PROSIDING SNTTM XXIII 2025
Volume 23, No. 1, Tahun 2025, 9 Oktober 2025
e-ISSN 2623-0313
p-ISSN 3032-1972

Design and development of a low-cost two-point bending tester for bamboo culm sheaths

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Abstract. Sound generation in musical instruments depends on the instrument's material properties. This is not yet completely understood for the bundengan musical instrument because the material properties of the bamboo culm sheath (*slumpring* in Javanese) that covers the bundengan's woven structure are unknown. The dominant vibration mode of the bundengan is transversal; thus, the bending modulus of elasticity is required. Bamboo culm sheaths are thin, lightweight, and relatively fragile, so they must be characterised by a bending tester that can deliver a small enough force at a constant deflection rate. This is essential to obtain sufficient data within the material's elastic region before the bamboo culm sheath breaks. It was observed that the structure of bamboo culm sheaths is similar to that of corrugated paperboard. Therefore, a two-point bending tester was designed and developed in accordance with the bending test standards for paper and paperboard. The design process comprises needs identification, design specification, and conceptual, preliminary, and detailed design. A prototype was then developed, calibrated, and tested. Tests on specimens made from thin aluminium plates yielded bending moduli of 75.15±5.90 GPa and 74.59±2.55 GPa for deflection angles of 5.4° and 15.3°, respectively. This indicates that the two-point bending tester can perform repeated tests with relatively good precision and accuracy, making it suitable for testing bamboo culm sheaths.

Keywords: bamboo culm sheath, modulus of elasticity, two-point bending, design, prototype

Received: 30 September 2025; **Presented:** 9 Oktober 2025; **Publication:** 9 March 2026
DOI: https://doi.org/10.71452/y4ket639

INTRODUCTION

A musical instrument produces sound through the vibration of its elements. When a guitar string is plucked, for example, the transmission of the vibration energy from the vibrating string to the saddle, bridge, top plate, and so on subsequently results in the vibration of the guitar body and the air in it, which will then generate acoustic waves that travel to our ear [1]. Hence, we hear the guitar sound. Such a vibroacoustic phenomenon depends, among other things, on the properties of the materials making up each part of the musical instrument. Consequently, to understand how a musical instrument works and why it sounds the way it does, we need to know its material properties.

The guitar is a well-known and relatively well-studied musical instrument. In comparison, one may likely have never heard of the bundengan before. This is, in fact, a traditional musical instrument from Wonosobo, Central Java, Indonesia [2]. As can be seen in Figure 1, the bundengan has a unique half-dome structure from a woven bamboo lattice covered with layers of bamboo culm sheaths (*slumpring* in Javanese). Its sound is generated from the vibration of several clipped strings and long, thin bamboo bars. Like a guitar, when these strings and bars are played, their vibration excites the woven lattice, causing the surrounding air to vibrate. These acoustic waves eventually reach our ears, enabling us to enjoy the gamelan-like sound characterising the bundengan. The following videos show how the bundengan is played and how it sounds: http://ugm.id/BundenganSong and http://ugm.id/BundenganImprov.

Several studies have been conducted to understand how the bundengan's clipped strings [3]–[9] and long, thin bamboo bars [10] influence the generated sound. A few works have also focused on the woven lattice structure [11]–[14]. However, a complete understanding of this structure cannot yet be obtained due to unknown material properties. Although bamboo is a popular natural material in the construction of musical instruments, mainly due to its mechanical and acoustical properties [15], currently available literature on bamboo and its uses has been more focused on the bamboo culms than the bamboo culm sheaths. Data on the material properties of apus bamboo (*Gigantochloa apus* (Schult.f.) Kurz) culm, which is used for the woven lattice structure of the bundengan, is readily available [16]. However, there is currently no data on the material properties of apus bamboo culm sheaths that form the outer layer of the lattice. One of the properties we need to know is the modulus of elasticity, which contributes to the structure's stiffness.

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Figure 1. The bundengan is fitted with (a) long, thin bamboo bars and (b) clipped strings.

Observing how the bundengan is usually played and the placement of the clipped strings and long thin bamboo bars, we can expect that the dominant vibration mode of the woven lattice structure is transversal vibration, i.e., directed perpendicular to the structure's surface. Furthermore, the bundengan musical instrument has been found to sound better when it is wet, which lies on the fact that bamboo culm sheaths are hygromorphic materials: they curl to a tubular form when wet and open to a planar form when dry [17]. Consequently, data on the bending modulus of elasticity of the bamboo culm sheath is essential. However, we must consider that bamboo culm sheaths are thin, lightweight, and somewhat fragile. Therefore, the bending test equipment needs to exert small enough force increments and not cause the culm sheaths to break too soon so that we can generate sufficient measurement data in the material's elastic region.

Figure 2 shows dry apus bamboo culm sheaths typically used to cover the bundengan's lattice structure. When observed closely, the cross-section of the culm sheath somewhat resembles that of corrugated paperboard with fibre structures connecting its inner (adaxial) and outer (abaxial) surfaces [18]. This led us to adopt the bending test methods for paper and paperboard to test the bamboo culm sheaths. Several standards describe paper and paperboard bending tests using the two-, three-, or four-point methods (ISO 5628:2019) or the resonance method (ISO 5629:2017). The two-point method is further differentiated into the L&W-type tester, incorporating a constant rate of deflection (ISO 2493-1:2010), and the Taber-type tester (ISO 2493-2:2010).

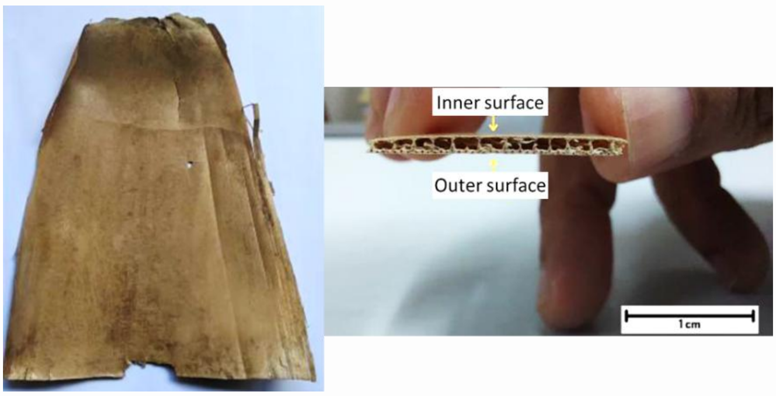

Figure 2. Apus bamboo culm sheath (left) has a structure (right) that resembles corrugated paperboard. (Adapted from [18])

This work aims to design and develop a two-point bending test equipment suitable for testing thin, lightweight materials such as bamboo culm sheaths, which are also quite fragile. The design followed the guidelines of relevant bending test standards for paper and paperboard. The developed equipment was tested

e-ISSN 2623-0313
p-ISSN 3032-1972

on its ability to deliver accurate and precise results under repetition. Such a bending tester will enable measurements of the bamboo culm sheath bending modulus so that the bundengan lattice structure can be further understood.

METHODOLOGY

General workflow

This work started with the engineering design process, which consisted of identifying needs, specifying design requirements, and performing conceptual, preliminary, and detailed design. In the conceptual design stage, several functions that the bending tester needed to fulfil were defined, and alternative solutions for each function were considered. The selected solutions were combined into a preliminary design, which was then made into a detailed design by deciding on the material, dimensions, assembly, electronics, etc. The preliminary and detailed designs were created in Autodesk Inventor v10. The design requirements served as guidelines for every decision-making process throughout the conceptual, preliminary, and detailed design stages.

A prototype was developed, calibrated, and tested based on the final design. Some components could be bought directly from suppliers, whereas some were self-made to fulfil custom requirements. Essential components were tested and calibrated before assembly to ensure that we understood how each performed individually, which could affect the performance of the assembled bending tester. The complete equipment was tested using specimens of known bending modulus of elasticity, the results of which were then analysed.

Specimen

To test the performance of the completed two-point bending tester, we used ten specimens made from a thin aluminium plate. The specimens have a length of 75±1 mm, a width of 20±0.3 mm, and a thickness of 0.5 mm. This thickness was chosen to ensure that the specimen was still within the tester's ability to bend without damaging the tester itself.

Analysis

The schematic of a two-point bending test is shown in Figure 3 based on ISO 5628:2019. The output data from the bending tests, i.e. the load and deflection angle within the elastic region, were analysed to determine the bending modulus of elasticity of the specimens using the following equation:

$$E = \frac{F \cdot L^2}{2\emptyset I} \qquad (1)$$

where E is the bending modulus of elasticity (N/mm^2), F is the load within the proportional limit (N), L is the length of the specimen measured from the support (mm), $\emptyset$ is the deflection angle (rad), and I is the moment of inertia (mm^4).

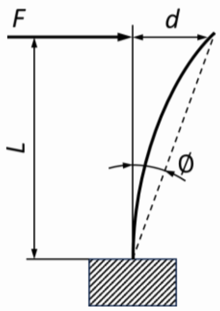

Figure 3. Schematic of a two-point bending test. (Adapted from ISO 5628:2019)

RESULTS AND DISCUSSION

Needs identification

The material properties of bamboo culm sheaths are essential to enable further analysis of how the bundengan musical instrument vibrates and generates sound. However, such data is not yet available. In particular, the bending modulus of elasticity is of interest because transversal vibration is observed to be the dominant vibration mode on the instrument. Furthermore, the bundengan sounds better when wet, the key to which lies in the ability of the bamboo culm sheath on its cover to curl when wet. Considering that bamboo culm sheaths are thin, lightweight, and relatively fragile materials, a particular bending tester is needed that can exert small enough force increments and not cause the culm sheaths to break too soon before sufficient measurement data in the material's elastic region is obtained.

Design requirements

The design requirements were generated based on several aspects. First, in terms of performance, the bending tester must provide rotation of the specimen up to 15° during the bending test, or at least 5° for specimens that break easily (ISO 5628:2019). It must also measure deflection angle and load accurately and precisely within ± 2% (ISO 5628:2019). Furthermore, it must withstand the load due to the bending test and be used repeatedly. In terms of manufacture, the bending tester should be made from parts or materials that are low-cost and easy to find and manufacture. It should also be easily assembled using simple tools and techniques. In terms of operation, the bending tester should be easy to operate and portable to carry around.

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It should also be able to test different types of bamboo culm sheaths.

The above design requirements were first used to select which bending method to follow. No difference is considered between the two-, three-, four-point bending methods or the resonance method regarding the required performance. In terms of manufacture and assembly, the L&W two-point method is considered better than the three-point method due to fewer parts needed to carry out the bending procedure. The Taber two-point, the four-point, and the resonance methods are inferior in this case. The three-point method is considered easier than the others in terms of the placement of the specimen on the support. However, the two-point method is deemed more portable. In the end, the L&W two-point bending method was selected.

Conceptual design

Figure 4 shows the functional model of the two-point bending tester to assist with the conceptual design stage. The specimen's end must be put on a holder by hand. The operator needs to ensure that the specimen is securely held, not so tightly that it might damage the specimen, but not so loosely that it might shift during the test. While doing so, the operator also needs to set the position of the specimen tip on the support to ensure that the tip will not slip off the support while the specimen is being rotated. Once ready, the end of the specimen needs to be rotated slowly. During this rotation, the deflection angle at the specimen end and the load exerted by the specimen tip on the support must be measured.

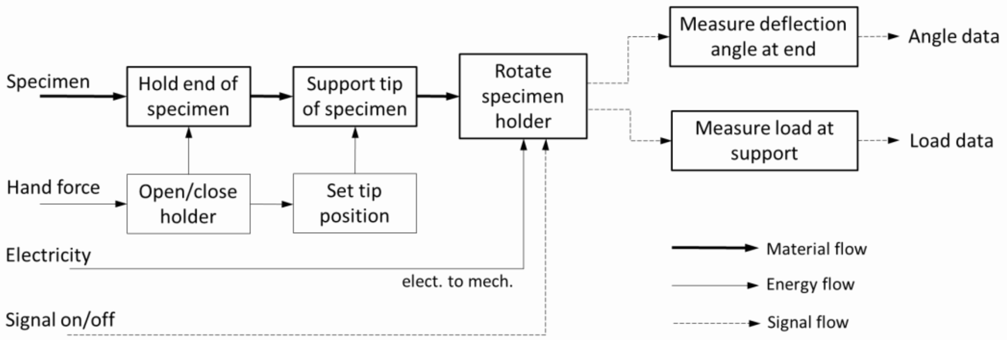

Figure 4. Functional model of the two-point bending tester.

For each function in the functional model, several alternative working mechanisms were considered. The options were evaluated against the design requirements, then one working mechanism was selected.

1. Specimen holder

   Two options were considered, i.e. using a screw clamp or a spring clamp. A screw clamp enables the operator to set the amount of force given to hold the end of the specimen by adjusting how many times the screw is turned. This can be useful to avoid crushing the specimen end when the specimens have different thickness or material fragility. However, it can be difficult to maintain a consistent level of grip force between one specimen and another, which may affect the test results. On the other hand, the spring clamp uses elastic potential energy to hold the end of the specimen, which means that it can provide consistent grip force for many specimens with relatively similar thickness. For this reason, we opted to use the spring clamp with a modification to accommodate specimens of different thicknesses or material fragilities. The modification will allow us to adjust the spring preload before carrying out a set of bending tests, depending on the specimen thickness or material fragility, to avoid damaging its end.

2. Specimen tip support

   The main consideration for the support is that it must be rigid enough to withstand the load exerted by the specimen tip during testing, while also transferring the same amount of load to the load measurement device. If the support deflects, then the measurement will not be accurate. Furthermore, the support should be in contact with the specimen surface uniformly on as small an area as possible, ideally a line, but the contact edge should not be so sharp that it can damage the specimen. Hence, a rectangular-shaped support with a curved contact edge was chosen.

3. Holder rotation actuator

   Here, we mainly considered electrical actuators rather than hydraulic, pneumatic, or spring actuators. Two alternatives were evaluated, i.e. a servo motor and a stepper motor. Servo motors are considered compact and easy to assemble and

e-ISSN 2623-0313
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operate. It can provide a sufficiently large torque and be electronically controlled to obtain the desired rotation angle. However, it may give a relatively large error between the programmed and the actual rotation angle, particularly for small turns. This becomes a concern because the deflection angle in the bending test of the bamboo culm sheath is only up to 15°. On the other hand, a stepper motor works by rotating in steps, each step moving a certain small angle. Hence, it is more consistent and accurate. Furthermore, if we know how big an angle the stepper motor turns for every step, then we don't need to add a separate device to measure the deflection angle. However, small stepper motors usually generate small torque, so a bigger stepper motor may be required. This may become an issue for the portability of the two-point bending tester. Therefore, an optimal stepper motor should be selected.

4. Load measurement device

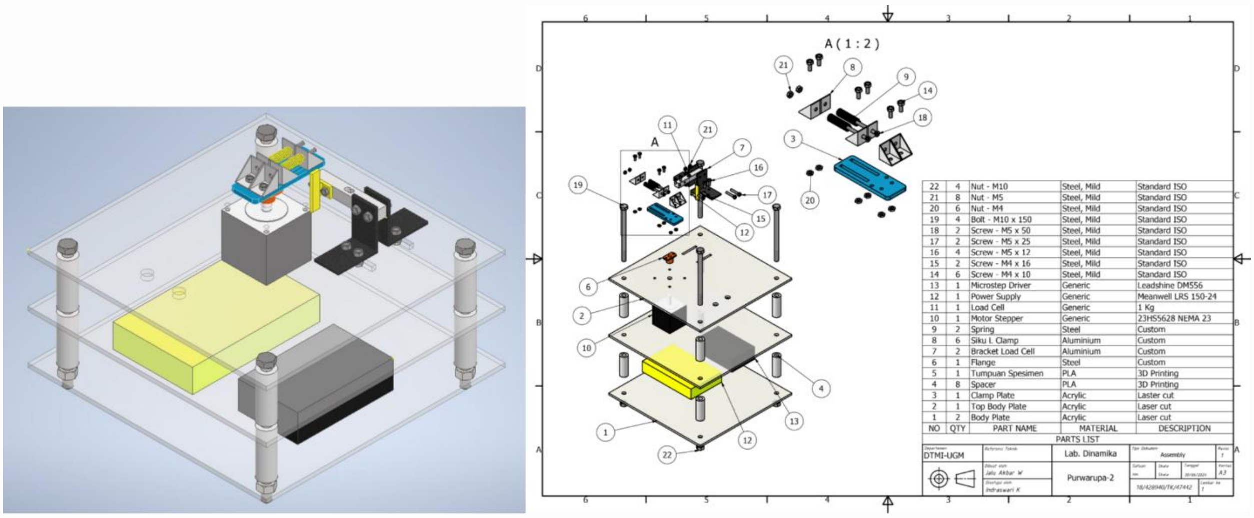
   A few options were considered, i.e. a force-sensitive resistor, a load cell, and a spring balance or dynamometer. The dynamometer was omitted because of concerns regarding its assembly and sensitivity (sensitive dynamometers are available but are more expensive). Force-sensitive resistors are also considered less sensitive and less accurate. Furthermore, their mainly plastic build can be tricky to assemble into the bending tester, particularly when involving hot soldering. Hence, the load cell was selected due to its accuracy, compact size, and ease of assembly.

Preliminary and detailed design

A preliminary design was made using the selected working mechanisms from the conceptual design stage. These parts were assembled onto a structure as shown in Figure 5(a).

Detailed design

The detailed design stage was carried out to determine the required geometry, dimensions, material, and manufacturing and assembly steps. Figure 5(b) shows the exploded view of the two-point bending tester. The construction is 300 mm x 300 mm in length and width, and its height is also around 300 mm.



(a) (b)

Figure 5. (a) Preliminary design and (b) detailed design of the two-point bending tester.

Manufacture and assembly

The completed two-point bending tester after manufacture and assembly is shown in Figure 6. It has three levels to accommodate the placement of various components. Each level was made from 5 mm acrylic plates, which were laser cut to obtain precise dimensions and locations of holes for mounting the components. The open structure allows heat from the devices to dissipate, thus preventing temperature increase to affect the measurement.

The stepper motor is equipped with a microstep driver, which controls the electrical power delivered from a DC power supply (through an adapter from the line power) to the stepper motor. This enables a smoother motor rotation. The control is done using an Arduino Nano. The axis of the stepper motor is connected to the brackets of the spring clamp specimen holder. The positions of the brackets can be adjusted before conducting a set of bending tests to change the spring preload and accommodate different specimen

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thickness. Next to the spring clamp holder, an aluminium bracket was placed to mount the load cell, with a 3D printed specimen tip support fastened on the load cell free end. Another Arduino Nano was used to read measurement data from the load cell, which was displayed on a small LCD screen for the operator to record. The load cell and the stepper motor were calibrated before assembly to ensure measurement error within ± 2% as required by the standard.

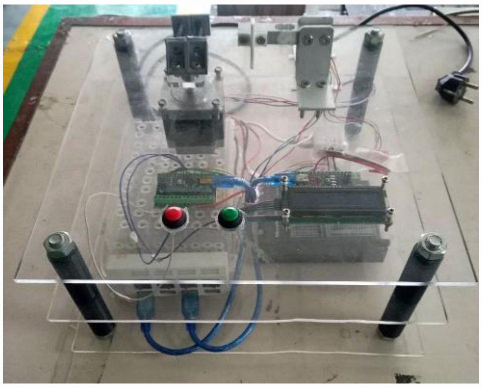


Figure 6. The completed two-point bending tester.

Performance test

The completed two-point bending tester was tested to see whether it can provide accurate and precise measurements. The test was carried out using 0.5 mm aluminium specimens as previously explained. The bending modulus of elasticity of aluminium is generally around 68–73 GPa, so the results from the two-point bending tester can be compared to this reference value.

The first set of tests was carried out on five specimens with a final deflection angle of 5.4°, the minimum target required by the standard. Each motor step rotated the holder 0.45°, so a total of 12 steps was needed. As shown in Figure 7(a), the load vs deflection angle graphs of the five specimens are relatively similar, especially up to 2.7°. Considering that data from 0.45° to 5.4° are still relatively linear, using Equation (1), the bending modulus of elasticity was calculated to be 75.15±5.90 GPa. Although relatively small, deviations between the graphs of the five specimens from 2.7° to 5.4° may have contributed to the standard deviation being 7.85% of the mean.

The second set of tests was carried out on another five specimens, reaching a final deflection angle of 15.3°. The motor step was now set to turn 0.9° each step, so 17 steps were needed. The results are shown in Figure 7(b), where the load vs deflection angle graphs of the five specimens are similar up to 6.3°. Using data within the proportional limit of the graphs, which was also up to 6.3°, the bending modulus of elasticity was calculated to be 74.59±2.55 GPa. Here, the standard deviation is only 3.41% of the mean.

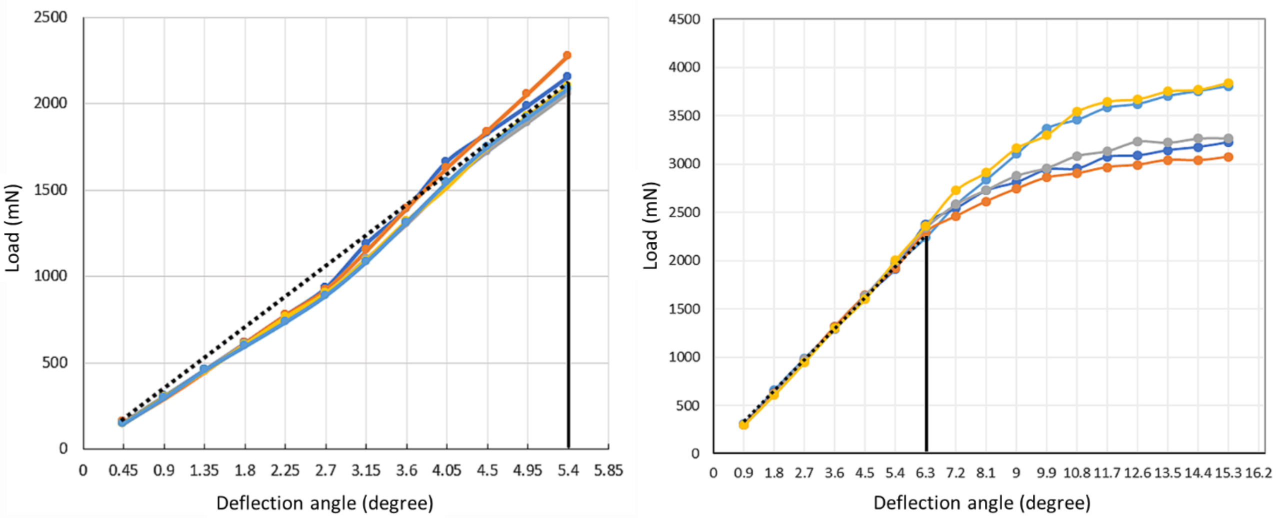
CONCLUSIONS

In this work, we have designed and developed a two-point bending tester specifically for thin, lightweight materials such as bamboo culm sheaths, which are also quite fragile. The performance of this two-point bending tester has been tested with specimens made from a 0.5 mm aluminium plate. The bending modulus of elasticity measured by this two-point bending tester was 75.15±5.90 GPa and 74.59±2.55 GPa for deflection angles of 5.4° and 15.3°, respectively. These results are within the bending modulus of elasticity of aluminium. This indicates the two-point bending tester can carry out repeated tests with relatively good precision and accuracy, so that it can be further used to test bamboo culm sheaths.

ACKNOWLEDGEMENT

The authors are grateful for the funding from the Faculty of Engineering, Universitas Gadjah Mada, through Hibah Penelitian Fakultas Teknik 2024, and for access to laboratory facilities at the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, to carry out the project.

e-ISSN 2623-0313
p-ISSN 3032-1972



(a) (b)

Figure 7. Bending test results of 0.5 mm aluminium specimens for a deflection angle up to (a) 5.4° and (b) 15.3°.

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