Bamboo culm vertical lever flattening mechanism with sodium bicarbonate softening process

A H Atienza *, A Alba, D A Respicio and M A Baratang
Mapua Institute of Technology at Laguna, Malayan Colleges Laguna, Pulo Diezmo Road, Cabuyao City Laguna 4025 Philippines

*ahsatienza@mcl.edu.ph

Abstract. Some constructions require flattening bamboo culms to be used for constructing flat surfaces. With such need for flattened bamboo culms, the aim of this research is to develop a cost-effective and novel way of flattening bamboo culms for the species, Schizostachyum lumampao or buho, by integrating a softening process using sodium bicarbonate water solution and application of steam, then be pressed by a pressing mechanism using counter-bending technique to eliminate spring back effect of the bamboo culm. An open vessel was filled with sodium bicarbonate and water solution tested at concentrations between 15% and 26% by volume and then heated by 1.5 kW immersion heater. Pressure vessel partially filled with water and a 3-kW immersion heater were used to generate steam for the bamboo culm to maintain its flexibility as it is pressed. The bamboo culms reached a mean degree of flatness of 0.91. Thinner “Buho” (bamboo culm) submerged at around 20% of NaHCO₃ concentration was successfully flattened within an average flattening time of ten (10) minutes, similar with thicker bamboo culm but submerged at concentration greater than 20% of NaHCO₃. The machine had been incorporated with batch-type process and showed an efficiency of 90.75%.

1. Introduction
Bamboo, as a construction material, is a suitable alternative to wood products to scale down wood consumption [1]. Bamboos tend to have a faster growth rate and have greater mechanical strength compared to some species of trees [2]. Some processes utilizing bamboo requires them to be flattened for various usage, such as for flooring, walling, or any furniture that require a flat surface but most businesses focusing on bamboo products perform them by using a bolo knife as a cutting tool to cut them into flat strips. This method tends to sacrifice the material strength of the bamboo and is considered time and labor intensive. This paper aims to flatten bamboo culms by integrating a softening process using sodium bicarbonate water solution and then be flattened by pressing mechanism while applying steam generated from the pressure vessel. The target result is a flat bamboo culm retaining its flatness without cracks or any damage. This research focuses on the flattening of bamboo culms of the species, Schizostachyum lumampao, also known locally as buho, in the Philippines.

The foundation of this research requires understanding on the properties of bamboo, the effects of sodium bicarbonate solution on bamboos, and the approach or parameters to be considered on the flattening of bamboo culms. Testing several bamboos where different percent of humidity were applied, shows that shear strength at around 60%-80% humidity is high [3]. Though not directly, since shear stress test does not determine flexural strength, this can tell roughly at which humidity the bamboo has
higher resistance to cracks from bending. Difficulty of flattening is mainly because of the bamboo’s curvature. Previous studies tried reducing the circumference difference, while other researchers decreased the tangential stress through reducing of modulus of elasticity. One difficulty is the difference of circumference between the inner and outer layer of bamboo culm. Bamboo is a unidirectional fiber-reinforced bio-composite. Due to the weak longitudinal interface strength among bamboo cells, anti-cleaving, and anti-shearing strength along the grain of bamboo is relatively low [4]. Circumference difference, Cd, is a quick indicator of difficulty in flattening a bamboo culm. Cd is the circumference difference of outer and inner layer whereas the difference in radius is the culm’s thickness. Thus, thicker culm means higher Cd, and higher Cd means the more difficult the flattening. A possible solution to counter the problem is by removing parts of inner zone in order to reduce the culm wall thickness. It was reported a better result of flattening a culm with thickness of 3mm compared to 4mm and 5mm [5]. Moreover, out of the three specimens, the 5mm wall thickness showed fractures during flattening. In the study of [6], pre-compressing method was introduced on the bamboo first to decrease the circumference of the outer zone. By pre-compressing, the outer circumference became smaller and the extension of compressed inner zone during flattening was compensated. Aside from removing the culm parts of outer zone, increasing the circumference of inner zone was also an option. This is possible by making non-penetrating cuts and indentations on inner surface. The study of [7] performed diagonal cuts on inner surface at angles 20° to 40° to bamboo longitudinal grain direction. Efficiency was low because at the time there were no special devices for cutting. This was improved in the work of [8] for a patented bamboo flattening with longitudinal grooves on inner surfaces. The grooves were marked by a gear with isosceles-triangle shaped racks, while the height of the racks was less than 2 mm and the distance between parallel racks was less than 3 mm. The grooves direction was parallel to longitudinal direction of bamboo culms.

Aside from the above mentioned, flattening bamboos can be done with softening agents or by heat treatment. A study included removal of outer node ridges and inner node diaphragms before softening with hot water [7]. Softened bamboo culms were pressed with hot press under three different processes; the softened culms were pressed directly, pressed gradually, and pressed gradually through a continuous press. However, many deep cracks were found, and efficiency was very low. Another study used hot water and high-pressure steam. Study presented by [6] developed a flattening process by pre-compressing bamboo culm before softening it using hot water. It was then pressed with a stainless-steel board, and then fixed with high pressure steam. The results indicated that the best steaming condition for circumferential compression of bamboo culm was 140°C for 30 min. The paper stated that the ideal compression ratio to flatten the bamboo cane was 14–19%, while the successful fixation treatment high-pressure was 180°C for 4 min. However, if pre-steamed bamboo is not softened well, bamboo culm might collapse during circumferential compression inside forming pipe. The variation of bamboo culm diameter was found to be a problem for this method.

Results show from the study of [9] that bamboo when simply submerging in water and heated at 120°C for 30 minutes, is compared to water added with NaHCO₃ submerged at the same setting for 30 minutes results to a 42% decrease in hardness of surface for outer culm and 54.6% decrease for inner culm. The chemical composition of bamboos is like that of wood which includes major components, such as cellulose, hemicellulose, and lignin. Sodium bicarbonate or NaHCO₃ solution with water reacts with the lignin, a rigid molecule of bamboos, and causes delignification or removal of lignin by a phenomenon called alkaline hydrolysis [10]. A good measure of flatness is the degree of flatness (DOF) that [11] took consideration, which is the ratio of difference between culm radius and culm height to the difference of culm radius to its thickness. Hence, a DOF of 1 pertains to a flat bamboo culm.

Briefly, the important methods of this research include an open vessel filled with sodium bicarbonate and water solution tested at concentrations between 15% and 26% by volume and then heated by 1.5 kW immersion heater. Then, to maintain the flexibility of bamboo as it is being pressed, a pressure vessel partially filled with water and a 3-kW immersion heater was used to generate steam and it was pressed with hot pressers called cartridge heaters. This study highlights the aid of both sodium
bicarbonate and heat treatment process for softening process for batch production of flattened bamboo culms

2. Materials and Methods
The study patterned the experiment from [11] in which instead of linseed oil, water is used as one of the softening agents. To start off with the initial testing, bamboo from species of *Schizostachyum lumampao* are cut between two nodes and then were cut half along its length. Water with concentration of 10% by volume of sodium bicarbonate or baking soda had been prepared and filled at the open vessel. Water had been filled partially in the pressure vessel. Any safety precautions had been considered before operating the mechanism.

![Figure 1. Bamboo culm in cartridge heater](image)

The power cable was connected to the main breaker and the 3-kW heater at the pressure vessel was turned on with temperature set at 100°C as it takes a while to generate steam from the pressure vessel. The 1.5 kW heater at the open vessel was turned on as well. After it reaches the desired temperature of 100°C, the bamboo culms were then submerged into the solution. 1 kW cartridge heater set as shown in Figure 1 was turned on as well with temperature set at 150°C. At a certain amount of time, the bamboo culms were then transferred to the curved molders where they are to be pressed. Ball valve was then be opened to introduce steam to the bamboo culms. The bamboo culms were gradually pressed up until they are counter bended. The bamboo culms had been transferred to the flat molder where it was pressed further.

The flattening procedure had been repeated until no spring back effect was observed. The resulting bamboo culm had been measured again of its height. If the height is equal to the thickness of the culm, it is considered flat. The test is considered successful if it achieved flatness of bamboo culm without any visible cracks.

3. Results and Discussion
DOF required measurements of the bamboo culm, such as radius of halved-bamboo culm, its final height after pressing, and its thickness. The objective was to have a DOF equal to 1 which translates to having a flat bamboo culm. From several trials, the DOF attained was 0.9075 with a machine efficiency of 90.75%. Major factors affecting the flattening of bamboos had been its thickness, time pressed, and % concentration of softening agent. 20% concentration of solution had been the favorable concentration to flatten the thinnest group of bamboos having 4.5mm to 4.7mm.
The formula used to measure the degree of flatness of the bamboo was inspired by the equation by [6]:

\[
\text{Degree of Flatness (DOF)} = \frac{(\text{radius of bamboo} - \text{final height of bamboo})}{(\text{radius of bamboo} - \text{thickness of bamboo})}
\]  

(1)

Table 1. Tabulation of Degree of Flatness with concentration and time

| Trial | Radius (mm) | Thickness (mm) | Final Height (mm) | Concentration of Solution (%) | Time Elapsed (mins) | DOF |
|-------|-------------|----------------|-------------------|-----------------------------|---------------------|-----|
| 1     | 25.0        | 4.7            | 7.0               | 15.0                        | 11.1                | 0.8867 |
| 2     | 26.0        | 4.5            | 5.4               | 22.0                        | 6.9                 | 0.9581 |
| 3     | 26.0        | 4.7            | 6.3               | 20.0                        | 9.5                 | 0.9249 |
| 4     | 25.0        | 5.0            | 7.5               | 15.0                        | 10.5                | 0.8750 |
| 5     | 24.0        | 4.8            | 6.5               | 18.0                        | 13.2                | 0.9115 |
| 6     | 25.0        | 4.7            | 6.5               | 18.0                        | 13.0                | 0.9113 |
| 7     | 25.0        | 5.5            | 7.5               | 22.0                        | 9.4                 | 0.8974 |
| 8     | 24.0        | 5.0            | 7.0               | 20.0                        | 11.5                | 0.8947 |
| 9     | 25.0        | 6.5            | 8.5               | 26.0                        | 7.5                 | 0.8919 |
| 10    | 26.0        | 4.5            | 6.5               | 18.0                        | 10.6                | 0.9070 |
| 11    | 26.0        | 4.7            | 6.4               | 22.0                        | 8.5                 | 0.9202 |
| 12    | 26.0        | 4.5            | 6.4               | 20.0                        | 8.3                 | 0.9116 |
| AVE   | 25.3        | 4.9            | 6.8               | 19.67                       | 10                  | 0.9075 |

Figure 2. Relation between bamboo thickness and concentration of solution, and relation between bamboo thickness and pressing time elapsed

It was observed that thickness 4.925 mm as the mean, 5.495 mm as one standard deviation, SD, above, and 4.355 mm as one SD below as shown in Table 1. From the data gathered, the thickness had been divided in thin regime and thick regime. The thickness is lower than 4.925 mm for the thin regime while those greater than mean thickness was categorized under the thick regime. Thicker bamboos above the mean tend to require longer time of pressing to flatten. Concentrations at less than 15% has negligible effect in the flattening process and caused several failed and split bamboo culms as seen in
Figure 2. Bamboo culms did not soften as much and most of them stiffened even more when flattened using heated pressers, and resulted to burnt, cracked, and split in half at less than 15% concentration as seen in Figure 3a. However, increased concentration of softening agent for more than 20% decreased the time needed to press the bamboo culm and still achieved about 0.9 DOF as shown in Figure 3b. The radius of the bamboo does not affect much on the flattening of bamboo as varying radii have varying results. Furthermore, the values of radius of bamboo on all the trials are close to one another.

From the trials done and results attained, thickness played a part on how easy the bamboo culms had been flattened. As shown in Figure 2a, the result of unsuccessful flattening results to cracked ones with radii. When the bamboo is properly flattened, this would result to better thickness as shown I Figure 2b with an average thickness from twelve (12) trials of 4.925 mm and one standard deviation, $\sigma$ or SD of 0.57 mm, with 4.925 mm as the midpoint, 5.495 mm as one SD above, and 4.355 mm as one SD below. However, beyond one standard deviation, $\sigma$, too thin and it may crack but also may be easier to flatten if treated better. Too thick, such as Trial 9 with 6.5 mm thick sample, and it would be difficult to flatten. From the results, no trial has exceeded less than one SD of thickness, meaning no bamboo is too thin as of the experiment done as the least thickness among the trials are at 4.5 mm thick. On the other hand, one trial, Trial 9, has exceeded one SD of thickness, meaning the bamboo is too thick compared to the average.

Notice that Trial 9 with the thickest culm tested has a larger DOF compared to Trial 1 and Trial 4. When the factor of concentration of solution comes in, Trial 1 and 4 have both 15% concentration of solution and have a time elapsed in pressing with 11.1 min. and 10.5 min, respectively, while Trial 9 has 26% concentration of solution and 7.5 min. time elapsed. This tells us that a slight increase in the percent concentration of the sodium bicarbonate solution cut off minutes of flattening of the semi-culm bamboo, either for bamboo that was thick or thin. 20% solution was the favorable concentration to flatten the thinnest group of bamboos having 4.5mm to 4.7mm, while higher concentration up to 26% was the favorable concentration for the thicker group of bamboos that were 4.8 mm and higher. This is supported by the fact that Trial 2 with 0.9581 DOF and 4.5 mm thickness, has the highest DOF.

![Figure 3](image-url)  
**Figure 3.** a) Cracked bamboo culms and b) flattened bamboo culms
Furthermore, 15% and higher up to 20% showed promising signs of flattening. The researchers observed that thinner bamboos flattened at range 15%-20%, while thicker bamboos flattened at range 20%-above. For an example, Trial 2 and Trial 9 had been compared. Trial 2 was 4.5 mm thin while Trial 9 was 6.5mm thick; however, both bamboos reached a degree of flatness close to 0.9 even though both had been pressed with the shortest time. A further explanation between thick and thin bamboos followed.

For the case of the group of thinnest bamboos with range 4.5 mm to 4.7 mm, the students observed that among the three trials with 4.5 mm thickness, an 18% concentration was enough to fully flatten the bamboo within the shortest time of ten (10) minutes. When the thickness increased to 4.7 mm, the bamboo flattened but took the longest time to flatten hence for thinner bamboos, a 15% ≤ percent concentration < 20% required more than ten (10) minutes to fully flatten, while a percent concentration of 20% flattened the bamboo at half the said time.

Concentrations at less than 15% has negligible effect in the flattening process and caused several failed and split bamboo trials. The researchers noticed that bamboos do not soften and most of them stiffened even more when flattened using heated pressers, and resulted to burnt, cracked, and split in half.

The radius of the bamboo does not affect much on the flattening of bamboo as varying radii have varying results. Furthermore, the values of radius of bamboo on all the trials are close to one another. The force applied to the bamboo is dependent on other parameters since other factors dictate how easy it is for the bamboo culms to flatten due to how much their temporary increase of flexural strength/modulus of rupture (in other words, withstanding bending force without cracking) is added from treatment of heat and softening agent.

4. Conclusion and Recommendation
Thinner “Buho” (bamboo culm) submerged at around 20% of NaHCO₃ concentration was successfully flattened within an average flattening time of ten (10) minutes, similar with thicker bamboo culm but submerged at concentration greater than 20% of NaHCO₃. No bamboo culms tested beyond 15% concentration had shown any signs of neither cracks nor scratch, and the bamboo culms reached a mean degree of flatness of 0.91. The flattening machine was fabricated using mostly materials used were mild steels, angle bars, GI sheets, and refrigerant tank, and installed with heaters for the solution, pressers, and to produce steam. The machine had been incorporated with batch-type process and showed an efficiency of 90.75%, determined through the relation of radius of the bamboo and its thickness.

The flattening process had involved submerging of bamboo in a sodium bicarbonate solution, and it was found that thickness of the bamboo affected both the percent concentration of sodium bicarbonate solution and the time to flatten the semi-circular bamboo culms. It was also found that the bamboo had been flattened at temperature of the solution at 60°C and temperature of the heated pressers at 150°C. Data had showed that an average of DOF of 0.91 or 91% was achieved with a 60°C heating of solution, a much lower needed temperature than the results of [11] where to achieve a DOF close to 1 or 100% required equal or more than 115°C linseed oil temperatures.

The researchers recommend for future studies to include density of bamboo culms as a parameter and study the effects of different densities in flattening bamboo culms. It will be also important to determine Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) of the flattened samples. A study on the inclusion of heater design for the inner culm radius while being pressed and a way to maintain the humidity of the bamboo culms as it is being pressed, such as: steam application or submerging on water can be taken also consideration.
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