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MATHEMATICAL ANALYSIS OF BAMBOO SPLITTING USING TWIN RIP SAW FOR STRIPS PRODUCTION

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INTRODUCTION

Laminated Bamboo Lumber (LBL), a woody composite material made from bamboo, has gained global acceptance as a sustainable substitute for conventional timber, especially those logged from natural forests. Currently, the main usage of LBL is for flooring and the product has a value of at least USD313 million in the international trade (Anon. 2017).

The bamboo composite is made of strips of bamboo, hence also known as Laminated Bamboo Strip Lumber (Wan Tarmeze 2005 and Lin et al. 2010), glued and laminated to each other to form a block. To produce bamboo strips, firstly, each bamboo pole has to be processed into splits. There are two popular methods of processing bamboo poles into splits: by a twin rip saw machine (Figure 1) and by a splitting machine (Figure 2). In the former, the distance between the circular saw blades dictates the width of the splits. The splits are then planed into strips having a rectangular cross-section profile (Wan Tarmeze et al. 2019).

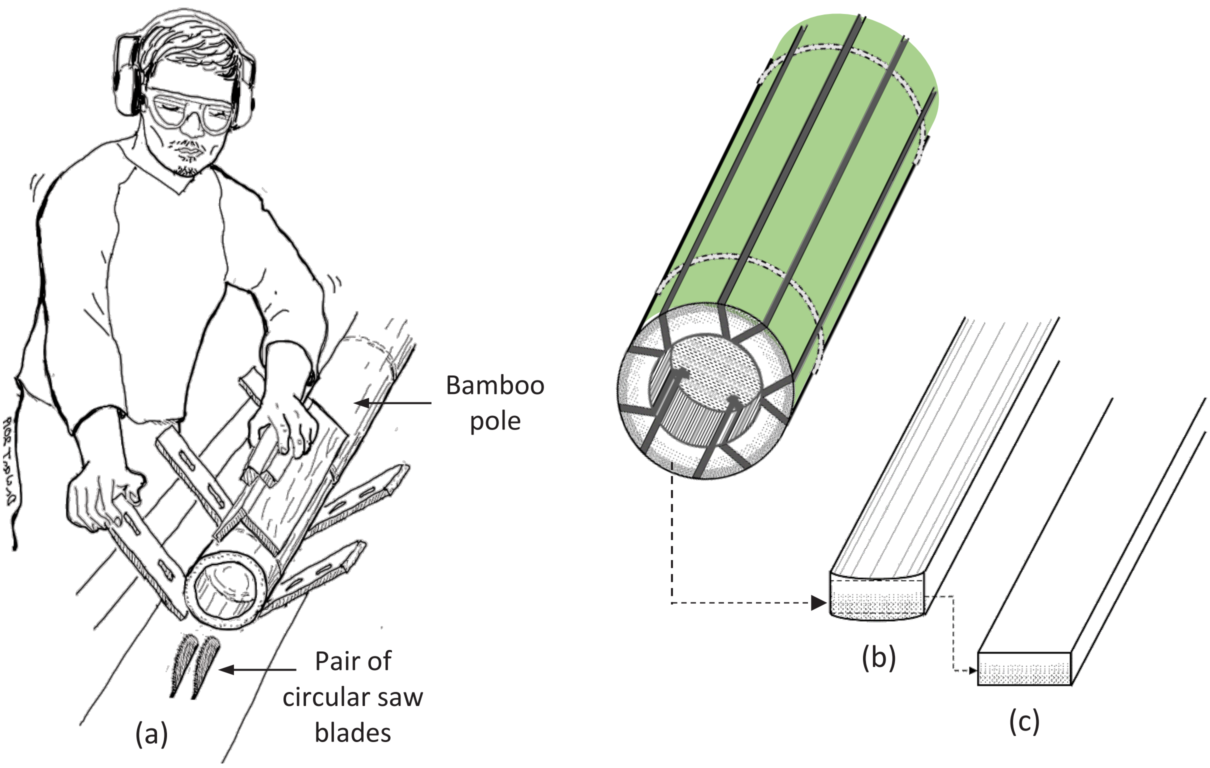


Figure 1 Longitudinal cutting of bamboo pole using a twin rip saw machine (a) to produce splits of fixed width (b) for making strips (c) of various thickness that later made into vertical LBL

The bamboo splitting machine (Figure 2) produces a number of bamboo splits (depending on the splitter blades number) in one push, thus it is a lot faster method when compared with the twin rip saw machine that produces only one split at a time, *i.e.*, after the operator has completely pushed the bamboo pole through the pair of circular saw blades underneath.

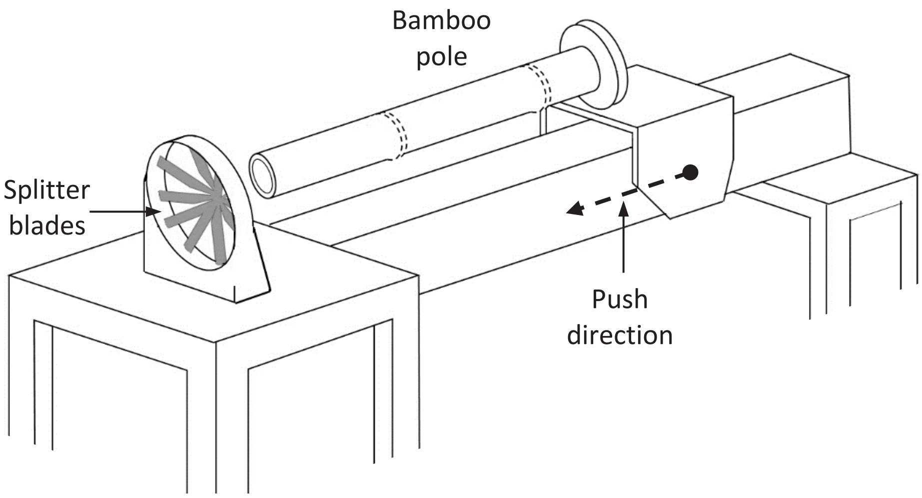


Figure 2 Bamboo splitting machine

Nevertheless, it is pertinent to understand that in the splitting machine method, the bamboo pole is not really cut, but rather is wedge-opened longitudinally by the blades and consequently separated into splits. Due to this circumstance, the bamboo separation lines (openings between the splits) may not be perfectly straight, but follows the straightness of the bamboo grain (longitudinal fibre). Hence, for bamboo poles that are known to have a less straight grain (wavy or crooked), for instance, due to their leaning posture while growing (as can be seen in sympodial bamboo – as opposed to the upright growing posture of monopodial bamboo, especially the Moso), splitting by the machine often ends up with crooked splits (Figure 3a). On the other hand, the twin rip saw machine cuts through and along the grain to produce perfectly straight splits (Figure 3b).

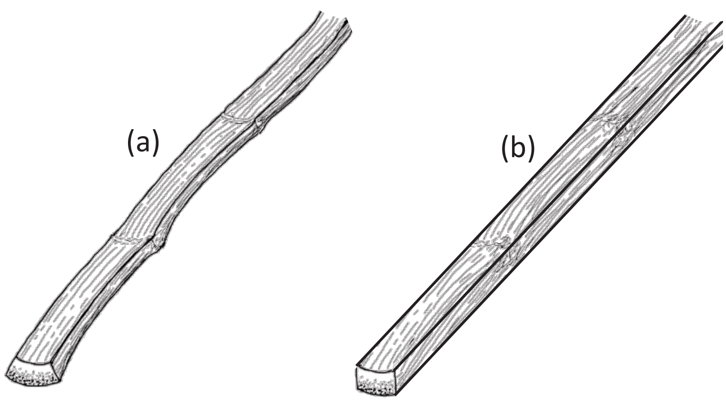


Figure 3 Splits produced from a bamboo pole with crooked grain: (a) using splitting machine and (b) using twin rip saw machine (notice how the saw blades cut through and along the grain)

Wan Tarmeze et al. (2019) discloses a mathematical algorithm to explain the relationship between bamboo diameter (Ø) and the number of splitter blades (N) that could guide bamboo product manufacturers to optimise the strips production. For example, to produce strips with rectangular cross-section 15 mm x 5 mm (width x height), the bamboo pole of 100 mm diameter and 6 mm thickness should be split into 18, i.e., using a splitter N18.

This article is to deliberate on the mathematical equations developed to calculate the number of strips that can be produced from a bamboo pole (of known diameter and wall thickness) using the twin rip saw splitting method. The validity of this mathematical work, which also enables the calculation of maximum strip height, was verified by comparing its results with those measured from AutoCAD drawings.

CROSS-SECTIONAL PROFILE OF BAMBOO POLE SPLIT BY TWIN RIP SAW

Figure 4 represents the cross-sectional cutting profile of a bamboo pole after a complete cycle of splitting by the twin rip saw method. At the beginning of the splitting process, the bamboo pole is pushed through the pair of circular saw blades and the first split is formed. Then, the operator rotates the bamboo pole, just enough to ensure that the next cut by the blades will produce the second split and an off-cut with the shape almost like an isosceles triangle having its apex touches the inner circumference line of the bamboo. The process is repeated until no more split can be made without cutting into the first split. At the end of this splitting cycle, there are N number of splits, off-cuts and a residue. The cross-sectional profile shape of the splits differs from that of the residue. The former is more like a rectangle, but the latter is more trapezoidal. The gaps between splits, off-cuts and the residue are made by the saw blades.

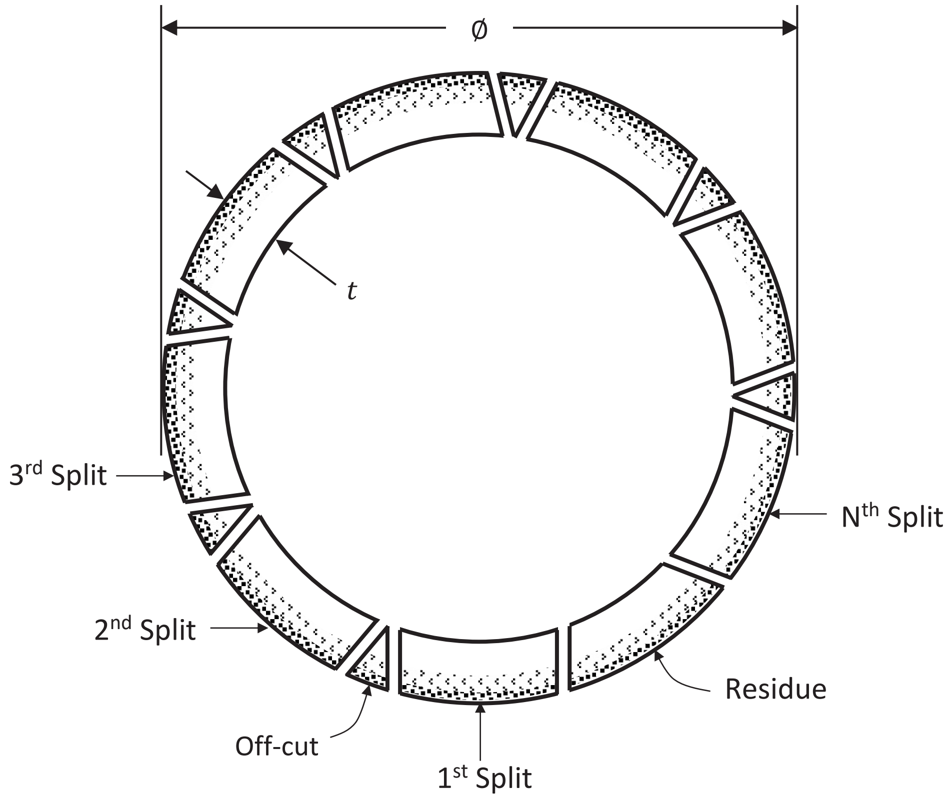
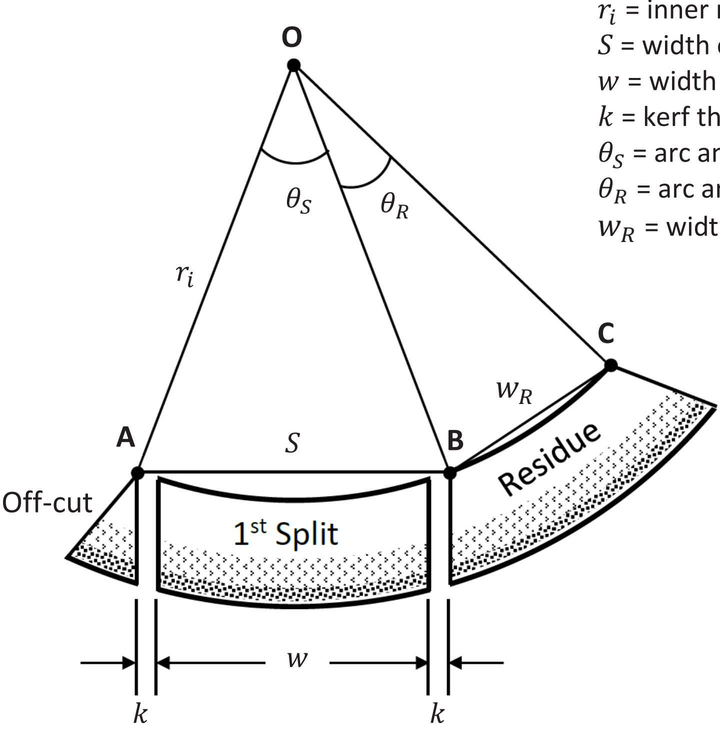


Figure 4 Cross-sectional cutting profile of bamboo pole after the completion of splitting process by the twin rip saw method. (Notes: Ø and t are diameter and wall thickness of the bamboo pole, respectively)

MATHEMATICAL EQUATIONS

Figure 5 shows the three products of bamboo splitting by twin rip saw method: off-cut, split and residue.



r_i = inner radius of the bamboo
S = width of the sector made by the cutting
w = width of the split (distance between the saws)
k = kerf thickness of the saw blade
θ_S = arc angle of the sector made by the cutting
θ_R = arc angle of the sector made by the residue
w_R = width of the sector made by the residue

Figure 5 The three products of bamboo splitting by twin rip saw method.

From the isosceles triangle OAB,

$$\frac{(S/2)}{r_i} = \sin\left(\frac{\theta_S}{2}\right) \quad => \quad S = 2r_i \sin\left(\frac{\theta_S}{2}\right)$$

$$\theta_S = 2\sin^{-1}\left(\frac{S}{2r_i}\right)$$

But, $S = w + 2k$ thus,

$$\theta_S = 2\sin^{-1}\left[\frac{(w+2k)}{2r_i}\right] \qquad ①$$

After the splitting process is completed, there will be N number of splits and a residue, therefore, the equation below applies.

$$(\mathrm{N} \times \theta_S) + \theta_R = 360°$$

$$\frac{360°}{\theta_S} = \mathrm{N} + \frac{\theta_R}{\theta_S} \qquad ②$$

But, dividing 360° by θ_S produces a decimal number as the following,

$$\frac{360°}{\theta_S} = N + (0.xxx) \qquad ③$$

where N is a full decimal number and $(0.xxx)$ is the decimal remnant.

Comparing ② with ③, $(0.xxx)$ is equal to θ_R divided by θ_S, thus,

$$\theta_R = (0.xxx) \times \theta_S \qquad ④$$

Now, from the isosceles triangle OBC (Figure 5),

$$w_R = 2r_i \sin\left(\frac{\theta_R}{2}\right) \qquad ⑤$$

Before we proceed further with the equation development, the following common rules for bamboo apply,

$$r_i + t = r_o$$

$$r_o = \frac{\phi}{2} \qquad ⑥$$

where t, r_o and ϕ are the bamboo thickness, outer radius and diameter, respectively, hence

$$r_i = \frac{\phi}{2} - t \qquad ⑦$$

Substitute ⑦ into ① and ⑤,

$$\theta_S = 2\sin^{-1}\left[\frac{(w + 2k)}{2\left(\phi/_2 - t\right)}\right] \qquad ⑧$$

$$w_R = 2\left(\frac{\phi}{2} - t\right)\sin\left(\frac{\theta_R}{2}\right) \qquad ⑨$$

So far, equations ① to ⑨ allow us to find the number of splits (N) and the width of the residue (w_R). The significance of knowing the value of w_R is that it may be large enough that the residue can be processed later into strip of the desired width. For instance, if the desired strip width is 20 mm, w_R may have a value of 21 mm. It is also worth to note that w_R should not be larger than S or otherwise it would have been cut as the N^{th} split.

Next, we are going to calculate the maximum height (h) of strip made from the split of known bamboo wall thickness (t). To begin with, let us have a look at the split and strip (DEFG dashed line rectangle) shown in Figure 6.

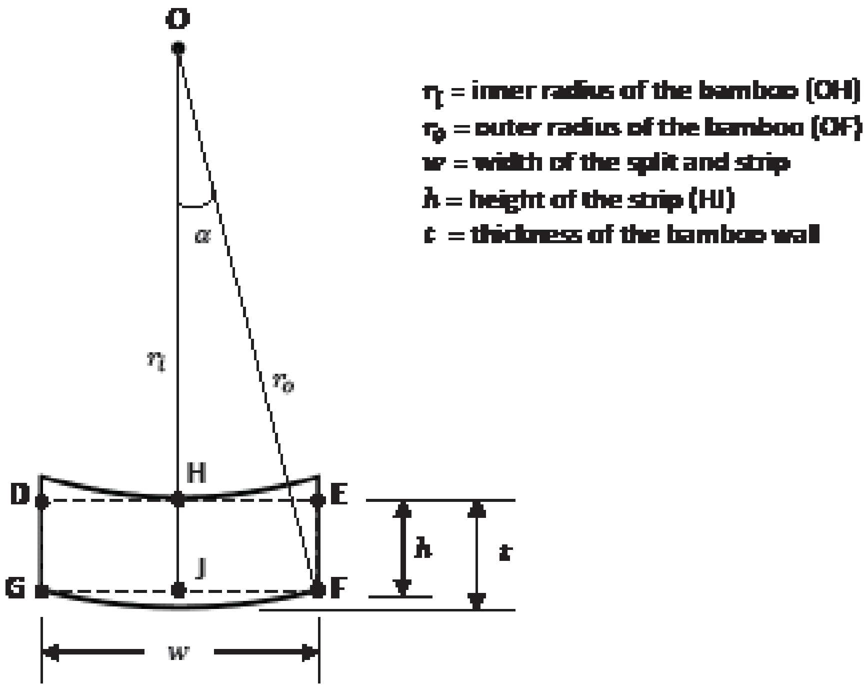


Figure 6 The planing of bamboo split into a strip (DEFG) with maximum recovery

From triangle OJF,

$$\frac{(r_i + h)}{r_o} = \cos\alpha$$

$$h = r_o \cos\alpha - r_i \qquad (10)$$

But,

$$\frac{\left(w/2\right)}{r_o} = \sin\alpha$$

therefore,

$$\alpha = \sin^{-1}\left(\frac{w}{2r_o}\right) \qquad (11)$$

Replace (11) into (10),

$$h = r_o \cos\left[\sin^{-1}\left(\frac{w}{2r_o}\right)\right] - r_i \qquad (12)$$

Substitute ⑥ and ⑦ into ⑫,

$$h = \frac{\emptyset}{2}\cos\left[\sin^{-1}\left(\frac{w}{\emptyset}\right)\right] - \frac{\emptyset}{2} + t \qquad ⑬$$

MATHEMATICAL WORK VERIFICATION

Calculation

Let us calculate the number of splits (N), width of the residue (w_R) and the height of strips (h) that can be produced from the bamboo pole in the example below using twin rip saw.

Example: The bamboo pole has diameter of 100 mm and wall thickness of 10 mm. It will be split by a twin rip saw with the distance between the saw equals 20 mm, and the saw kerf thickness is 3 mm.

$\emptyset$ = 100 mm, t = 10 mm, w = 20 mm, k = 3 mm

Calculation steps

1. Use ⑧ to find θ_S

$$\theta_S = 2\sin^{-1}\left[\frac{(20+6)}{2\left(\frac{100}{2}-10\right)}\right]$$
$$= 37.931°$$

2. Find N by replacing θ_S into ③,

$$\frac{360°}{\theta_S} = 9.49088$$
$$= 9 + (0.49088)$$

hence, N = 9 splits.

3. Now, use ④ to find θ_R,

$$\theta_R = (0.49088) \times 37.931$$
$$= 18.620°$$

4. Next, substitute the θ_R value into ⑨ to calculate w_R,

$$w_R = 2\left(\frac{100}{2} - 10\right)\sin\left(\frac{18.620}{2}\right)$$
$$= 12.942 \text{ mm}$$

5. Finally, to find height of the strip (h) can be made from the split, using equation ⑬,

$$h = \frac{100}{2}\cos\left[\sin^{-1}\left(\frac{20}{100}\right)\right] - \frac{100}{2} + 10$$

$$= 8.9898 \text{ mm}$$

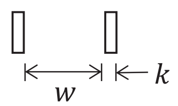
6. The results can be tabulated as below:

Properties (unit)	Symbol	Value
Bamboo Diameter (mm)	$\emptyset$	100
Bamboo Thickness (mm)	t	10
Split Width or Distance between Saw Blades (mm)	w	20
Saw Blade Thickness (mm)	k	3
Arc angle of the sector made by the cutting	θ_S	37.931
Arc angle of the sector made by the residue	θ_R	18.620
Number of Splits	N	9
Width of Residue (mm)	w_R	12.942
Height of Strip (mm)	h	8.9898

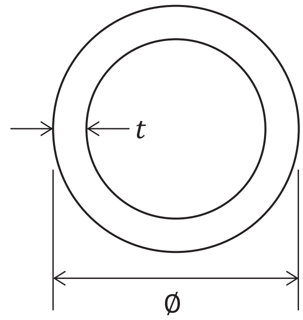
Measurement by AutoCAD

AutoCAD software (Onstott 2016) has a feature that allows the user to measure distances between points in the drawings. The following steps were developed to enable the verification of the bamboo splitting mathematical equations.

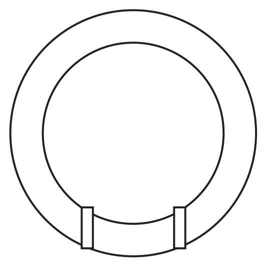
STEP 1 Draw a pair of rectangles representing twin saw blades with known w and k values, e.g., 25 mm and 3 mm, respectively.



STEP 2 Draw two circles representing bamboo with known $\emptyset$ and t values, e.g., 150 mm and 13 mm, respectively.

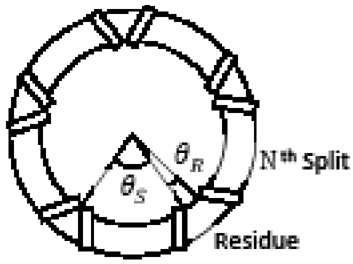


STEP 3 Place the pair of rectangles at the lowest part of the bamboo as if the split is made by the twin saw blades.



1st Split

STEP 4 Repeat Step 3 by placing the next pair of rectangles (or split) just next to the previous (as in Figure 4), in clock-wise direction until no more space available for another split. What remains is the residue. Count the number (N) of the split. Measure angles θ_S and θ_R and display the values.



STEP 5 Draw a rectangle inside the first split representing a strip. Measure the strip height (h) and the residue width (w_R) and display the values.

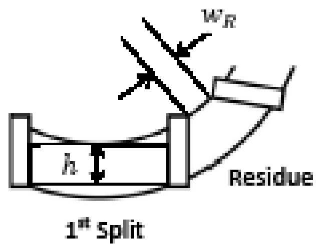


Figure 7 shows the actual AutoCAD print-out of the bamboo splitting by twin rip saw described in the above example. The identical values of N, w_R and h of both calculation and AutoCAD drawing confirm that the mathematical equations that have been developed are valid.

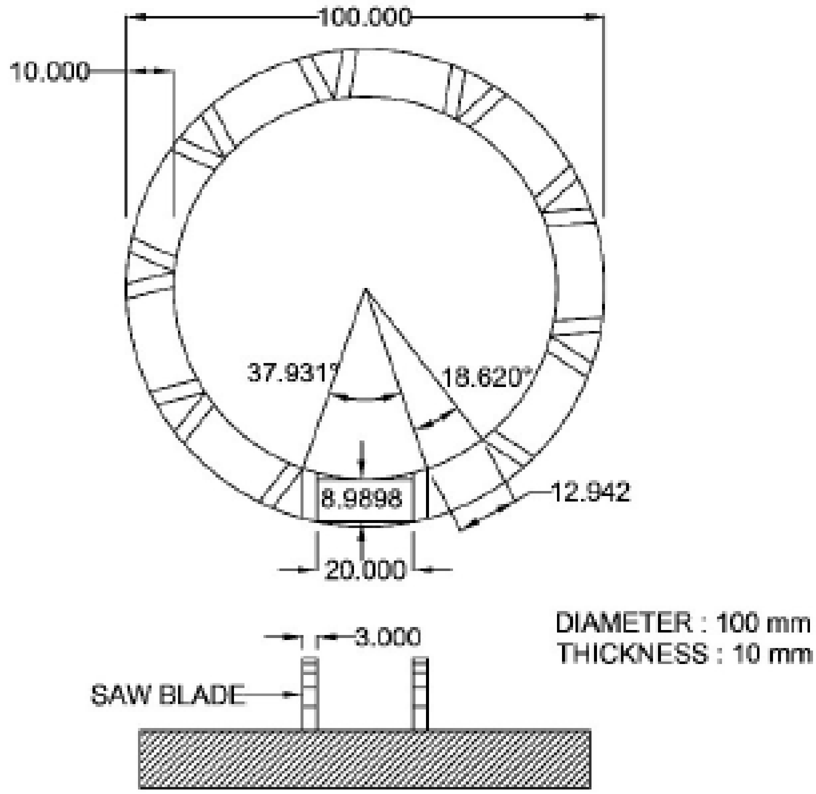


Figure 7 Actual AutoCAD print-out of the bamboo splitting described in the example

Relationship between ϕ, t, N, w_R and k

The above calculations can be repeated for other combinations of bamboo diameter and thickness as well as for different twin rip saw configuration. The results can be presented as graphs such as Figure 8 and Figure 9 (for w = 20 mm and k = 3 mm). The graphs allow bamboo processors to quickly determine how many splits can be produced from a bamboo pole and how wide is the residue. The bamboo processor only need to measure the diameter and thickness of the bamboo pole. For instance, if ϕ is 200 mm and t is 9 mm, then r_i is 91 mm and from Figure 8, the corresponding N and w_R are 21 and 24 mm, respectively. The result also shows that for this particular r_i, w_R is greater than the targeted w of strip which is 20 mm. Hence, the residue should be further processed into a strip of the desired width. Some of other r_i values are also corresponded to w_R greater than 20 mm (area of Figure 8 rendered in red).

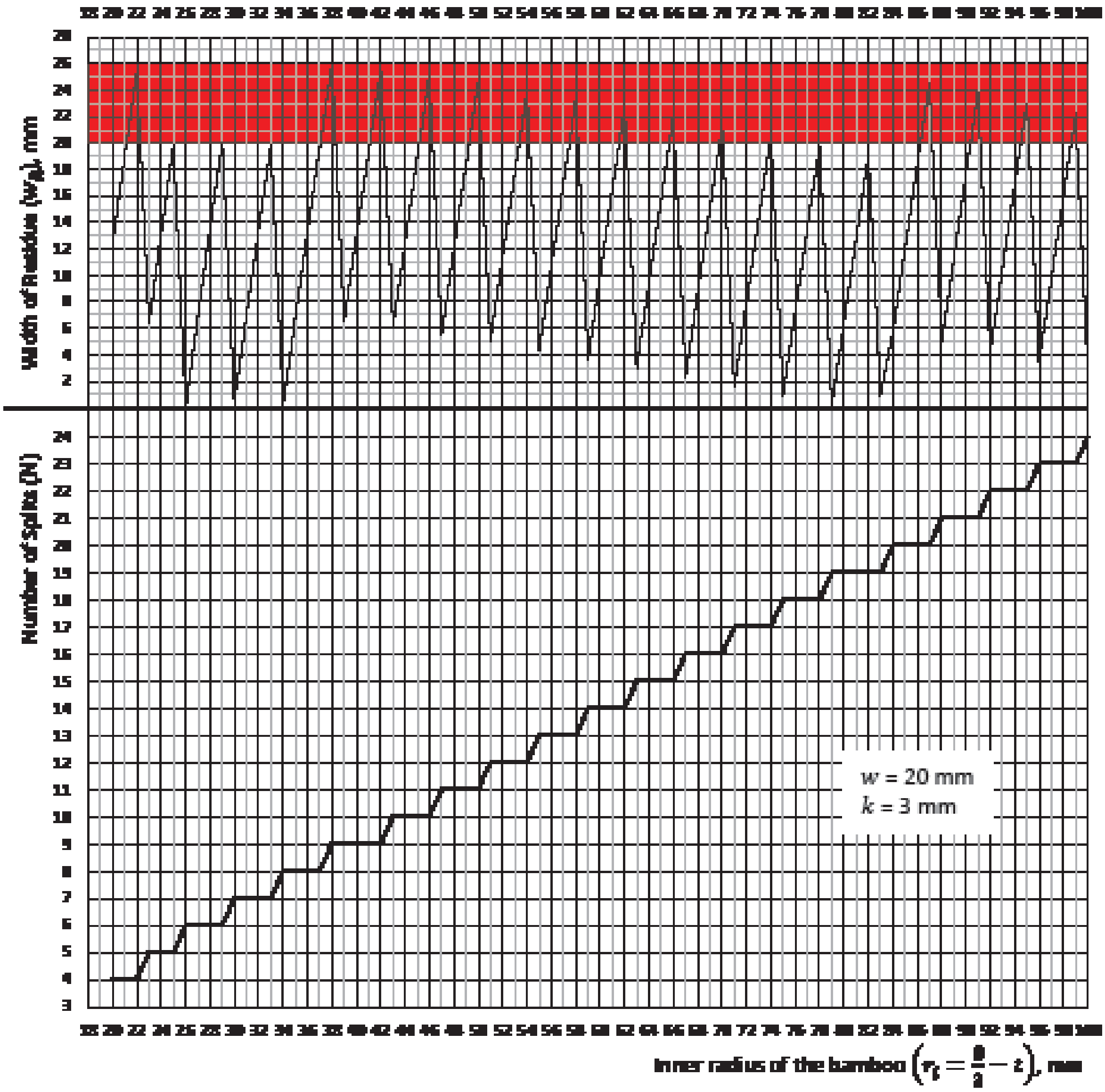


Figure 8 Number of splits (N) and width of the residue (w_R) obtained from bamboo poles split using twin rip saw with 20 mm gap (w) and 3 mm blade kerf thickness (k).

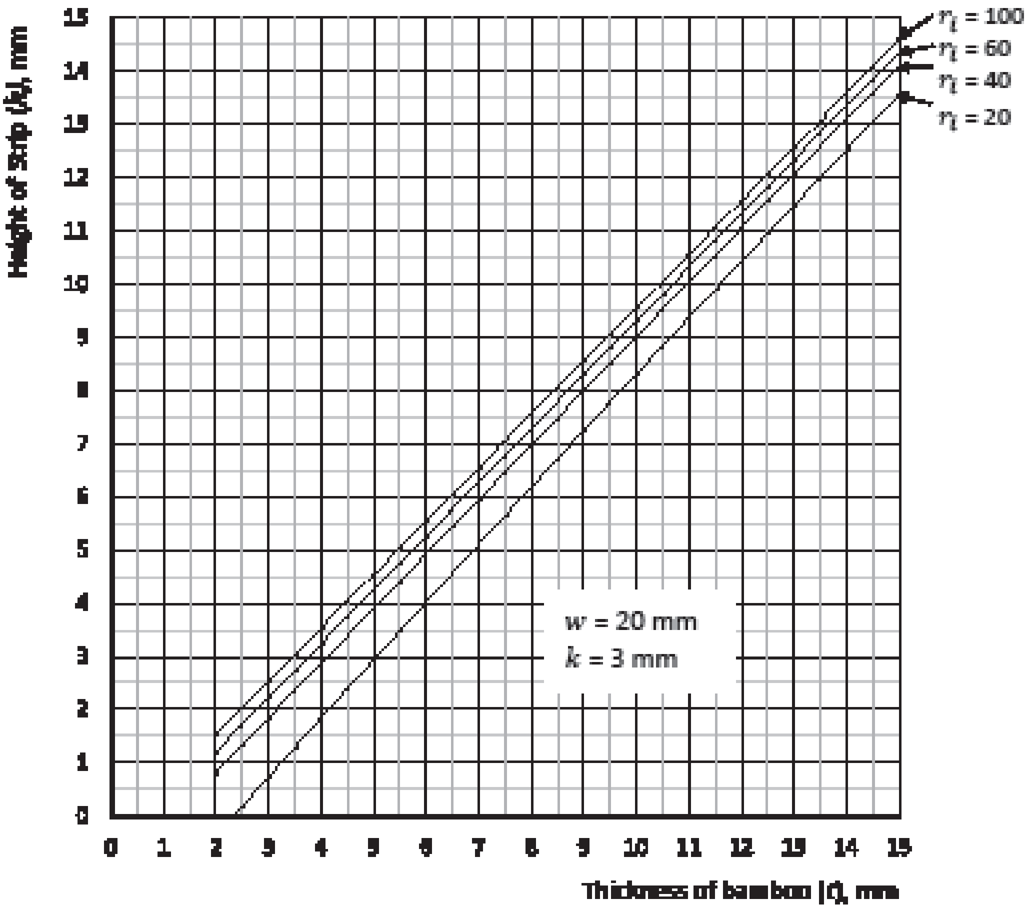


Figure 9 Relationship of bamboo thickness (t) and strip height (h) for bamboo poles when split using twin rip saw with 20 mm gap (w) and 3 mm blade kerf thickness (k)

Figure 9 reveals that as the r_i value gets bigger, the percentage of strip height over split thickness is getting smaller. As an example, for bamboo thickness of 12 mm, the strip height is 11.6 mm when r_i is 100 mm compared to 10.4 mm when r_i is only 20 mm.

CONCLUSION

The bamboo splitting using twin rip saw method has been analysed mathematically. The equations developed enable bamboo processors to calculate how many splits can be produced from a bamboo pole of known diameter and thickness. Moreover, the width of residue can also be calculated and the result would help the bamboo processor whether to keep the residue for strip making or to discard it as waste. Since the model is based on a perfect circle, but in reality, some bamboo poles are not, it is recommended that the bamboo processors use the smallest diameter as the input for the calculations. Furthermore, as has been discussed in Wan Tarmeze et al (2019), the innermost layer of bamboo wall known as pith ring is water-impermeable and brittle, thus should always be excluded from a strip. Therefore, the practical value of maximum strip height shown in Figure 9 must be reduced by the pith ring thickness.

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Mathematical equations were developed and verified by AutoCAD drawings to describe the process of bamboo pole splitting using twin rip saw method in bamboo strips production. The equations enable bamboo processors to calculate the number of splits and the width of the residue that can be produced from bamboo poles of known diameter and wall thickness. The results of this analysis are also presented as graphs that could be used by the bamboo processors to quickly determine the number of splits, residue width and optimum strip height.

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