22.1 | 18.3 | 21.2 | | 21.9 | 27.5 | 25.0 | 18.4 | 28.8 | 26.7 | | 35.8 | 33.7 |
| 7 | 15.7 | 18.0 | 22.8 | 25.3 | 22.6 | | 23.0 | 30.7 | 28.5 | 19.6 | 32.4 | 25.3 | | 39.3 | 36.6 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

**Table 2b—Average principal force in newtons**

| | Average principal force (N)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.48 | Palapi 0.50 | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perhuetamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guacharaco 0.78 | Parajuba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 36.7 | 71.1 | 64.8 | 0.0 | 57.6 | 64.3 | 98.6 | 94.5 | 107.5 | 93.2 | 121.7 | 102.3 | 103.9 | 125.2 | 113.9 |
| 3 | 55.0 | 94.0 | 87.3 | 82.5 | 94.5 | 117.5 | 131.5 | 122.1 | 116.1 | 96.0 | 164.1 | 158.3 | 147.2 | 172.5 | 162.5 |
| 6 | 44.3 | 81.4 | 72.0 | 67.7 | 81.3 | 0.0 | 105.8 | 104.7 | 100.4 | 84.4 | 136.2 | 116.6 | 0.0 | 132.6 | 126.9 |
| 7 | 43.6 | 89.2 | 80.3 | 66.5 | 114.8 | 0.0 | 132.1 | 122.0 | 107.8 | 114.1 | 158.5 | 146.8 | 0.0 | 170.1 | 163.9 |
| **Wet, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 34.3 | 47.7 | 52.5 | 0.0 | 44.7 | 44.6 | 58.6 | 69.7 | 76.5 | 53.0 | 81.7 | 63.4 | 99.5 | 97.2 | 78.7 |
| 3 | 56.1 | 63.4 | 94.0 | 61.1 | 72.3 | 75.2 | 84.0 | 87.1 | 96.9 | 71.6 | 106.1 | 88.6 | 129.7 | 127.1 | 117.9 |
| 6 | 39.9 | 50.2 | 73.0 | 51.0 | 63.4 | 0.0 | 63.1 | 77.8 | 71.3 | 57.0 | 85.9 | 69.7 | 0.0 | 104.8 | 96.0 |
| 7 | 46.8 | 55.8 | 72.1 | 75.3 | 69.0 | 0.0 | 70.1 | 88.7 | 88.7 | 61.3 | 98.5 | 77.5 | 0.0 | 122.1 | 113.8 |
| **Dry, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | 58.9 | 117.7 | 87.0 | 0.0 | 101.1 | 113.3 | 161.7 | 145.9 | 175.0 | 155.6 | 203.7 | 170.4 | 173.0 | 195.2 | 168.9 |
| 3 | 79.1 | 146.7 | 127.1 | 126.3 | 145.5 | 192.8 | 195.1 | 182.7 | 200.8 | 178.3 | 246.7 | 242.5 | 256.3 | 247.2 | 242.8 |
| 6 | 67.0 | 129.8 | 123.8 | 108.7 | 124.5 | 0.0 | 167.1 | 160.8 | 161.4 | 149.4 | 218.9 | 191.1 | 0.0 | 190.8 | 182.8 |
| 7 | 79.9 | 132.9 | 132.6 | 97.4 | 149.4 | 0.0 | 189.0 | 168.3 | 190.2 | 179.8 | 228.8 | 202.3 | 0.0 | 227.0 | 221.2 |
| **Wet, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | 59.9 | 72.1 | 84.4 | 0.0 | 71.8 | 73.6 | 91.7 | 116.6 | 111.3 | 79.9 | 126.4 | 102.7 | 175.3 | 153.7 | 136.8 |
| 3 | 83.0 | 93.8 | 123.6 | 92.9 | 106.6 | 110.2 | 125.6 | 134.0 | 153.5 | 102.6 | 161.1 | 137.7 | 194.9 | 188.1 | 182.3 |
| 6 | 63.5 | 77.2 | 98.4 | 81.2 | 94.1 | 0.0 | 97.3 | 122.3 | 111.4 | 81.7 | 128.2 | 118.8 | 0.0 | 159.4 | 149.8 |
| 7 | 69.7 | 80.2 | 101.3 | 112.5 | 100.7 | 0.0 | 102.3 | 136.5 | 127.0 | 87.3 | 144.1 | 112.5 | 0.0 | 174.9 | 162.7 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

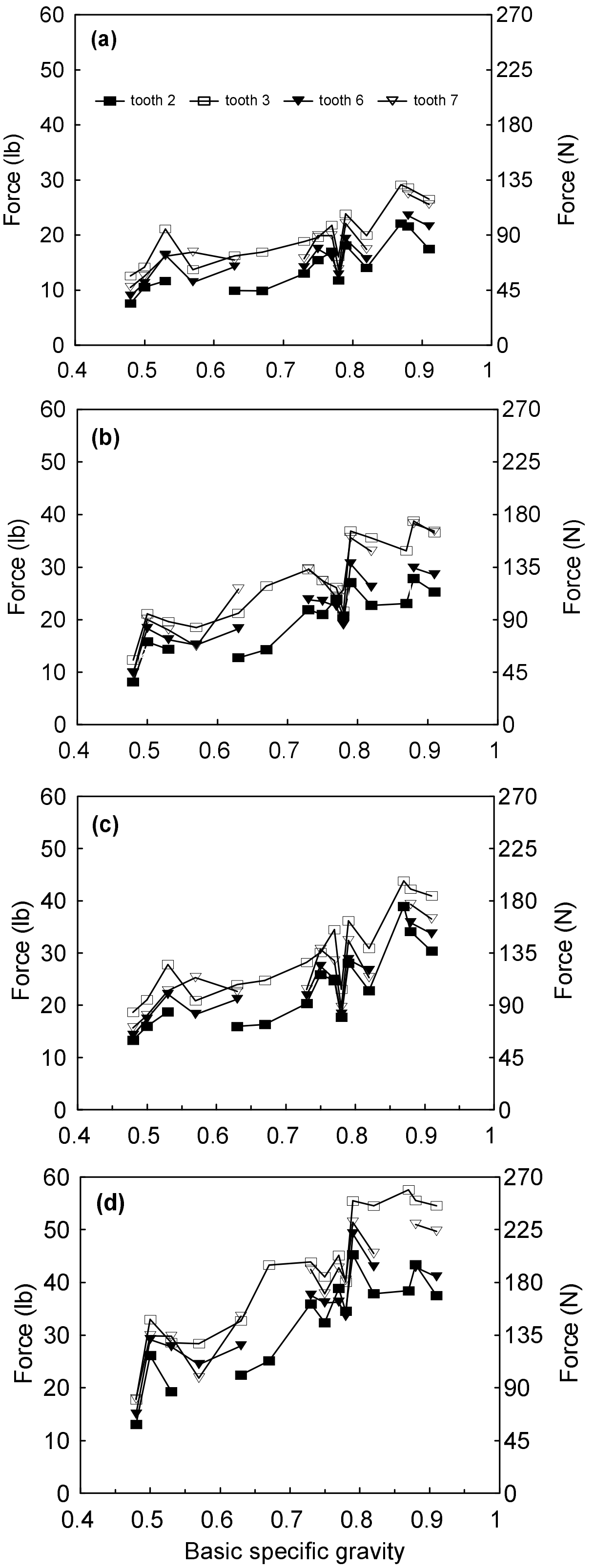

**Figure 6—Average principal cutting forces for species tested at four different conditions: (a) wet, 0.010-in. (0.25-mm) chip, (b) dry, 0.010-in. (0.25-mm) chip, (c) wet, 0.020-in. (0.50-mm) chip, (d) dry, 0.020-in. (0.50-mm) chip.**

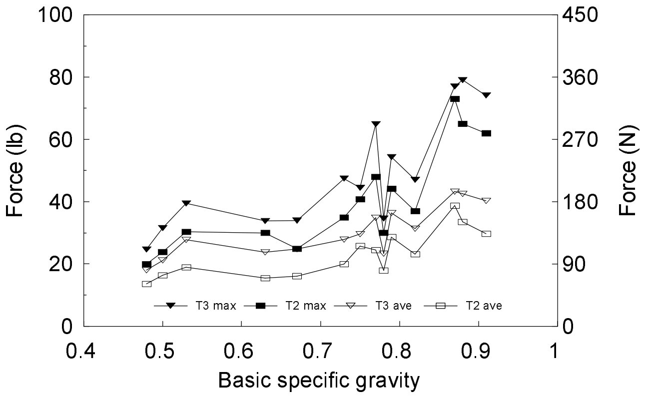

**Figure 7—Maximum and average forces for wet wood, 0.020-in. (0.50-mm) chip.**

characteristics, may explain the difference between observations and expectations based on specific gravity. Chardin (1958) said this difference could be 25%, more or less.

## Chip Thickness

A clear and statistically significant difference existed between the force levels generated at different chip thicknesses. Tooth 2 cut three chip levels, and the results are presented in Figure 8 for wet wood; results were similar for dry wood. When the chip thickness doubled from 0.010 to 0.020 in. (0.25 to 0.50 mm), the force increased by an average factor of 1.6. When the chip thickness tripled, the factor of increase was 2.2. These numbers apply to both wet and dry wood. For a bad tooth, the effect of chip thickness depended on how much of the defect was engaged by the wood. For the other good tooth (number 6), the force ratio for doubling of the chip thickness was approximately 1.55 overall. Expressing this in a mathematical relationship gives

$$\frac{F_2}{F_1} = \left[\frac{\text{chip}_2}{\text{chip}_1}\right]^n$$

where $F_1$ is the force needed to cut chip thickness 1 ($\text{chip}_1$); $F_2$ is force needed to cut chip thickness 2 ($\text{chip}_2$); $n$ is a value ranging from 0.63 to 0.68 for the cases presented here. Kivimaa (1950) showed that doubling the chip thickness caused the main cutting force to increase by a factor of approximately 1.6, which agrees well with our results.

There were a significant number of cases, for both dry and wet wood, where the principal force for a 0.020-in. (0.50-mm) chip using tooth 2 was not much greater than for a 0.010-in. (0.25-mm) chip using tooth 3.

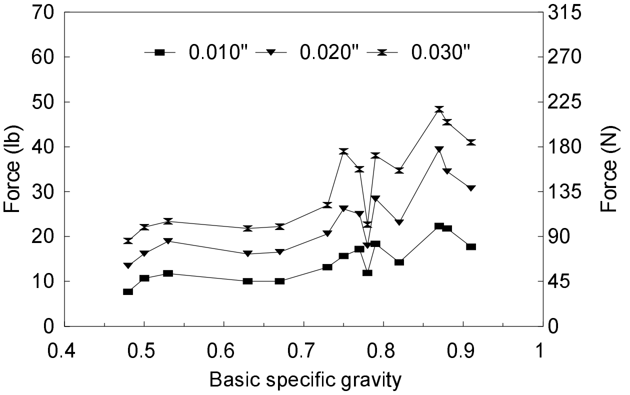

Figure 8—Principal force for tooth 2 cutting wet wood.

### Moisture Content

It is not unusual for tropical hardwoods to be sawn in a partially dry condition. Our results for dry and wet wood were significantly different in the statistical sense for a given chip thickness. Cutting dry wood usually requires more force, up to twice that of wet wood. However, cutting dry wood with a 0.010-in. (0.25-mm) chip and wet wood with a 0.020-in. (0.50-mm) chip appeared to be similar. Figure 9 shows the ratio of forces for dry compared with wet wood; one data point appears to be questionable. Chardin (1954) suggested that the force is decreased when cutting wood with a high moisture content, but not so for high density woods. Our results indicated that even high density woods required less force when wet, although the effect of moisture content appears to be species dependent. Others have studied the effect of different moisture content levels when cutting a single species (Kivimmaa 1950). The main significance of moisture content may be its effect on chip formation and tooth wear.

### Outcome

Peak forces (teeth 2 and 3) were 1.4 to 2.1 times as large as average forces. Doubling the chip thickness typically increased the force by a factor of 1.6. No significant difference existed in the forces for dry wood with a 0.010-in. (0.25-mm) chip and wet wood with a chip twice as thick.

## Normal Force

Normal force measures whether the tooth is being pulled into the wood, or repelled by it, and it acts parallel to the feed. Its direction is very sensitive to tooth sharpness, rake and clearance angles, and chip thickness.

In our measurement system, when the tooth was repelled by wood, the normal force was positive (+); when engaged by the wood, the normal force was negative (–).

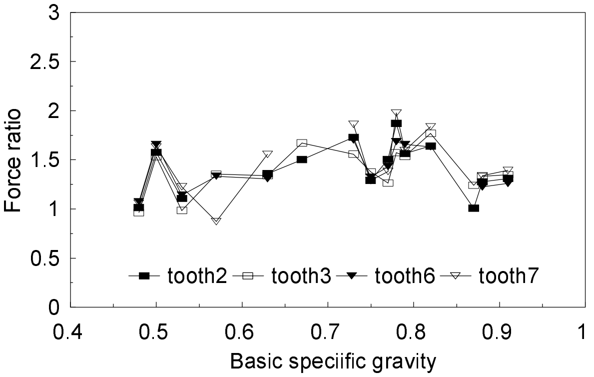

Figure 9—Ratio of principal forces for dry compared with wet wood, for combined chip thicknesses.

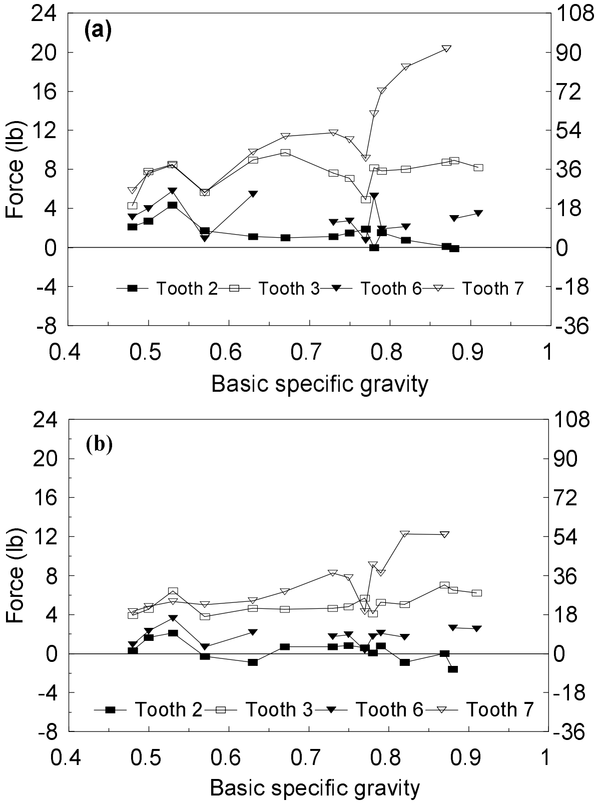

Figure 10—Normal cutting forces: (a) dry wood, 0.010-in. (0.25-mm) chip, (b) wet wood, 0.010-in. (0.25-mm) chip.

### Tooth Effects

For a chip thickness of 0.010 in. (0.25 mm), all the teeth were significantly different in the statistical sense, based on a general linear model, but at 0.020 in. (0.50 mm), the two good teeth (2 and 6) appeared to be similar, and the two bad teeth (3 and 7) appeared to be similar. Teeth 3 and 7 tended to be repelled by the wood (+ normal force), and these were the teeth with the largest defects. Figure 10 displays the normal forces for the two conditions that define the range of response.

Regardless of moisture content, the normal force tended to be positive for a 0.010-in. (0.25-mm) chip (Table 3). The chip formed with this shallow penetration of the knife had little integrity and did not generate any force on the rake face to offset forces acting on the clearance face tending to repel the tooth. Even for the 0.020-in. (0.50-mm) chip, only the good teeth had a negative normal force and only for basic specific gravity in the upper half of the range. In this case, there was sufficient penetration and the (incised but unsevered) chip had sufficient integrity to generate forces on the rake face tending to pull the tooth into the wood. In contrast, a dull tooth must be well indented into the wood before it will cut, because dulling reduces the clearance angle at the tip. This increases the surface area in contact with the wood on the clearance face, hence the force tends to repel the tooth.

The largest average values of normal force were generated by tooth 7, up to 20 lb (89 N) (Ipe, dry, 0.010 in. (0.25 mm)). This was no surprise because this tooth was the most damaged on the clearance face. With the thinner chip, the normal force was typically 40% the magnitude of the principal force; for the thicker chip, it was typically 20%. Tooth 3 was similar to tooth 7 for basic specific gravity less than 0.7; it generated normal forces ranging from 13% to 30% of the magnitude of the principal force. We did not make a calculation for the good teeth because of the variation in sign from positive to negative, indicating directional change from positive to (more favorable) negative.

### Range

Normal force is subject to fluctuations in the course of a single cut, even when the average value is close to zero. For example, the average normal force generated by tooth 2 for wet wood at a 0.010-in. (0.25-mm) chip never exceeded ±2 lb (±8.9 N); for dry wood at chip 0.020 in. (0.50 mm), it was within ±4.5 lb (±20 N). However, in a single cut for the same specimens, normal force had appreciable excursions, roughly symmetric about zero, especially for higher density wood (Fig. 11). For a bad tooth (3), the entire envelope shifted toward the positive side. For dry wood with the thicker chip, the excursions were twice as large, exceeding 30 lb (133 N) at the highest wood density. McKenzie (1960) reported oscillation in the normal force when cutting dry wood, compared with steady forces in saturated wood.

### Chip Thickness, Moisture Content, Species

No consistent, statistically significant relationship among the variables of chip thickness, moisture content, basic specific gravity, and normal force was found in this study. For tooth 2, the normal force appeared to increase with moisture content less than it did at a basic specific gravity of 0.7 and not be affected by chip thickness. Above a basic specific gravity of 0.7, chip thickness seemed to have a larger influence on normal force than did moisture content. As the chip increased, normal force became more negative (tooth is engaged by wood) (Fig. 12). Stewart (1991) stated that high normal forces (positive in our case) indicate scraping rather than cutting, and this may have applied to tooth 7 for dry wood (Fig. 10), at least for the damaged part of the tooth. He also stated that the normal force is generally more sensitive to wear than is the principal force.

### Outcome

Normal force can be reduced by cutting wet wood, especially when using teeth that have some defects. The worst case is cutting dry wood with a thin chip. Large, positive normal forces, tending to repel the tooth, can be an indicator of wear or damage and contribute to wear.

## Lateral Force

The lateral force is the sum of the forces acting on both sides of the sawtooth. A sawtooth with perfect symmetry, cutting a uniform work piece, would presumably have a net lateral force of zero. However, these conditions are rarely met, due to some combination of tooth asymmetry, chip formation, and wood properties. For example, knots in spruce can generate peak lateral forces that occasionally equal the principal cutting force in clear wood (St-Laurent 1971). Density gradients also generate lateral forces (Axelsson 1994). Lateral force can have a negative effect on sawing accuracy to the degree that it influences deflection of the tooth or blade (St-Laurent 1970, 1971).

### Tooth Effects

Tooth 2 generated a very small average lateral force for all species and all test conditions, being within ±1.3 lb (±5.8 N) (Fig. 13a). Tooth 3 generated the largest lateral forces, and the worst case averaged nearly 18 lb for three high density species, cut dry at a 0.020-in. (0.50-mm) chip. For all test conditions, tooth 3 generated lateral forces averaging 35% to 40% of the principal force (of a good tooth), and in some cases, 60% (Table 4). These values are somewhat greater than those reported by St-Laurent (1970) in his experiments on spruce, pine, and birch. He measured lateral forces (for a damaged tooth) that ranged up to 30% of the principal force for a normal tooth.

Teeth 6 and 7 produced large average lateral forces, similar in magnitude to each other but opposite in sign and of a lesser magnitude than tooth 3. At first glance, the graphs for these teeth look somewhat like mirror images (Fig. 13b); statistically, they are not significantly different.

The sign of the lateral force (+ or –) is determined by the direction of the force, as viewed from the face of the tooth. For example, the average lateral forces for tooth 3 (broken left corner) were negative, acting on the left side of the tooth.

**Table 3a—Average normal force in pounds**

| | Average normal force (lb)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.40 | Palapi 0.50 | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perhuetamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guacharaco 0.78 | Parajuba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 2.1 | 2.7 | 4.4 | | 1.7 | 1.1 | 1.0 | 1.1 | 1.5 | 1.9 | 0.0 | 1.5 | 0.8 | 0.1 | –0.1 |
| 3 | 4.3 | 7.8 | 8.5 | 5.7 | 9.0 | 9.7 | 7.6 | 7.1 | 4.9 | 8.2 | 7.9 | 8.0 | 8.7 | 8.9 | 8.2 |
| 6 | 3.1 | 4.0 | 5.8 | 0.9 | 5.5 | | 2.6 | 2.7 | 0.7 | 5.3 | 1.9 | 2.1 | | 3.0 | 3.5 |
| 7 | 5.9 | 7.7 | 8.6 | 5.7 | 9.9 | | 11.5 | 11.9 | 11.2 | 9.3 | 13.9 | 16.2 | | 18.7 | 20.6 |
| **Wet, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 0.3 | 1.7 | 2.1 | | –0.3 | –0.9 | 0.7 | 0.7 | 0.8 | 0.6 | 0.1 | 0.8 | –0.9 | 0.0 | –1.6 |
| 3 | 3.9 | 4.6 | 6.4 | 3.8 | 4.7 | 4.6 | 4.7 | 4.8 | 5.7 | 4.1 | 5.3 | 5.1 | 7.1 | 6.5 | 6.2 |
| 6 | 0.9 | 2.3 | 3.6 | 0.7 | 2.2 | | 1.8 | 1.9 | 0.4 | 1.8 | 2.1 | 1.7 | | 2.6 | 2.6 |
| 7 | 4.4 | 4.9 | 5.4 | 5.1 | 5.5 | | 6.4 | 8.4 | 7.9 | 4.4 | 9.2 | 8.4 | | 12.4 | 12.3 |
| **Dry, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | 2.1 | 1.6 | 4.1 | | 1.5 | 0.6 | –1.1 | –1.0 | –1.1 | 0.8 | –4.4 | –1.7 | –3.0 | –4.2 | –3.5 |
| 3 | 5.0 | 8.0 | 9.2 | 4.8 | 9.6 | 11.1 | 7.1 | 6.3 | 8.2 | 9.1 | 6.0 | 7.8 | 6.4 | 6.9 | 5.7 |
| 6 | 3.1 | 3.6 | 6.1 | –0.7 | 4.7 | | 0.3 | 0.0 | –1.2 | 4.5 | –2.6 | –1.6 | | –1.4 | 0.1 |
| 7 | 7.4 | 6.2 | 9.8 | 4.4 | 9.0 | | 8.0 | 8.1 | 7.3 | 6.9 | 8.9 | 12.5 | | 13.3 | 15.4 |
| **Wet, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | –0.6 | 0.2 | 1.4 | | –1.3 | –2.6 | –1.1 | –1.5 | –1.2 | –1.1 | –2.8 | –1.6 | –4.4 | –3.6 | –5.0 |
| 3 | 3.3 | 3.6 | 6.0 | 2.1 | 4.3 | 3.6 | 3.4 | 3.1 | 4.0 | 3.0 | 3.5 | 3.9 | 3.8 | 4.7 | 4.6 |
| 6 | 0.3 | 0.7 | 2.2 | –0.9 | 1.1 | | –0.2 | –0.5 | –1.8 | 0.1 | –0.9 | –1.8 | | –1.4 | –0.9 |
| 7 | 3.5 | 3.5 | 4.6 | 3.8 | 4.3 | | 4.9 | 5.7 | 5.3 | 3.0 | 6.5 | 6.8 | | 8.5 | 9.4 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

**Table 3b—Average normal force in newtons**

| | Average normal force (N)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.48 | Palapi 0.50. | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perthuetamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guacharaco 0.78 | Parajuba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 9.5 | 12.0 | 19.4 | 0.0 | 7.7 | 5.0 | 4.5 | 5.0 | 6.7 | 8.4 | 0.0 | 6.8 | 3.4 | 0.5 | -0.5 |
| 3 | 19.1 | 34.7 | 37.8 | 25.2 | 39.9 | 43.3 | 34.0 | 31.5 | 21.8 | 36.4 | 34.9 | 35.7 | 38.9 | 39.6 | 36.5 |
| 6 | 13.9 | 17.8 | 25.8 | 4.1 | 24.4 | 0.0 | 11.5 | 12.2 | 3.3 | 23.5 | 8.5 | 9.5 | 0.0 | 13.3 | 15.6 |
| 7 | 26.2 | 34.1 | 38.1 | 25.3 | 44.1 | 0.0 | 51.2 | 52.9 | 49.8 | 41.2 | 61.7 | 72.2 | 0.0 | 83.2 | 91.6 |
| **Wet, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 1.5 | 7.4 | 9.5 | 0.0 | -1.3 | -3.8 | 3.2 | 3.2 | 3.8 | 2.8 | 0.4 | 3.7 | -3.9 | 0.1 | -7.0 |
| 3 | 17.5 | 20.3 | 28.6 | 17.0 | 20.8 | 20.3 | 20.7 | 21.5 | 25.4 | 18.2 | 23.6 | 22.5 | 31.4 | 29.0 | 27.8 |
| 6 | 4.2 | 10.3 | 16.2 | 3.1 | 9.8 | 0.0 | 7.9 | 8.6 | 1.6 | 7.9 | 9.4 | 7.6 | 0.0 | 11.8 | 11.4 |
| 7 | 19.5 | 21.8 | 24.1 | 22.6 | 24.5 | 0.0 | 28.6 | 37.3 | 35.2 | 19.4 | 41.0 | 37.2 | 0.0 | 55.2 | 54.9 |
| **Dry, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | 9.5 | 7.0 | 18.4 | 0.0 | 6.7 | 2.8 | -4.9 | -4.7 | -5.0 | 3.5 | -19.5 | -7.7 | -13.2 | -18.6 | -15.8 |
| 3 | 22.1 | 35.7 | 40.7 | 21.6 | 42.8 | 49.2 | 31.5 | 28.1 | 36.7 | 40.6 | 26.6 | 34.7 | 28.6 | 30.7 | 25.3 |
| 6 | 13.6 | 16.2 | 27.2 | -3.2 | 20.7 | 0.0 | 1.1 | 0.1 | -5.4 | 20.1 | -11.7 | -7.2 | 0.0 | -6.1 | 0.3 |
| 7 | 33.0 | 27.4 | 43.4 | 19.7 | 40.1 | 0.0 | 35.7 | 36.2 | 32.4 | 30.7 | 39.7 | 55.8 | 0.0 | 59.1 | 68.4 |
| **Wet, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | -2.5 | 1.1 | 6.2 | 0.0 | -5.7 | -11.3 | -5.0 | -6.5 | -5.3 | -5.0 | -12.4 | -6.9 | -19.4 | -16.2 | -22.3 |
| 3 | 14.9 | 16.2 | 26.6 | 9.4 | 19.1 | 15.9 | 15.0 | 14.0 | 17.7 | 13.5 | 15.6 | 17.2 | 17.0 | 20.7 | 20.4 |
| 6 | 1.2 | 2.9 | 9.8 | -4.0 | 4.9 | 0.0 | -0.8 | -2.4 | -7.9 | 0.6 | 4.0 | -7.8 | 0.0 | -6.3 | -4.1 |
| 7 | 15.6 | 15.6 | 20.5 | 16.8 | 19.1 | 0.0 | 21.8 | 25.5 | 23.4 | 13.5 | 28.8 | 30.4 | 0.0 | 37.9 | 41.6 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

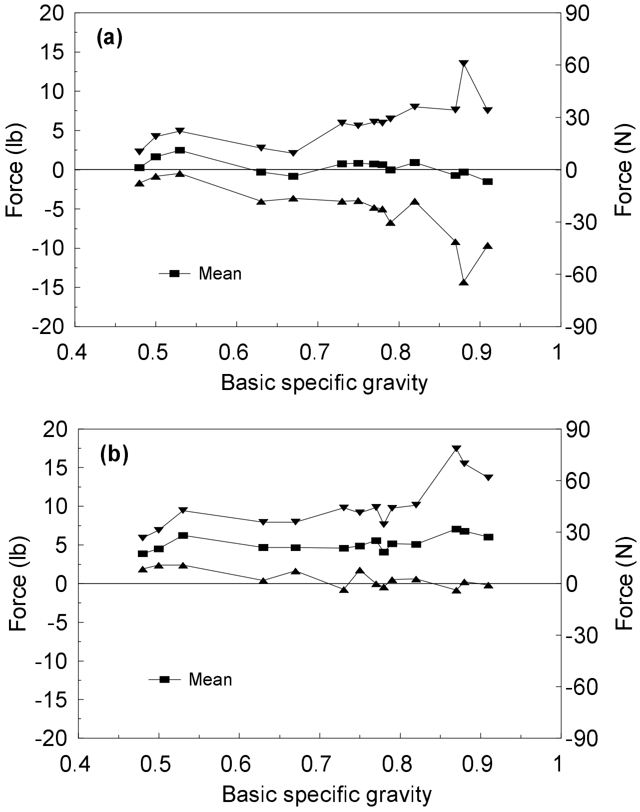

**Figure 11—Normal force range for a single cut in wet wood with a 0.010-in. (0.25-mm) chip: (a) tooth 2, (b) tooth 3.**

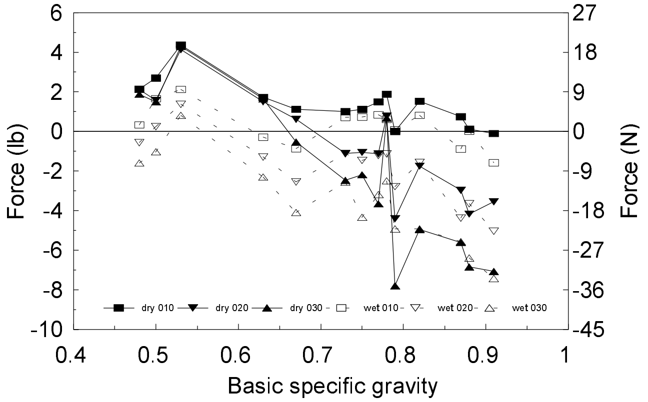

**Figure 12—Tooth 2 normal force, wet and dry wood, at three chip thicknesses.**

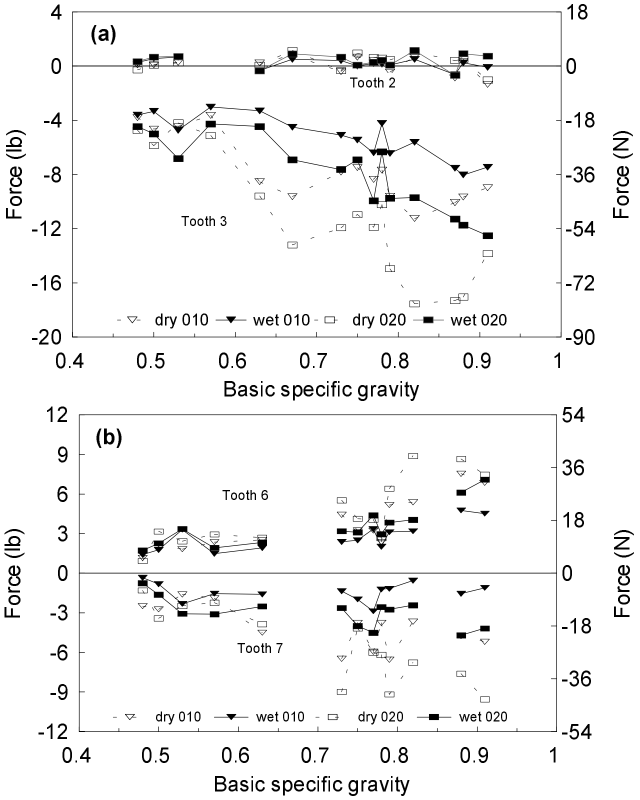

**Figure 13—Lateral forces: (a) teeth 2 and 3 (b) teeth 6 and 7.**

Tooth 7, having a rounded left corner, also had negative lateral forces. Figure 3d shows that this tooth was also chipped along the right side of the cutting edge, but the corner was still intact. Tooth 6 had positive lateral forces and appeared to be slightly rounded on the right corner with reduced side clearance (Fig. 3b).

## Range

Even though the average lateral force can be quite small for a given set of conditions, the range (minimum to maximum) within a single cut can be quite large. The range for tooth 2 (Fig. 14) was roughly symmetric about zero, increasing to ±12 lb (±53 N) above a basic specific gravity of 0.7. The range appeared to be greater for dry wood and to increase with chip thickness. The effect of a bad tooth, such as tooth 3, is to shift the range away from zero (more negative in this case). Axelsson (1994) stated that the fluctuation of the lateral force increases with wear, even though the level of the force does not change much.

**Table 4a—Average lateral force in pounds**

| | Average lateral force (lb)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.40 | Palapi 0.50 | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perhue-tamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guach-araco 0.78 | Para-juba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 0.1 | 0.1 | 0.3 | | 0.2 | 0.8 | –0.4 | 0.7 | 0.4 | 0.2 | –0.4 | 0.7 | –0.9 | 0.4 | –1.3 |
| 3 | –3.8 | –4.6 | –4.4 | –3.6 | –8.5 | –9.6 | –7.8 | –7.5 | –8.3 | –7.7 | –9.6 | –11.2 | –10.1 | –9.7 | –9.0 |
| 6 | 1.2 | 2.2 | 1.8 | 2.4 | 2.5 | | 4.4 | 3.3 | 3.2 | 2.4 | 5.2 | 5.4 | | 7.5 | 6.9 |
| 7 | –2.5 | –2.7 | –1.6 | –1.9 | –4.5 | | –6.5 | –3.8 | –5.9 | –3.8 | –6.5 | –3.7 | | –4.7 | –5.2 |
| **Wet, 0.010-in. chip** | | | | | | | | | | | | | | | |
| 2 | 0.3 | 0.6 | 0.7 | | –0.3 | 0.5 | 0.4 | 0.0 | 0.2 | 0.2 | 0.1 | 0.5 | –0.6 | 0.2 | –0.1 |
| 3 | –3.6 | –3.3 | –4.7 | –3.0 | –3.3 | –4.5 | –5.1 | –5.4 | –6.4 | –4.2 | –6.4 | –5.6 | –7.5 | –8.0 | –7.5 |
| 6 | 1.4 | 1.8 | 3.3 | 1.5 | 1.9 | | 2.4 | 2.5 | 3.3 | 2.0 | 3.1 | 3.2 | | 4.8 | 4.5 |
| 7 | –0.3 | –0.8 | –2.3 | –1.5 | –1.6 | | –1.4 | –2.0 | –2.9 | –1.2 | –1.2 | –0.5 | | –1.6 | –1.1 |
| **Dry, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | –0.3 | 0.1 | 0.3 | | 0.1 | 1.2 | –0.3 | 1.0 | 0.6 | 0.6 | 0.5 | 1.1 | 0.4 | 0.5 | –1.0 |
| 3 | –4.8 | –5.9 | –4.2 | –5.2 | –9.7 | –13.3 | –12.1 | –11.1 | –12.0 | –10.3 | –15.1 | –17.7 | –17.5 | –17.2 | –14.0 |
| 6 | 0.9 | 3.2 | 2.4 | 2.9 | 2.7 | | 5.5 | 4.1 | 4.1 | 2.7 | 6.4 | 8.9 | | 8.6 | 7.5 |
| 7 | –1.3 | –3.5 | –2.5 | –2.3 | –3.9 | | –9.1 | –4.2 | –6.1 | –6.2 | –9.3 | –6.8 | | –7.7 | –9.6 |
| **Wet, 0.020-in.-chip** | | | | | | | | | | | | | | | |
| 2 | 0.3 | 0.7 | 0.7 | | –0.3 | 0.9 | 0.7 | 0.1 | 0.3 | 0.4 | 0.1 | 1.2 | –0.7 | 0.9 | 0.7 |
| 3 | –4.5 | –5.0 | –6.8 | –4.3 | –4.5 | –6.9 | –7.6 | –6.9 | –9.9 | –6.3 | –9.8 | –9.7 | –11.3 | –11.7 | –12.5 |
| 6 | 1.7 | 2.3 | 3.4 | 1.9 | 2.3 | | 3.2 | 3.1 | 4.4 | 3.0 | 3.8 | 4.1 | | 6.1 | 7.1 |
| 7 | –0.7 | –1.6 | –3.1 | –3.1 | –2.5 | | –2.6 | –4.0 | –4.5 | –2.5 | –2.7 | –2.4 | | –4.7 | –4.2 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

**Table 4b—Average lateral force in newtons**

| | Average lateral force (N)[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tooth | Odoum 0.48 | Palapi 0.50. | Jebe 0.53 | Pardillo 0.57 | Merecure 0.63 | Chupon 0.67 | Perthuetamo 0.73 | Grapia 0.75 | Zapatero 0.77 | Guacharaco 0.78 | Parajuba 0.79 | Purguo 0.82 | Mora de Guayana 0.87 | Puy 0.88 | Ipe 0.91 |
| **Dry, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 0.4 | 0.4 | 1.3 | 0.0 | 1.1 | 3.5 | -1.8 | 3.0 | 2.0 | 0.7 | -2.0 | 3.1 | -3.8 | 1.6 | -5.9 |
| 3 | -16.9 | -20.7 | -19.8 | -16.1 | -37.9 | -42.8 | -34.8 | -33.3 | -37.1 | -34.1 | 42.8 | -50.0 | -44.8 | -43.0 | 39.8 |
| | | | | | | | | | | | | | | - | |
| 6 | 5.2 | 9.8 | 8.2 | 10.5 | 11.3 | 0.0 | 19.8 | 14.5 | 14.4 | 10.6 | 23.1 | 24.0 | 0.0 | 33.5 | 30. |
| 7 | -11.0 | -12.1 | -7.1 | -8.4 | -20.0 | 0.0 | -28.8 | -16.7 | -26.4 | -16.7 | -29.1 | 16.3 | 0.0 | -21.1 | -23.1 |
| **Wet, 0.25-mm chip** | | | | | | | | | | | | | | | |
| 2 | 1.2 | 2.5 | 3.0 | 0.0 | -1.4 | 2.3 | 1.8 | 0.0 | 0.9 | 1.0 | 0.4 | 2.2 | -2.8 | 1.1 | -0.4 |
| 3 | -16.0 | -14.8 | -21.0 | -13.4 | -14.7 | -20.1 | -22.7 | -24.2 | -28.5 | -18.8 | -28.6 | -25.0 | -33.5 | -35.7 | -33.2 |
| 6 | 6.2 | 7.9 | 14.8 | 6.6 | 8.5 | 0.0 | 10.6 | 11.1 | 14.9 | 9.0 | 13.9 | 14.2 | 0.0 | 21.2 | 20.1 |
| 7 | -1.4 | -3.6 | -10.2 | -6.8 | -7.1 | 0.0 | -6.0 | -8.7 | -12.8 | -5.4 | -5.2 | -2.4 | 0.0 | -6.9 | -4.9 |
| **Dry, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | -1.2 | 0.4 | 1.1 | 0.0 | 0.4 | 5.2 | -1.4 | 4.3 | 2.9 | 2.6 | 2.1 | 4.7 | 1.9 | 2.2 | 4.5 |
| 3 | -21.2 | -26.4 | -18.8 | -23.0 | -43.1 | -59.3 | -53.6 | -49.3 | -53.5 | -46.0 | -67.3 | -78.9 | -77.9 | -76.7 | -62.3 |
| 6 | 4.2 | 14.1 | 10.9 | 13.1 | 12.0 | 0.0 | 24.6 | 18.4 | 18.1 | 11.8 | 28.5 | 39.6 | 0.0 | 38.5 | 33.3 |
| 7 | -5.8 | -15.4 | -11.1 | -10.0 | -17.3 | 0.0 | -40.4 | -18.8 | -27.0 | -27.8 | -41.2 | -30.4 | 0.0 | -34.2 | -42.9 |
| **Wet, 0.50-mm chip** | | | | | | | | | | | | | | | |
| 2 | 1.5 | 3.0 | 3.2 | 0.0 | -1.5 | 4.0 | 3.0 | 0.4 | 1.4 | 2.0 | 0.4 | 5.2 | -3.0 | 4.1 | 3.3 |
| 3 | -19.9 | -22.2 | -30.3 | -18.9 | -19.9 | -30.8 | -33.9 | -30.7 | -44.2 | -28.2 | -43.4 | -43.1 | -50.1 | -52.1 | -55.7 |
| 6 | 7.7 | 10.1 | 15.0 | 8.6 | 10.4 | 0.0 | 14.2 | 13.9 | 19.5 | 13.2 | 17.1 | 18.0 | 0.0 | 27.2 | 31.5 |
| 7 | -3.3 | -7.1 | -13.6 | -13.7 | -11.1 | 0.0 | -11.7 | -17.8 | -20.0 | -11.3 | -12.2 | -10.8 | 0.0 | -20.9 | -18.5 |

[a] Number following species is specific gravity based on ovendry weight and green volume.

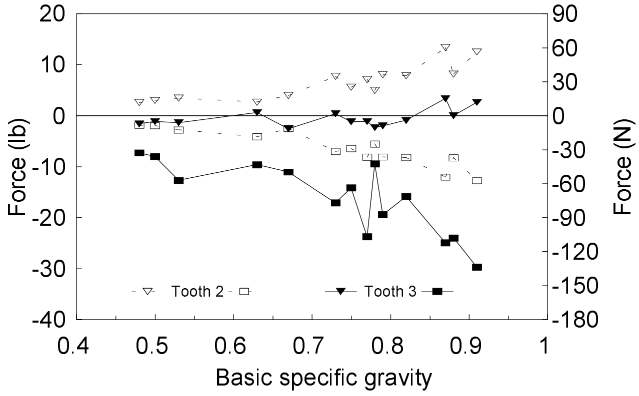

**Figure 14—Lateral force ranges (teeth 2 and 3) for a single cut in wet wood with a 0.020-in. (0.50-mm) chip.**

### Basic Specific Gravity, Chip Thickness, Moisture Content

No discernible trend for average lateral force for low values of basic specific gravity existed. For teeth 2 and 6, none of the test conditions produced significantly different results for the lateral force. However, for basic specific gravity greater than 0.6, the lateral force for all teeth except tooth 2 apparently increased in magnitude with both basic specific gravity and chip thickness (Fig. 15). For teeth 3 and 7, there was no simple, consistent result for statistical significance. However, it is clear that the best case is cutting wet wood at a thin chip (Fig. 15a), and the worst case is dry wood at a thick chip (Fig. 15b). The conditions of a dry 0.010-in. (0.25-mm) chip and wet 0.020-in. (0.50-mm) chip are not easily distinguished from each other.

### Outcome

In general, any asymmetry in the tooth caused by mounting, grinding, or damage may result in the generation of a lateral force, as will any gradients in wood properties along the cutting path. The highest lateral forces observed were generated by a tooth with a damaged corner, while cutting dry, high density wood, giving average forces up to 18 lb (80 N) for a chip thickness of 0.020 in. (0.50 mm). This is nearly 30% of the principal force for the same tooth (60% of that of a good tooth). This would appear to have implications for sawing accuracy.

## Conclusions

In this study, peak principal forces were 1.4 to 2.1 times as large as average forces. Doubling the chip thickness typically increased the principal force by a factor of 1.6. No significant difference existed in the forces for dry wood with a 0.010-in. (0.25-mm) chip and wet wood with a chip twice as thick.

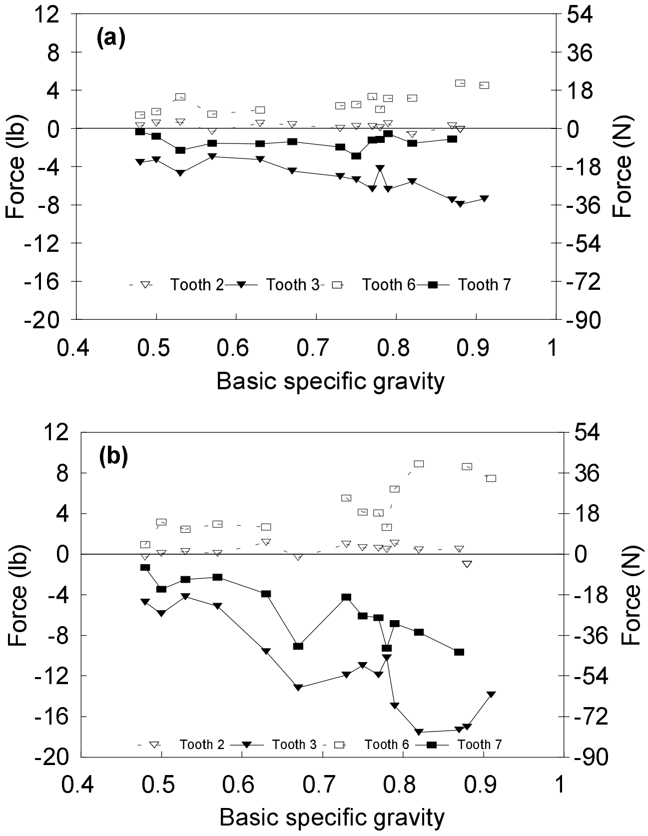

**Figure 15—Lateral cutting force: (a) wet wood and a 0.010-in. (0.25-mm) chip, (b) dry wood and a 0.020-in. (0.50-mm) chip.**

Normal force can be reduced by cutting wet wood, especially when using teeth that have some defects. The worst case is cutting dry wood with a thin chip. Large, positive normal forces, tending to repel the tooth, can be an indicator of wear or damage and contribute to wear.

Asymmetry in the tooth caused by mounting, grinding, or damage can result in the generation of a lateral force. The highest lateral forces observed were generated by a tooth with a damaged corner, while cutting dry, high density wood, giving an average lateral force equal to nearly 60% of the principal force for a good tooth. This appears to have implications for sawing accuracy.

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