Designing a Florida Gator Ukulele

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Abstract—**This report details the design process of a 3D printed Florida Gators-shaped ukulele to fix deformation and other issues in a previous iteration of the design, print the ukulele's head and neck in addition to the body, and print the ukulele in three different materials (PLA, wood-filled PLA, and stainless steel-filled PLA) to compare timbres of the instruments made from the materials. The previous iteration of the design was manufactured as a prototype where deformation in the body can be seen. Bending and buckling calculations were performed on the body, neck, and head of the ukulele design to ensure they could withstand a string tension of 148 N typical for a concert ukulele. Finite element analysis was used to confirm bending calculations in the body and neck. 4 mm thick braces were added to the underside of the ukulele soundboard to prevent buckling, the failure mode of the body. Three ukuleles, one in each material, were manufactured and assembled by 3D printing the body, neck, and head and purchasing all other parts. The intonation of all was slightly off due to improper sanding of the nut. A small amount of deformation occurred in the body with the new design but nothing beyond what is typical of instruments like ukuleles and guitars. The wood-filled instrument had the most vibrant and full timbre, followed by the stainless steel-filled instrument and then the PLA instrument.**

Index Terms—**Bending, Buckling, Design Process, Ukulele**

I. Introduction

THIS document serves to detail the design process of a 3D printed Florida Gators-themed ukulele. This project incorporates previous work done to manufacture a prototype Gator Ukulele. Objectives for this project include fixing the deformation from the prototype ukulele by performing engineering calculations, fixing other issues found in the prototype ukulele, 3D printing the neck and head in addition to the body, and 3D print the ukulele three times in three different materials (PLA, wood-filled PLA, and stainless steel-filled PLA) to compare the timbres of the instruments.

Ukuleles are comprised of multiple parts including the body, neck, head, nut, fretboard, bridge, and saddle (Fig. 1). Ukuleles come in multiple different sizes. Each has a different standard scale length (the distance between the bottom of the nut and the center of the saddle) to ensure the ukulele plays the correct notes at the correct frets. A concert ukulele (15-inch scale length) size was chosen for the original prototype due to having a reasonable-sized body for at-home 3D printers to print. The nut height also affects the intonation of the ukulele (its ability to play the correct notes at different frets). Nut height affects how far away the strings are from the fretboard, which in turn changes their effective length when they are pressed down onto the fretboard and what note they play. The nut and string slots in the nut must place the strings at an appropriate height such that the intonation of the ukulele is correct. The soundboard of a ukulele should be as flexible as possible while still supporting the body to produce the fullest sound.

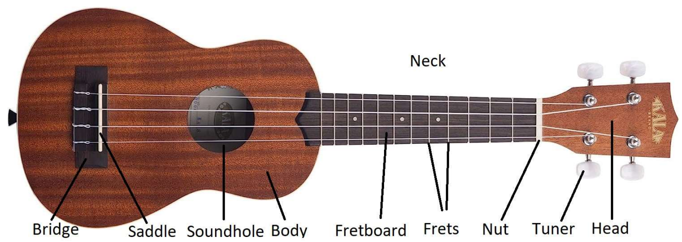

Fig. 1. Parts of a ukulele [1]. The top of a ukulele body is called the soundboard, the sides of the body are the sides, and the back of the body is called the back.

From March 2022 through March 2023, a nearly fully 3D-printable concert ukulele was designed using Oaktown Strings pineapple concert ukulele as a basis for dimensions with wall thicknesses of about 2.0 mm for the body [2]. This includes the bridge, saddle, body, fretboard, neck, nut, and head, making the only stock-bought parts the tuners and strings (Fig. 2). In January 2024, a mixed prototype was designed and manufactured with the only 3D printed part being the body which was split into two halves (Fig. 3). Multiple issues were present in the manufactured second prototype including too much glue being used, Gorilla glue expanding, a small surface area between the two body parts to be glued, and the soundboard bending (Fig. 4).

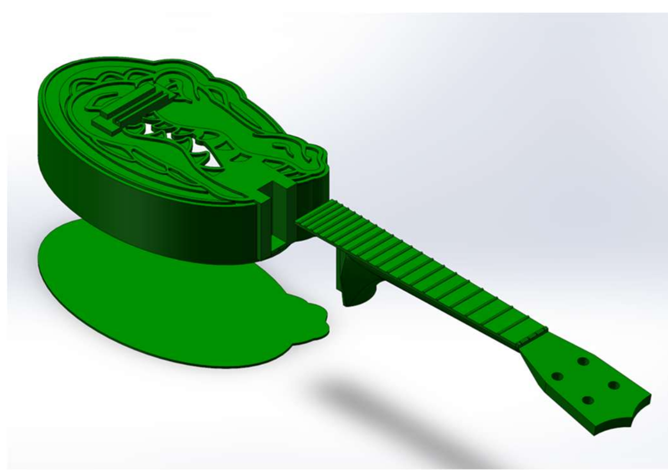

Fig. 2. First prototype design.

Fig. 3. Manufactured second prototype design.

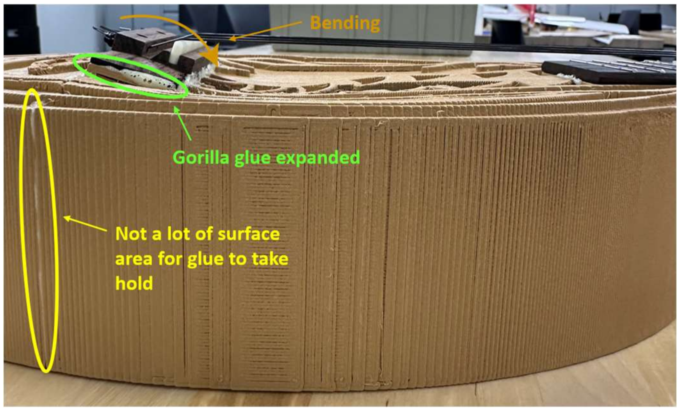

Fig. 4. Notated issues present in the second prototype.

To design the body, head, and neck of the ukulele, approximate bending stress (σ_b) and buckling force (P_{cr}) were calculated. Bending stress was calculated using (1) where M is the moment on the approximate beam, y is the distance from the neutral axis, and I is the moment of inertia of the cross-section. M is calculated using (2) where F is the force on the beam and d is the distance from the force to the neutral axis.

$$\sigma_b = \frac{My}{I} \tag{1}$$

$$M = Fd \tag{2}$$

y and I are dependent on beam geometry. For a rectangular cross-section, y is calculated using (3) and I is calculated using (4) where b is the width of the beam's cross-section and h is the height of the beam. For a semielliptical cross-section, y is calculated using (5) and I is calculated using (6) where a is half the width of the top of the cross-section and b is the height of the beam.

$$y_{rectangular} = \frac{h}{2} \tag{3}$$

$$I_{rectangular} = \frac{bh^3}{12} \tag{4}$$

$$y_{semielliptical} = \frac{4b}{3\pi} \tag{5}$$

$$I_{semielliptical} = ab^3\left(\frac{\pi}{8} - \frac{8}{9\pi}\right) \tag{6}$$

Buckling was calculated using Euler's critical load (7) where E is the Young's modulus of the material, I is the moment of inertia of the cross-section, and L_e is the effective length of the beam. L_e is calculated for cantilever beams using (8) where L is the length of the beam.

$$P_{cr} = \frac{\pi^2 EI}{L_e^2} \tag{7}$$

$$I_{semielliptical} = ab^3\left(\frac{\pi}{8} - \frac{8}{9\pi}\right) \tag{8}$$

It is important to note that when calculating these values, 100% infill is being assumed since the part's entire cross-sectional area is being accounted for. A 3D printed part's effective strength will be lower at lower infills.

Concert ukuleles typically have 33 lbf (~148 N) of force acting on them from string tension [3]. Material properties of printed PLA filament based on print orientation and raster angle were retrieved from [4]. Based on [4], printing a part on-edge (Fig. 5) provides the greatest strength and, thus, all parts were planned to be printed on-edge with a 45° raster angle to maximize strength.

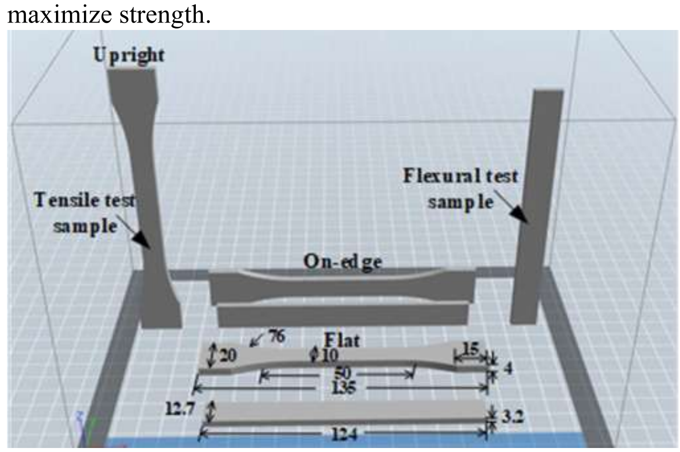

Fig. 5. Print orientations and geometry of test samples from [4]. On-edge ensures bending occurs along layer lines.

II. Design Process

The initial design of the ukulele from the previous iterations already accounted for scale length, flat surfaces for the bridge and fretboard to be glued to, and holes sized for the tuners.

Body Design

A. Calculations

The body was approximated as a beam to perform calculations and find how thick the top needed to be to not deform based on the geometry of the prototype. At first, a rigidly fixed beam was used for this analysis, but a cantilever beam was ultimately used instead to better approximate the component connection between the neck and body (Fig. 6).

Since a minimum thickness for the soundboard is ideal, (1) and (7) were solved for h using a rectangular cross-section, as shown in (9) and (10). Given that wood-filled PLA and metal-filled PLA tend to be weaker than standard PLA [4], a factor of safety of 2 was designed for to ensure the exact same ukulele design could be printed in all three materials to best compare timbre of the instruments.

Using the strength for PLA printed on-edge with a 45° raster angle of 109.5 MPa measured from the bending test in [4], a minimum height of 0.78 mm was to prevent bending. Using the Young's modulus for PLA printed on-edge with a 45° raster angle of 800.5 MPa from the tensile test in [4], a minimum height of 6.67 mm. This shows that buckling is the failure mode.

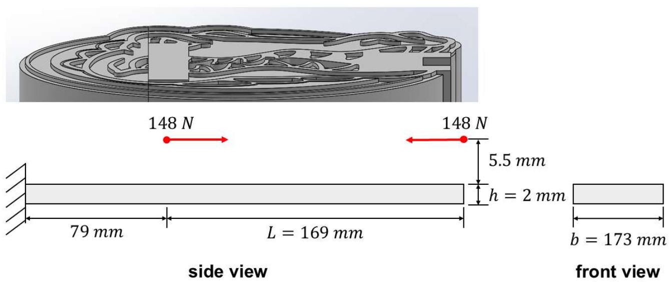

Fig. 6. Geometry, loads, and boundary conditions of cantilever beam approximation for ukulele body calculations.

$$h_{bending} = \sqrt{\frac{6Fd}{b\sigma_b}} \tag{9}$$

$$h_{buckling} = \sqrt[3]{\frac{12P_{cr}(2L)^2}{\pi^2 Eb}} \tag{10}$$

B. Design Changes

With 6.67 mm being an estimate thickness to prevent buckling, 4 mm thick braces were added under the soundboard based on where the most deformation occurred in the prototype (Fig. 7). This increased the thickness of the original soundboard from a 2 mm minimum and 6.57 mm maximum (Fig. 8) to a 6 mm minimum and 8.57 mm maximum (Fig. 9).

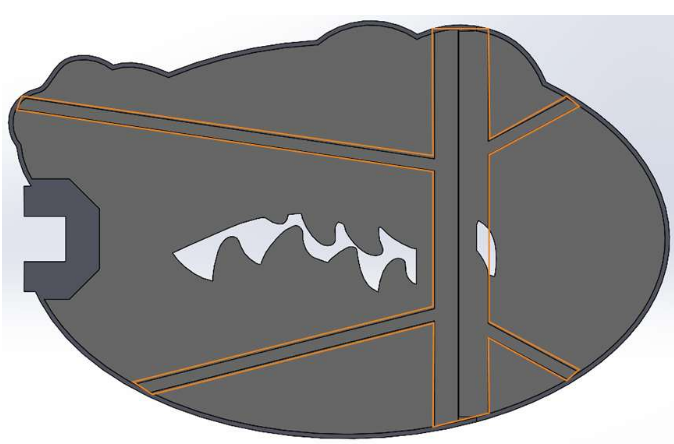

Fig. 7. Braces added to underside of soundboard on body. The angle of the angled braces was chosen arbitrarily to balance reinforcement and vibration of the soundboard, consistent with typical practices in ukulele design given that a flexibility and acoustic analysis are outside the scope of this project.

Fig. 8. Original minimum and maximum thickness of the soundboard on prototype.

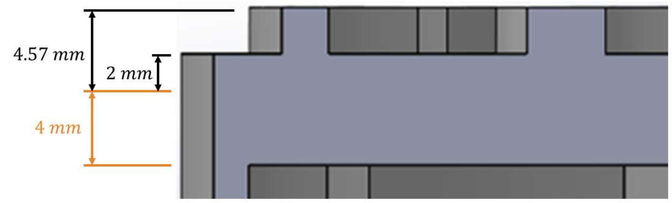

Fig. 9. New minimum and maximum thicknesses of the soundboard with braces added. View of body taken below the bridge where thickness was increased entirely across the body.

C. Finite Element Analysis

Using the new design, a finite element analysis was conducted to confirm the design's maximum stress. Abaqus was used to conduct the simulation.

First, the full model was used. Since Abaqus Student Edition was being used, a maximum of 1000 nodes is allowed. Thus, the body model was simplified in four iterations down to a simplified version of only the soundboard (no walls or back) with the new braces (Fig. 10). Material properties of 800.5 MPa for Young's modulus [4] and 0.35 for Poisson's ratio [5] were used. A general static step was used for analysis. This resulted in a maximum stress of about 0.67 MPa based on the stress concentration temperature contour (Fig. 12), confirming that bending stress is not a concern in the deformation of the soundboard.

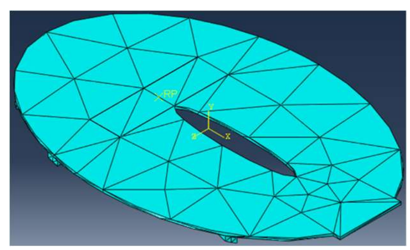

Fig. 10. Tetrahedral mesh with global size of 50 for the simplified soundboard model. Contains 971 nodes.

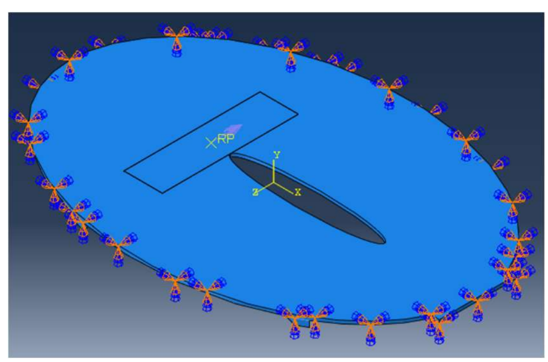

Fig. 11. Loads and boundary conditions placed on the simplified soundboard model. The moment is given a value of 963.48 N-mm and the boundary condition is an encastre.

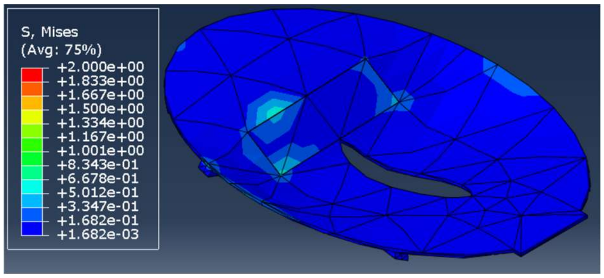

Fig. 12. Stress results of the finite element analysis of the soundboard.

Neck Design

A. Calculations

The neck was also approximated as a beam to perform calculations using the geometry of the original ukulele design. Specifically, the beam was estimated between the halfway point between the tuning pegs to the point just before the neck thickens at a rapid rate as it meets the body (Fig. 13). A cantilever beam with a semicircle cross-section was initially used, but a cantilever beam with a semielliptical cross-section was ultimately used instead to better mirror the actual geometry of the neck (Fig. 13).

Using (1), a bending strength of 0.73 MPa was calculated which is well below the strength of the material of 109.5 MPa. Using (7), a critical load of 421 N was calculated which is much greater than the string tension of 148 N. This shows that this neck design should not deform.

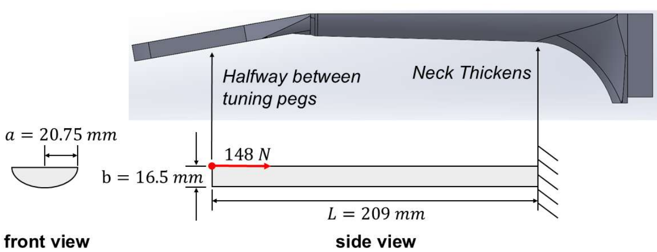

Fig. 13. Geometry, load, and boundary condition for cantilever beam approximation of neck.

B. Finite Element Analysis

Once again using Abaqus, a finite element analysis simulation was conducted to confirm the design's maximum stress. Material properties of 800.5 MPa for Young's modulus [4] and 0.35 for Poisson's ratio [5] were used. A general static step was used for analysis. This resulted in a maximum stress of about 1.57 MPa based on the stress concentration temperature contour (Fig. 16), confirming that bending stress is not a concern for the neck and that no design changes are necessary.

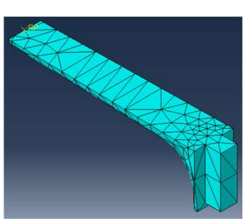
Fig. 14. Tetrahedral mesh with global size of 25 for the neck. Contains 905 nodes.

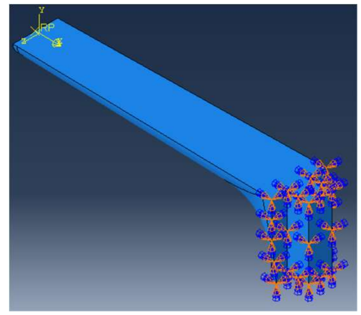
Fig. 15. Loads and boundary conditions placed on the neck model. The force is given a value of 148 N and the boundary condition is an encastre.

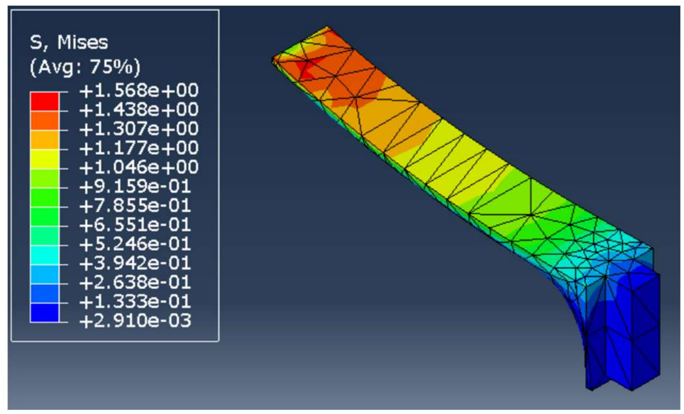

Fig. 16. Stress results of the finite element analysis of the neck.

Head Design

The head from the initial ukulele design was analyzed at the smallest cross-section: the cross-section at the lower two tuners. Once again, a cantilever beam approximation was used (Fig. 17). Using (1), a bending strength of 2.99 MPa was calculated which is well below the strength of the material of 109.5 MPa. Using (7) and a generous approximation of the entire length of the head from the upper tuners, a critical load of 1676.7 N was calculated which is much greater than the string tension of 148 N. This shows that this head design should not deform and that no design changes are necessary.

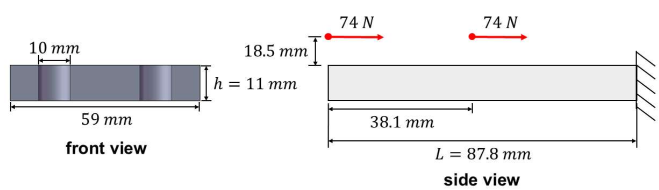

Fig. 17. Geometry, loads, and boundary condition for cantilever beam approximation of head.

Connection Design

To make gluing the parts easier, alignment extrusions were added to each component. This ensured parts would stay aligned during clamping and drying of the glue. Tolerances for the parts were initially approximated as 0.2 mm from prior experience using a Bambu Lab X1C 3D printer. These parts were to be printed on a Prusa MK4 so tolerances were refined using test prints printed in the same orientation as the final pieces would be printed.

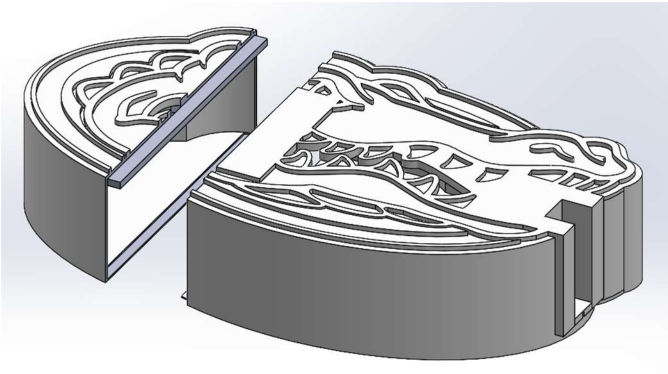

Fig. 18. Body with alignment extrusions between the upper and lower body pieces. Tolerances finalized at 0.25 mm.

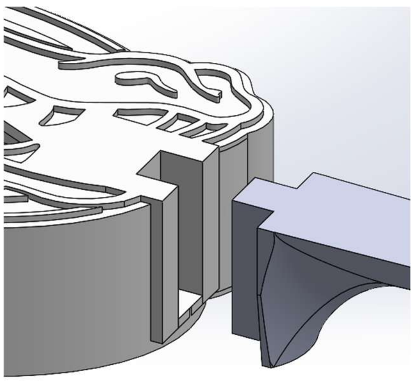

Fig. 19. Neck and body with alignment extrusions between the two pieces. Tolerances finalized at 0.2 mm.

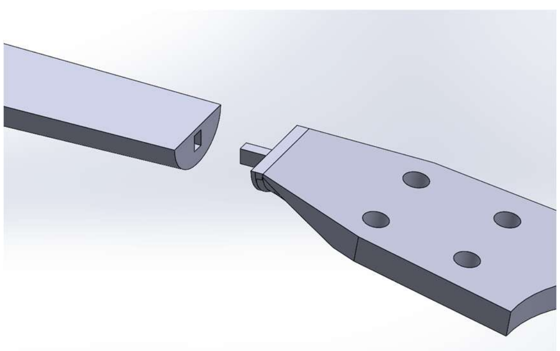

Fig. 20. Neck and head with alignment extrusions between the two pieces. Vertical tolerance finalized as 0.35 mm. Horizontal tolerance finalized as 0.45 mm.

Glue Selection

The smallest cross-section planned to be glued was the connection between the neck and head. Using the conservative estimate of the bending stress in the neck found via finite element analysis, this means the glue used must have a strength greater than 1.57 MPa. Krazy glue, for example, has a strength of 1000 lb/in^2 (6.89 MPa) [6]. Thus, stronger glues like gorilla glue should be okay to use as well.

III. Manufacturing & Assembly

3D Printing

The two body parts, neck, and head were sliced using PrusaSlicer and printed on a Prusa MK4 3D printer. All parts were printed at 100% infill in an on-edge orientation with a 45° raster angle to ensure strengths matched calculated values. All parts were printed aligned to the x-axis of the print bed except for the neck and head of the PLA ukulele which were printed at a 45° angle in the xy-plane of the bed.

R3D PLA was used with standard Prusa PLA, printer, and organic support settings to make the PLA ukulele. A 0.4 mm brass nozzle was used with this filament. The neck

HATCHBOX Wood PLA containing 11% wood fibers was used with standard printer and organic support settings with a raft, 210°C first layer print head temperature, 200°C print head temperature, 60°C bed temperature, and a -0.2 mm z-axis offset to make the wood-filled PLA ukulele. A 0.6 mm Prusa Nozzle ObXidian was used with this filament. HATCHBOX Wood PLA needed to be dried in a filament dryer before and during use due to the hygroscopic nature of the filament. Without drying, significant bed adhesion and layer splitting issues occurred.

Protopasta Stainless Steel Filled PLA containing 60% stainless steel powder by weight was used with standard printer and organic support settings with a raft, 215°C first layer print head temperature, 200°C print head temperature, and 60°C bed temperature to make the metal-filled PLA ukulele. A 0.6 mm Prusa Nozzle ObXidian was used with this filament.

Cleanup

Once parts were printed, organic supports were removed, and areas were sanded when necessary. Certain sections of the wood body needed to be glued with Gorilla Super Glue after printing due to layer splitting.

Assembly

The head, neck, two body parts, fretboard, and bridge all needed to be glued to be assembled. The PLA ukulele was glued first using Gorilla Glue Clear, requiring a clamp time of 2 hours and a cure time of 24 hours. The face of the head and neck intersection did not perfectly line up most likely due to the 45° orientation they were printed in on the xy-plane of the printer bed. This caused the glue to not cover the full surface area between the parts in a thin layer, eventually leading to the alignment piece and entire head snapping off once the ukulele was tuned. Thus, the parts were sanded down and re-glued using IPS Weld-On 16, a significantly stronger glue with a work time of 5-6 minutes and a cure time of 24 hours.

The wood-filled and metal-filled ukuleles were then glued using IPS Weld-On 16 for all filament-filament connections, Gorilla Glue Clear for all filament-wood connections such as the bridge and fretboard, and Gorilla Super Glue the nut.

The stock nuts purchased for the ukuleles needed to be shortened in height to ensure correct intonation. This was done by sanding the bottom of the nuts, placing it on the neck, checking string height, and continuing to sand until strings at the second fret were about 1.25 mm from the fret and strings at the twelfth fret were about 3.5 mm from the fret. Once at a correct height, the nut was glued to the head using Gorilla Super Glue.

The saddle was placed in the bridge as saddles are not typically glued. Tuners were then placed, bolted, and screwed into their appropriate holes in the head. Finally, the ukulele was strung and tuned.

IV. Results

The PLA ukulele (Fig. 21), wood-filled ukulele (Fig. 22), and metal-filled ukulele (Fig. 23) were all manufactured as playable instruments with the body, neck, and head 3D printed. The PLA ukulele's intonation was slightly flat from the nut not being sanded enough while the wood-filled and metal-filled ukuleles' intonations were slightly sharp from the nut being sanded too much. A small amount of deformation can be seen at the bridge of each ukulele.

When testing the ukuleles by playing them, the wood-filled ukulele was clearly the loudest with the fullest sound, followed by the metal-filled ukulele and then the PLA ukulele. The three instruments had notably different timbres, and all three were quieter than similar instruments on the market.

Active labor hours to manufacture each ukulele was 11.25 hours while total manufacturing time (including printing time and glue curing time) was 72 hours. A detailed breakdown of manufacturing and assembly time can be found in Appendix A.

The PLA ukulele cost about \$73.44. The wood-filled PLA ukulele cost about \$76.37. The metal-filled PLA ukulele cost about \$248.43. These costs are material costs and do not include tool costs (such as sandpaper, 3D printers, filament dryers, etc.) or labor costs. A detailed breakdown of cost for each ukulele can be found in Appendix B.

Fig. 21. PLA ukulele.

Fig. 22. Wood-filled PLA ukulele.

Fig. 23. Metal-filled PLA ukulele.

V. Discussion

The objectives of this design project were to take the previously designed 3D printable ukulele and fix the deformation in the body, 3D print the neck and head in addition to the body, and manufacture the ukulele in three different materials.

The ukuleles do function as decently working instruments, but their intonations are slightly off. The first ukulele manufactured, the PLA one, was a learning experience that improved the results of the intonations on the second two ukuleles. However, the wood-filled and metal-filled ukuleles were both over-sanded due to not considering the slight deformation that would still occur at the bridge, lowering the strings the slightest bit more once fully tuned. Sanding of the nut occurred without the strings fully tuned and, thus, caused the strings to be slightly too close to the fretboard once tuned. This can be prevented simply by slightly under-sanding the nut, something that comes with experience and that an experienced luthier most likely would have accounted for.

During manufacturing and assembly, the PLA ukulele's head broke off from its neck due to the lack of a flat surface between the two parts. Future iterations need to ensure that part intersections are flat either from sanding or from printing along a single axis of the print bed as much as possible. Nonetheless, a strong glue like IPS Weld-On 16 can compensate for these types of issues as well due to its high strength.

Wood-filled PLA can be particularly difficult to print with, causing layers to split and additional gluing to occur during the cleanup part of the manufacturing process. This can be prevented by thoroughly drying the filament prior to and during use to the point that filament from the roll can snap fairly easily in one's hands.

Metal-filled PLA is significantly more expensive than regular PLA and wood-filled PLA, causing the stark price difference between the metal-filled ukulele and the other two ukuleles. However, it may still be a worthy investment for a ukulele player looking for a specific timbre.

All three ukuleles were quiet compared to full wood ukuleles. This is most likely due to the flexibility of the back of the body and stiffness of the front of the body. Typically, the back of a guitar or ukulele should be stiffer than the soundboard to bounce sound back toward the soundboard. However, these ukuleles had a thin back that could easily bend and a stiff soundboard due to the thick braces under the soundboard and thick gator design over the soundboard. These new instruments did not deform like the prototype, but it is almost certain that there is a better balance for the soundboard between structure and flexibility to produce a better sound.

The neck and head were printed at 100% infill, though it is highly likely that decreasing the infill could have decreased the cost of the parts without causing them to fail. Decreasing infill density does decrease part strength, but with a factor of safety in buckling for the neck calculated to be about 4 for example, there is room for a decrease in strength.

Key limitations with this process included using Abaqus Student Edition which limited finite element analysis simulations to 1000 nodes and performing manufacturing in a high humidity environment which may have contributed to the moisture content of the wood-filled PLA.

VI. Conclusion

Three ukuleles (one PLA, one wood-filled PLA, and one stainless steel-filled PLA) were 3D printed and assembled with stock parts. These ukuleles had minimal deformation in the body that is not out of the ordinary for similar instruments and successfully worked as instruments, playing notes close to that of a typical concert ukulele. Wood-filled PLA produces the best timbre of the three materials used, followed by stainless steel-filled PLA and then regular PLA. Future designs should incorporate the acoustics of the instrument into calculations to produce better sounding ukuleles, decrease infill density in the neck and head to decrease costs, and explore how these findings can be scaled up to larger instruments with greater tension like steel string guitar or scaled down to smaller instruments like a soprano ukulele.

APPENDIX

Appendix A: Assembly Time

TABLE I
MANUFACTURING & ASSEMBLY TIME

Step Num.	Step	Labor Hours	Hours
1	3D Print Body Upper	2	26.25
2	3D Print Body Lower	1	8.25
3	3D Print Neck	1	5.75
4	3D Print Head	1	3.5
5	Printed Part Cleanup	2	2
6	Glue Head to Neck	0.25	
7	Glue Bridge to Body Upper	0.5	
8	Glue Body Upper and Lower	0.5	24
9	Glue Neck to Body	0.25	
10	Glue Fretboard to Neck	0.5	
11	Sand Nut for Intonation	1.5	1.5
12	Glue Nut	0.25	0.25
13	String Ukulele	0.5	0.5
	TOTAL TIME:	11.25	72

Hours listed for 3D printed parts is the amount of time it took to print. All glued parts took a total of 24 hours to cure.

Appendix B: Cost Breakdowns

Cost tables for each ukulele only detail material cost; labor cost and tool cost are not included.

TABLE II
PLA UKULELE COST BREAKDOWN

Item	Unit Cost	Quantity	Cost
R3D PLA Filament	$30/1000 g	966.01 g	$28.98
Ernie Ball Nylon Strings	$5.99/pack	1	$5.99
C. B. Gitty Concert Ukulele Fretboard	$13.99 + $4.49 ship.	1	$18.48
MGB Guitars Concert Ukulele Bone Bridge, Nut, & Saddle Kit	$5.00	1	$5.00
SEPHUE Ukulele Tuning Pegs	$13.99	1	$13.99
Glue	(estimate)		$1.00
		TOTAL COST:	$73.44

TABLE III
WOOD-FILLED PLA UKULELE COST BREAKDOWN

Item	Unit Cost	Quantity	Cost
HATCHBOX Wood Filled PLA Filament	$30/1000 g	1,063.72 g	$31.91
Ernie Ball Nylon Strings	$5.99/pack	1	$5.99
C. B. Gitty Concert Ukulele Fretboard	$13.99 + $4.49 ship.	1	$18.48
MGB Guitars Concert Ukulele Bone Bridge, Nut, & Saddle Kit	$5.00	1	$5.00
SEPHUE Ukulele Tuning Pegs	$13.99	1	$13.99
Glue	(estimate)		$1.00
		TOTAL COST:	$76.37

TABLE IV
METAL-FILLED PLA UKULELE COST BREAKDOWN

Item	Unit Cost	Quantity	Cost
Protopasta Stainless Steel Filled PLA Filament	$50/500 g	2,039.70 g	$203.97
Ernie Ball Nylon Strings	$5.99/pack	1	$5.99
C. B. Gitty Concert Ukulele Fretboard	$13.99 + $4.49 ship.	1	$18.48
MGB Guitars Concert Ukulele Bone Bridge, Nut, & Saddle Kit	$5.00	1	$5.00
SEPHUE Ukulele Tuning Pegs	$13.99	1	$13.99
Glue	(estimate)		$1.00
		TOTAL COST:	$248.43

Stainless-steel filled PLA is significantly more dense than normal or wood-filled PLA, causing the increase in quantity of material used. It is also significantly more expensive than normal or wood-filled PLA.

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