

HU 3910 - Guitar Soundboard Modeling

By Isaac Edelman, Michael McNulty, & Bob Provost

Introduction

The acoustic guitar is a complex mechanical system where the soundboard (guitar top) must be thin enough to vibrate but strong enough to withstand tension from the strings. This project explores the overlap of traditional lutherie and modern engineering by using finite element analysis to simulate how different design parameters affect the structural viability of the guitar top.

The Team

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The Project

Our goal for this project was to simulate the properties of a guitar top and its bracing in a digital environment so that the mechanical design parameters can be adjusted with an understanding of how it would perform structurally. We specifically also investigated how adjusting the X-bracing or implementing a lattice style soundport affects the structural integrity of a guitar under the load applied by the guitar strings in tension.

Background Research

We conducted a literature review and attended a library consultation to help our general understanding beyond surface level design. Key findings included:

Ken Parker's "Etude" series: Insights into how the arching and thickness of the plate (soundboard) contribute to its strength. Observing the construction of a real guitar top helped us with the construction of our virtual model.

<https://kenparkerarchtops.com/etude-making-the-plates>

American Lutherie Society: Historical data on bracing evolution and the structural role of the bridge. After learning about different types of bracing and their history, we decided to focus our analysis around X-bracing, as it is the most popular type and can easily be modified.

<https://luth.org/>

Material Properties: We identified Sitka Spruce as the industry standard, focusing on its Young's Modulus and Poisson's Ratio to define how the wood deforms under load.

<https://link.springer.com/content/pdf/10.1007/978-3-030-89381-1.pdf>

Information on how the acoustic guitar works and its specific properties.

<https://theacousticguitarist.com/how-the-acoustic-guitar-works/>

Methods

- Literature review: Utilized WPI Library databases and independent research to deepen our understanding of guitars and develop a plan for analysis
- Obtaining the model: Through our research we drafted a model using found dimensions and adjusted as necessary.
- Decide on parameters: Based on our discussions with Professor Manzo and brainstorming as a group we developed our desired parameters, including:
 - Thickness of top and bracing
 - Material used
 - Hole number, location, and size
 - Bracing pattern
 - Idea of a lattice guitar
- Draft new guitar models: Through our desired parameters, we created our models using SolidWorks after our meetings with Dr. Hera in COMSOL.

- Data analysis: Once the new designs reached their final stages in modeling we ran different structural tests and gathered data to analyze.
- Final report - Once all the data was gathered we compiled our findings into a final report and presentation.

Simulation Software

COMSOL Multiphysics: Initially, we used this software for its advanced acoustic structure interaction capabilities. We received training from Dr. Hera on how to run these types of analysis over the early weeks of our project. We determined that COMSOL is the recommended tool for future groups to analyze how structural changes affect the actual sound profile. However, the modeling-to-simulation pipeline was too complicated for our intended project, and we found that SolidWorks Simulation has sufficient features for our purposes..

SolidWorks Simulation: We used this software for the bulk of our structural testing. It allowed us to work rapidly in examining static stress and different plots from our tests. Additionally, since we also used SolidWorks for modeling the soundboard, it made the simulation pipeline easy since we could directly run simulations on model configurations as opposed to having to export and import models to a different software.

Key Parameters

The main goal of our research was to determine how varying the design parameters of the guitar top would affect its ability to withstand load. We found a lot of this information through our background research mentioned in the prior section, however we also brainstormed some more esoteric parameters and design variations to test. The actual simulation results will be shown and analyzed in the next section, with this section being an explanation of the meaning and rationale behind the parameters we chose.

As a “baseline” for our experimentation, we used our research on modern guitars combined with a partial schematic we found to construct a CAD model of the soundboard with adjustable parameters. Specifically, our base model was constructed from the “Dreadnought” style of guitar from the Bromo Guitars website, and acted as the default on which we modified and tested parameters independently. Additionally, our default model did not have any bracing, as we wanted to test the limits of the guitar plate alone without assistance, since this would provide more insight for potential modifications to the structure. For example, if a luthier wanted to change the sound profile of the guitar by changing the bracing, it would be more helpful to know how a soundboard without bracing behaves, as any added bracing would only strengthen the soundboard.

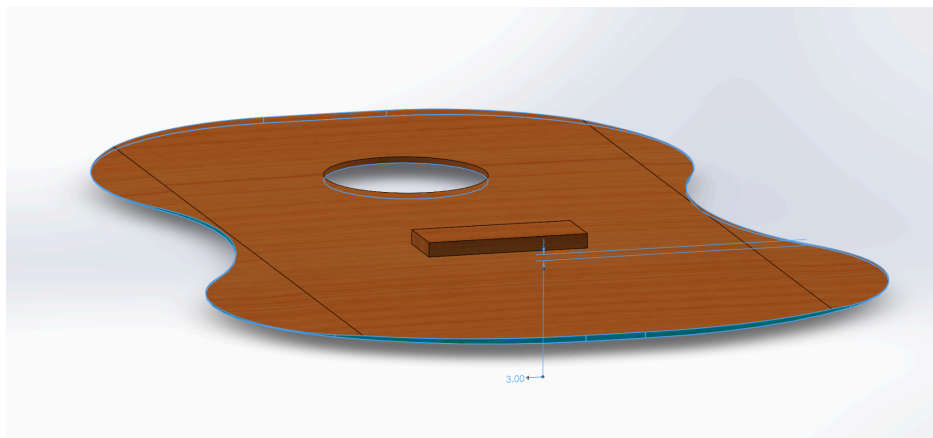
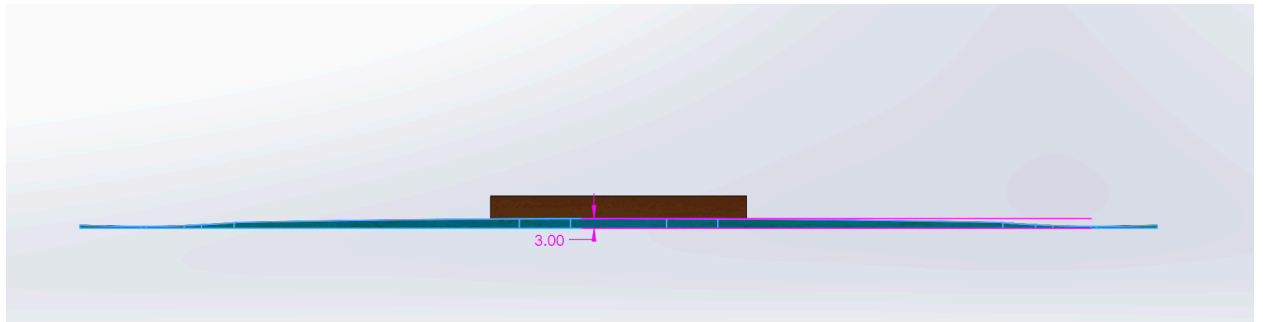
Finally, for all simulations, the tension of the strings was represented by a 500 N load distributed over the face of the bridge. This value was found during our initial research as an average string tension, but this could end up being higher or lower for any individual guitar. We decided not to study this in depth since we knew that force and stress are directly related, so testing different tensions wouldn’t grant us any new insight.

Material:

The first and foremost parameter we wanted to test was the soundboard material, as we knew that material properties would significantly impact the strength of the board. However, contrary to our initial assumptions, changing the soundboard material had little effect on the actual stress values calculated by the simulation. Therefore, instead of running many simulations with different materials, we realized we could simply find the maximum stress predicted for one baseline material (we chose Cedar) and compare that to the yield stress of our desired material to determine a factor of safety. This makes the study much simpler and more streamlined, as the mechanical properties of materials can be easily sourced online or through published research.

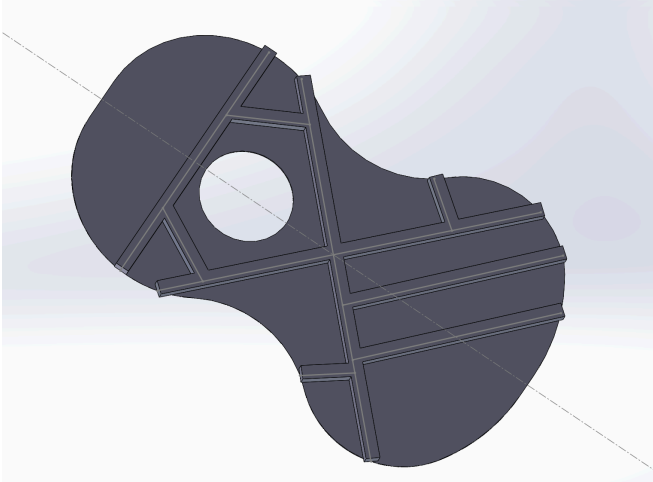
Loft/thickness:

One of the other biggest structural parameters of a guitar soundboard is its thickness; specifically, we found that the thickness of the center axis of the guitar – known as the “loft” – had a large effect since the majority of the load from the strings is transmitted through the bridge and to the centerline. Therefore, we ran simulations with loft thickness varying from 2-5 mm at 1mm increments. The 2mm minimum was chosen due to this being the minimum thickness allowable in our model, and the 5mm maximum was chosen to avoid making the plate unable to vibrate and generate sound.



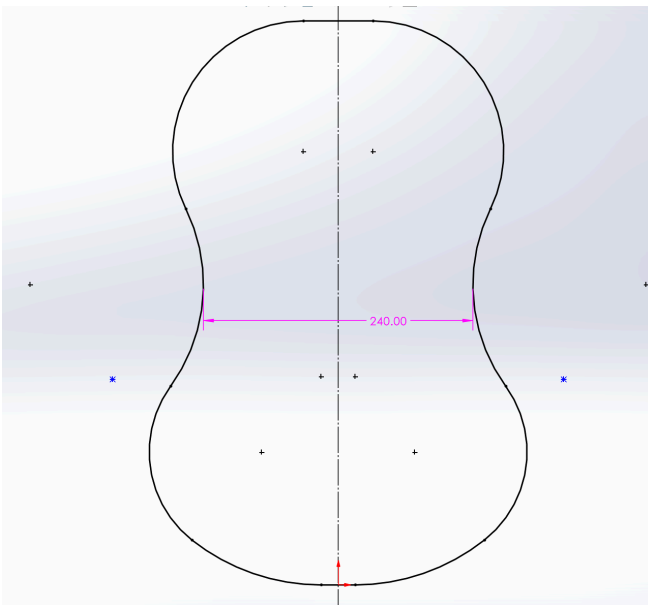
Bracing:

To test the importance of bracing, we ran simulations on the aforementioned loft thickness values but with the addition of an X-brace pattern for added support. While real-life bracing has a complex shape to gain maximum effectiveness with the least material, we simply wanted to study the strengthening effects of the bracing. Therefore, our bracing consisted of rectangular extrusions that were 10mm wide and 15mm tall, visually matching the references we used.



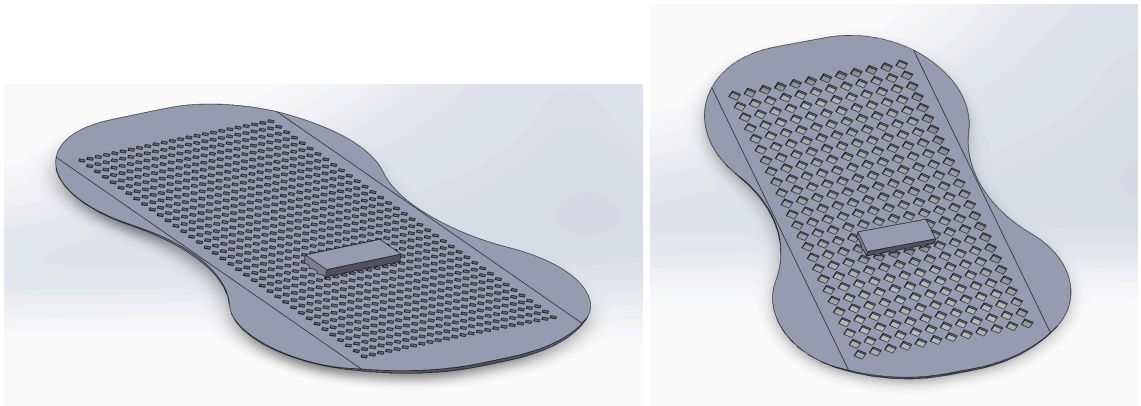
Pinch width

The pinch width of the soundboard, also known as the waist, is the width of the inwardly-curved segment near the middle of the guitar (pictured below, highlighted dimension). We chose this parameter for a similar reason to the loft thickness: it has an effect near where the load is applied, so it is likely to cause noticeable changes in the material properties.



Lattice:

This design variation was inspired by Professor Manzo, who talked with us about using our results to potentially design a guitar in a lattice pattern with overlapping strips of wood. While this exact design was difficult to replicate with our knowledge of Solidworks, we were able to approximate the structure by adding small diamond-shaped holes to the soundboard, similar to how a lattice would look and behave. We added one variation with a rather coarse lattice and another variation with a finer lattice to test the differences.



Miscellaneous:

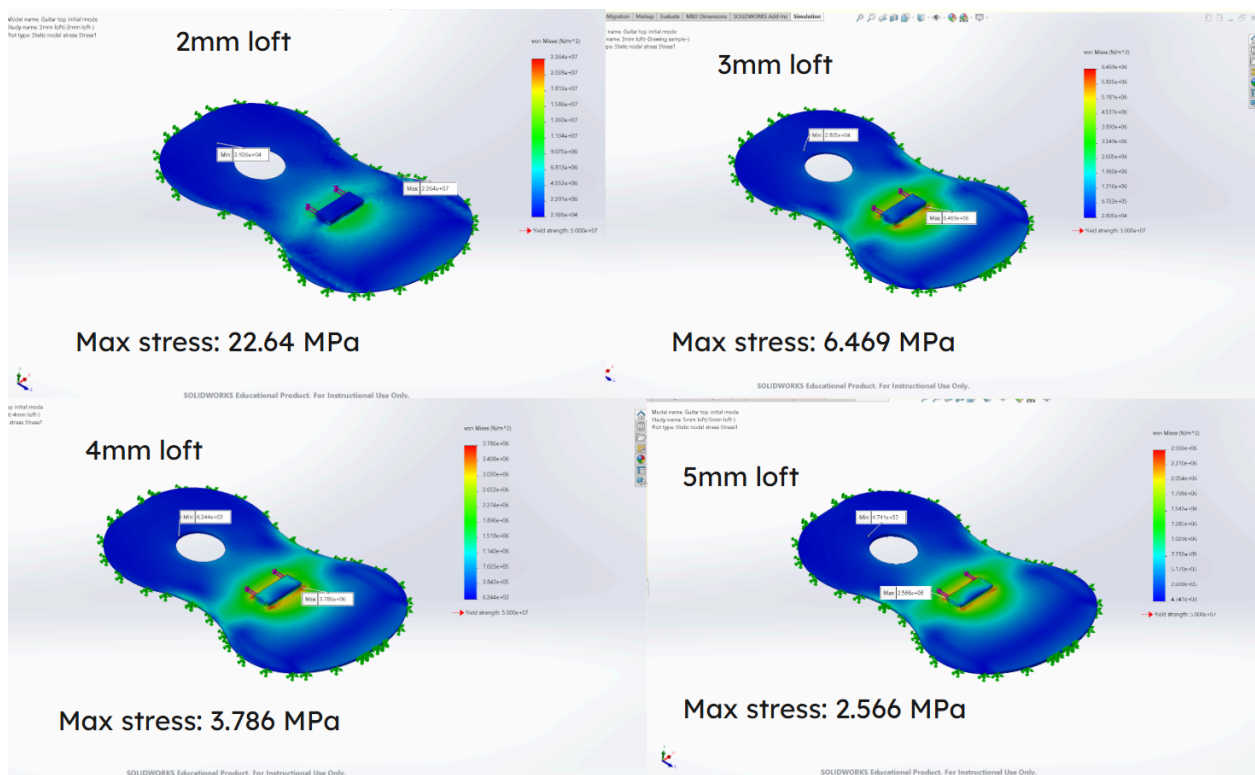
There were many more parameters we added to the model that we didn't end up studying in depth, either due to them not having much of an effect in initial testing, or due to them being very minor and seemingly unimportant parameters that we could not dedicate time to. Additionally, other parameters ended up being difficult to change without making the model invalid, so they were left in their default state. It could be beneficial to study these parameters more in future research, but we chose not to pursue them to limit our scope. These parameters included, among others:

- Size and position of the soundport
- Size and position of the bridge
- Thickness of the edges of the guitar
- Width of the upper and lower bouts (ie. the outwardly-curved segments at the top and bottom of the guitar)
- Radius of curvature of the loft and recurve segments

Results & Analysis

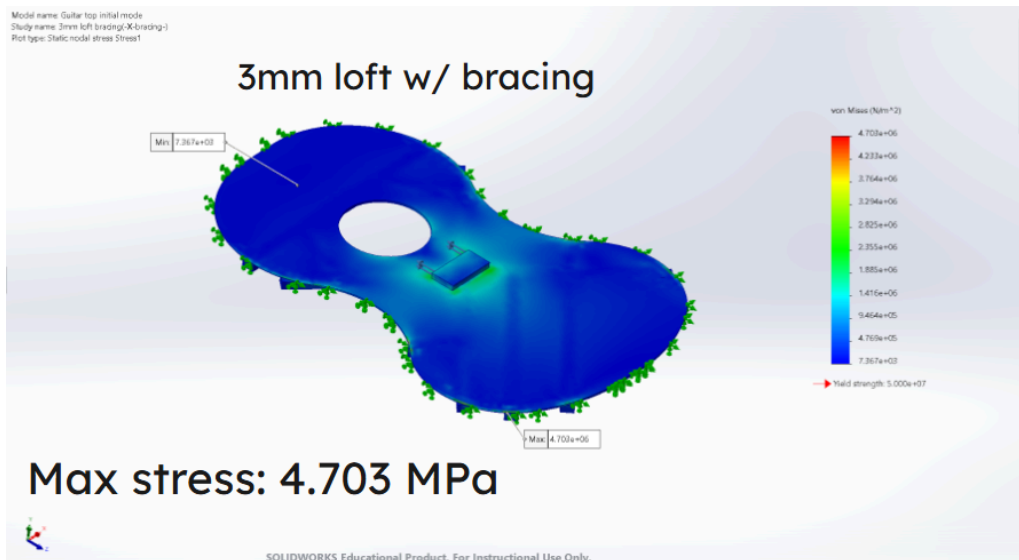
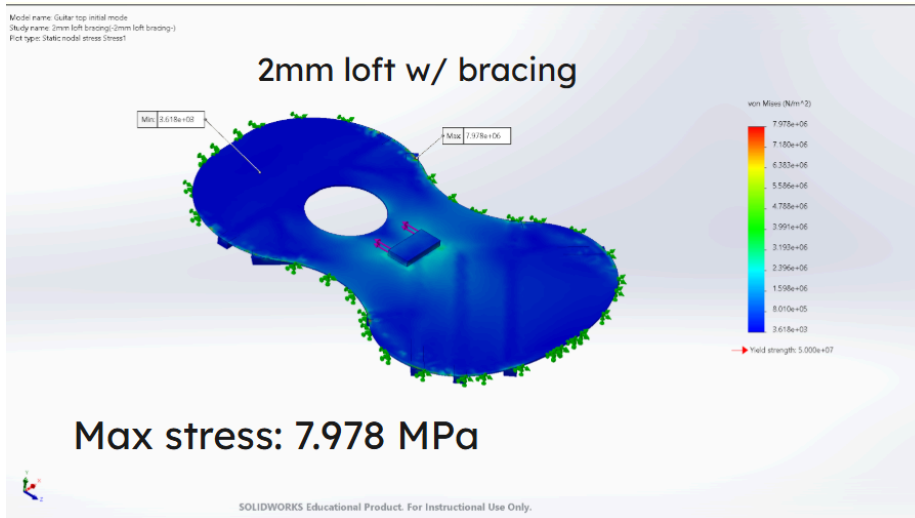
Loft thickness

The loft thickness had a predictable effect, where thinner plates led to a higher maximum stress due to the same force over a smaller area. However, there were diminishing returns where the stress plateaued for the thicker plates, not improving much beyond 3mm. However, the 2mm plate definitely had a higher stress than the others.



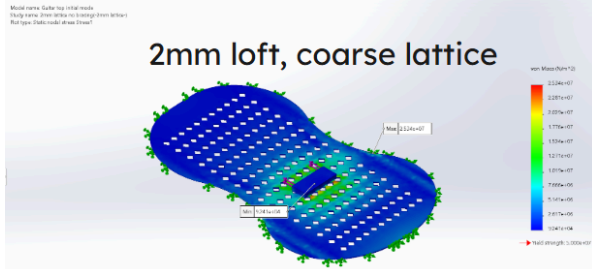
Bracing

As expected, the addition of bracing decreased the maximum stress a lot for the thinner plates, making them much less likely to fail. Additionally, similar to the last case, the presence of bracing had less of an effect on the thicker plates.

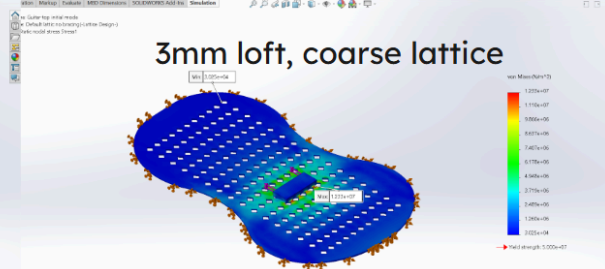


Lattice

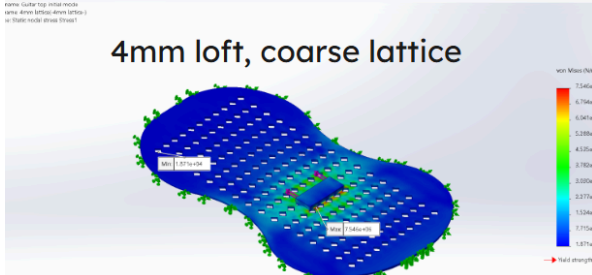
The lattice design decreased the overall amount of material and increased the number of jagged edges, increasing the points of high stress on the plate. The finer lattice made this more of a problem. The addition of bracing helped make this less severe.



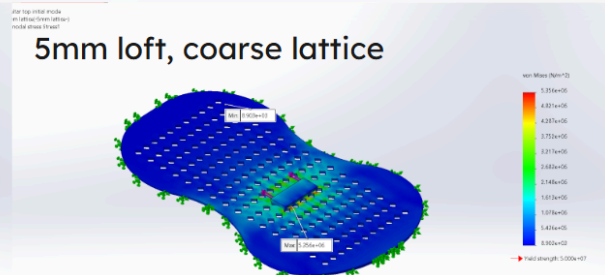
Max stress: 25.34 MPa



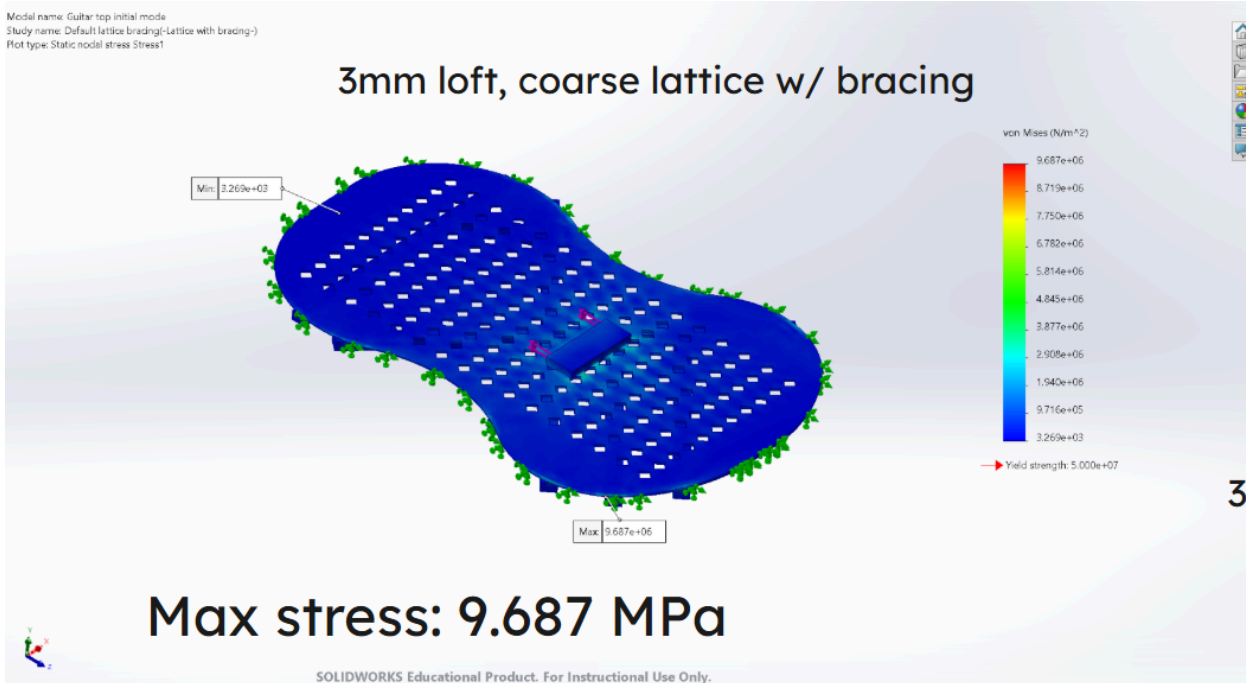
Max stress: 12.33 MPa



Max stress: 7.546 MPa



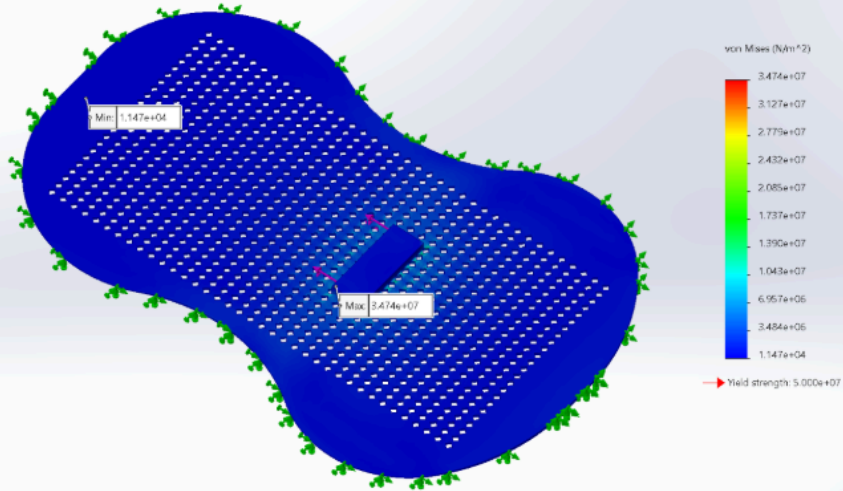
Max stress: 5.356 MPa



Max stress: 9.687 MPa

Model name: Guitar_top_initial mode
Study name: Finer lattice(- Finer lattice)
Plot type: Static nodal stress Stress1

3mm loft, fine lattice



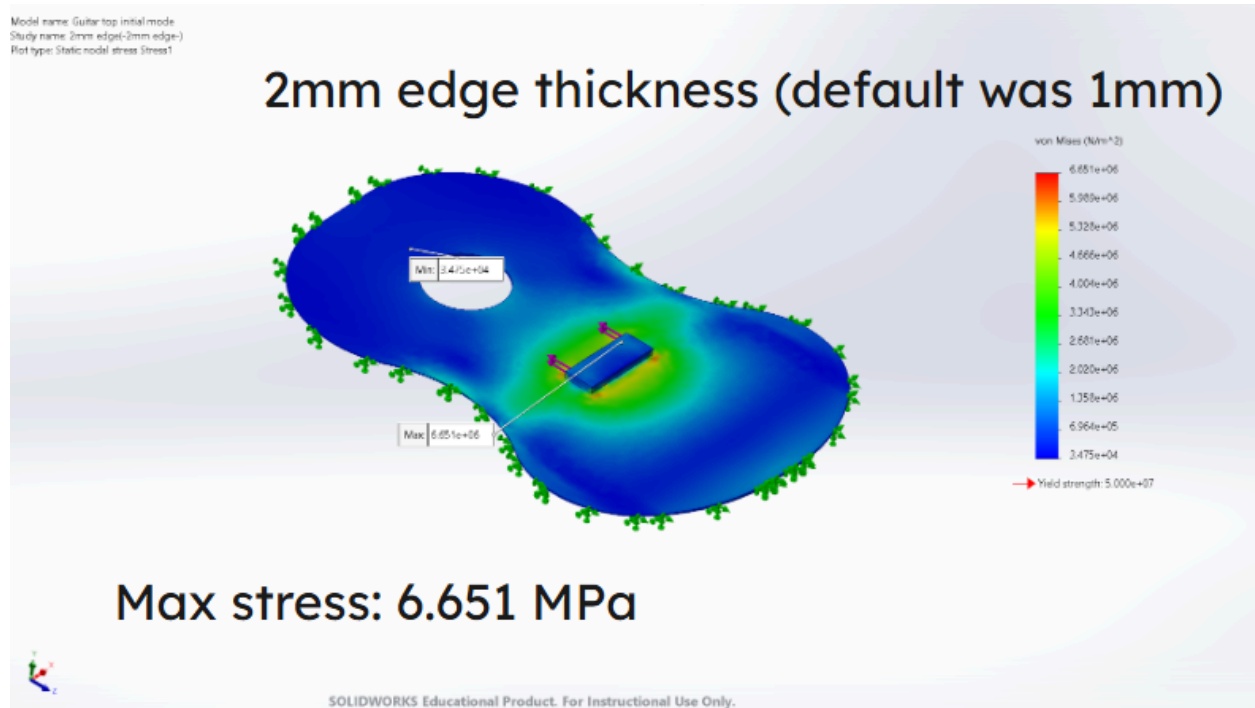
Max stress: 34.47 MPa



SOLIDWORKS Educational Product. For Instructional Use Only.

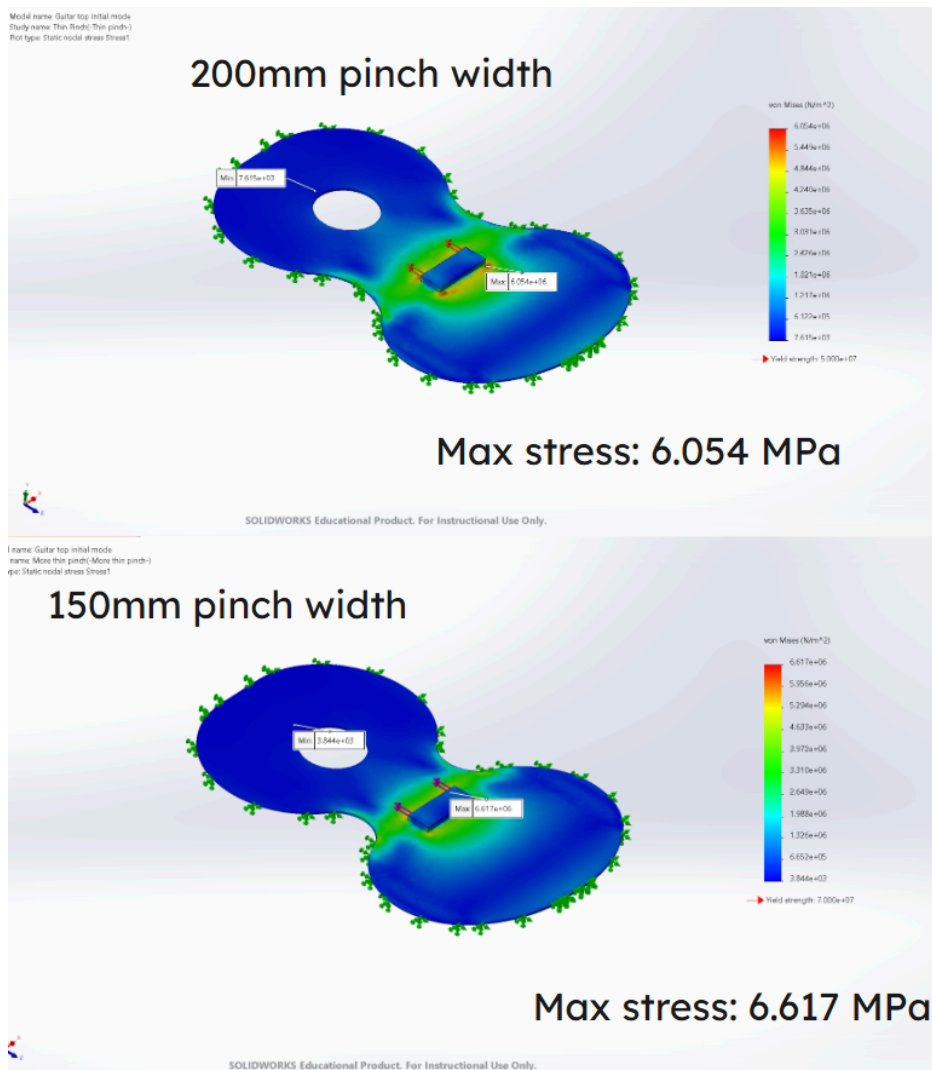
Edge thickness

As explained beforehand, the edge thickness was tested initially but was found to have very little effect on the stress experienced by the plate due to its far distance from the point of application of the force.



Pinch width

This parameter had some interesting behavior. The pinch width of the default model was 240 mm. While we had expected decreasing this value to increase the stress felt, it actually decreased a small amount when it was changed to 200 mm. We theorize that this is due to the way the geometry of the soundboard changes with this different dimension. However, we are unsure exactly what the cause is, especially since further decreasing the pinch width resulted in the expected increase in stress.



Discussion - Limitations & Challenges

- Material complexity: Wood is orthotropic so it is stronger along the grain. Our initial simulations used isotropic assumptions, which may oversimplify stiffness in certain directions
- Data scarcity: It was difficult to find specific structural dimensions for our guitar models so we used educated estimates based on our found schematics and general knowledge.
- Software learning curve: Transitioning from COMSOL to SolidWorks required significant time due to our initial guidance and time spent determining which would be best for our project. To determine the best software, we had multiple consultations with Dr. Hera, a senior scientific applications scientist in the Academic and Research Computing Support Group. Dr. Hera trained us to use the software, and guided us to narrow the range of our study to structural analysis.
- Time Restraint: Since we only had 7 weeks to work on this project, we were not able to expand our parameters very widely. Instead, we focused on developing a base method to test these parameters, so that more data can be gathered in the future using our model and method. We also focused our research on structural analysis of the guitar top rather than analyzing sound quality.

Future Work

The next logical step for future groups is to use COMSOL to see how the sound and frequencies of the guitars change after different design parameters are applied. Future groups should model the air cavity inside the guitar to see how the structural bracing

changes the air mode and volume. Another idea, if time allows, is validating a group's results by building a physical guitar top and measuring actual deflection.

Sources

Brauchler, A., Gonzalez, S., Vierneisel, M., Ziegler, P., Antonacci, F., Sarti, A., & Eberhard, P. (2022). Model-predicted geometry variations to compensate material variability in the design of classical guitars. <https://doi.org/10.21203/rs.3.rs-2014605/v1>

De la Cruz, G., & Castro, J. J. (2012). Acoustics of the guitar. *Revista Mexicana de Física E*, 58(1), 1–14. <https://www.scielo.org.mx/pdf/rmfe/v58n1/v58n1a1.pdf>

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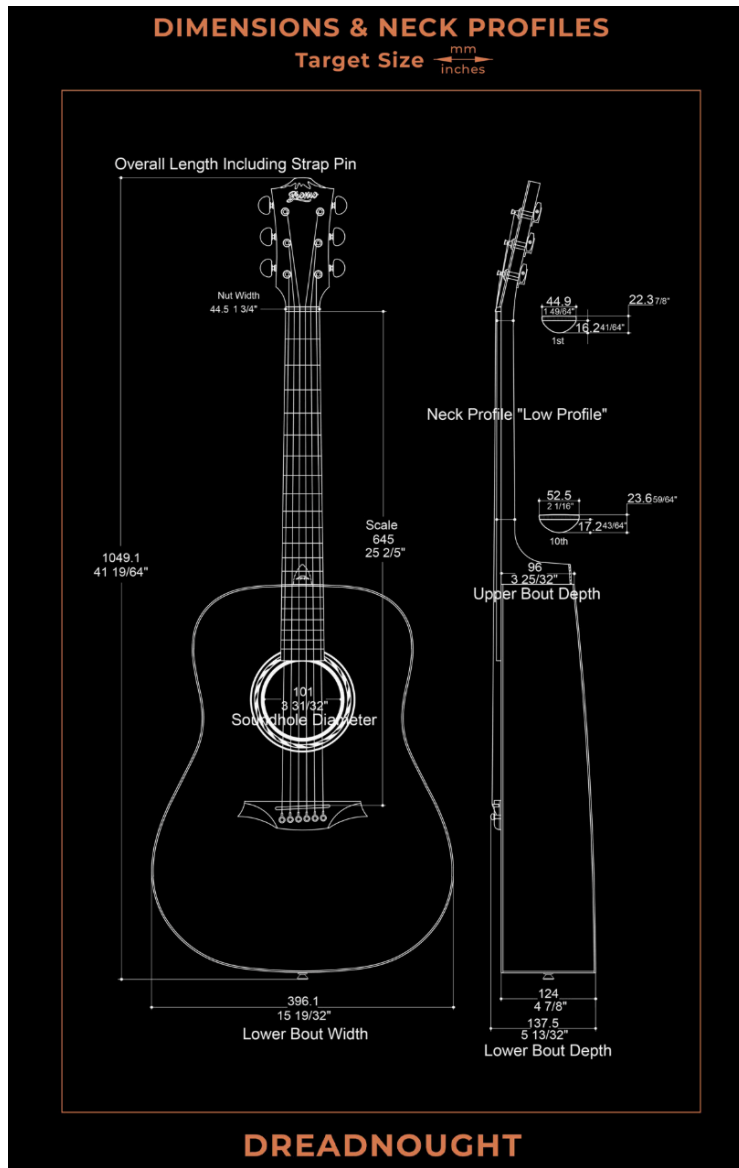
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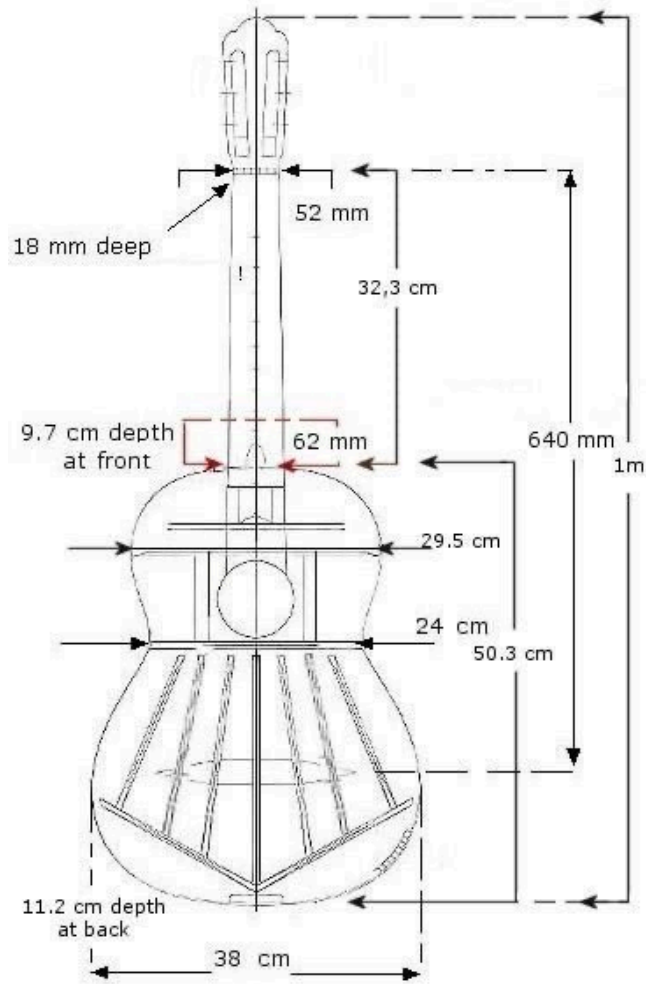
Viala, R., Placet, V., & Cogan, S. (2021). Model-based evidence of the dominance of the guitar brace design over material and climatic variability for dynamic behaviors. *Applied Acoustics*, 182, 108275. <https://doi.org/10.1016/j.apacoust.2021.108275>

Wolf, D., & Ruina, A. (2022). *Physics of the guitar*. Springer Cham. <https://doi.org/10.1007/978-3-030-89381-1>

Appendix

Default guitar measurements:





Sources for guitar schematics:

<https://bromoguitars.com.au/category/shape/parlour/>

Yield strengths of common materials:

https://www.engineeringtoolbox.com/young-modulus-d_417.html

Parameter Values for Default Model:

Model Parameter	Default value (mm)
Lower width@Base sketch'	336.6172

Upper width@Base sketch'	295
Pinch width@Base sketch'	240
Height@Base sketch'	503
Upper neck width@Base sketch'	62
Bridge declination@Base sketch'	317
Loft@Base Extrude	3
Edge thickness@Top arch	1
Loft radius@Top arch	6000
Recurve radius@Top arch	400
Recurve length@Top arch	50
Height@Bridge	30
Width@Bridge	80
Center vertical offset@Bridge	0
Thickness@Bridge extrude	10
Diameter@Sound hole	80
Declination@Sound hole	100