

Vibrational Analysis of 3D Printed Structures for Ideal Characteristics

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ABSTRACT

Vibrational Analysis of 3D Printed Structures for Aerospace

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The purpose of this project is to create data and research the vibrational characteristics of 3D printed structures and the effects of various 3D printing parameters on those characteristics. Using school utilities and a personal printing machine, a complete process for manufacturing and analysis was done. FDM was used to print the structures used in the project while a combination of Ansys and SolidWorks were used for modelling and simulation. Data was recorded and calculations were done to find specific values. An increase in the infill density led to a general increase in the stiffness of the system. Adding an angle to the printed structure also provided greater stiffness with angles greater than 15 degrees providing less improvements to the stiffness. Data accuracy is confirmed through coherence for recorded data. Further tests should be done to improve the accuracy of the data through refined variation in parameters and material testing.

ACKNOWLEDGEMENTS

I acknowledge knowledge.

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Symbols

Symbol	Definition	Units (SI)
Q	Quality Factor	
Greek Symbols		
ω	Natural Frequency	Hz
ζ	Damping Coefficient	
Subscripts		
Acronyms		
SLA	Stereolithography	
SLS	Selective Laser Sintering	
FDM	Fused Deposition Modeling	
CAD	Computer Aided Design	
FEM	Finite Element Analysis	
PLA	Polylactic Acid	
FEM	Finite Element Method	
FEA	Finite Element Analysis	
STL	Standard Tessellation Language	

1. Introduction

1.1 Motivation

3D printing has become a widely adopted method to create a wide variety of structures. It utilizes additive manufacturing, a form of manufacturing that continuously builds a structure layer by layer [1]. Its ability to create complex shapes quickly and cost effectively has made it a high priority tool for many, whether it be from someone using it for a hobby or an engineering company using it for manufacturing parts. The increased use of 3D printing brings it closer to becoming one of the most popular manufacturing methods. The expected outcome of this is it being introduced to largescale industries.

In the current aerospace industry, 3D printing has become a relatively new method to manufacture lightweight parts. Airbus has been using 3D printed brackets and venting pipes in planes such as the A320 and A350 starting in 2017 with success in reducing time and weight [2]. Its capabilities were proven and show signs of maintaining their presence within the industry. Other aerospace companies have also adopted this method around the world and thus make this method quite popular.

Since this has been a recently adopted method, there is little development made to improve or analyze the method. Although there are many articles on the capabilities of 3D printers and different filaments, there exist only a handful of research done specifically for the effects of 3D printing settings, such as orientation or direction, on the mechanical and vibrational characteristics of the structure. There are many aspects to 3D printing that are effective in creating a proper structure such as techniques and setting parameters. This leaves room for more research and further improvement of the additive manufacturing method otherwise known as 3D printing.

1.2 Literature Review

1.2.1 General Knowledge & History

Additive manufacturing, later known as 3D printing, was an idea originating in the 1980's as a resin polymerized by UV light popularized by Chuck Hull as stereolithography (SLA) [3]. The .stl file format that he created is still used in the current state of 3D printing, further amplifying his contributions and his significance to the history of 3D printing. The following methods of 3D printing to come after Chuck's SLA were selective laser sintering (SLS) by Carl Deckard in 1987 and fused deposition modeling (FDM) by Scott Crump in 1989 [3]. SLS utilizes lasers to solidify powder materials whereas FDM extrudes filament, typically a form of plastic, through an adjustable nozzle. FDM and SLA make up many 3D print types used, with FDM being the most popular due to its cheaper costs and ease of use [4].

A significant event that occurred in the market of 3D printing was the expiration of patents for FDM technology by Stratasys owned by Crump. The main patent for license of the FDM method expired on October 30 of 2009 and following this, an open-source project called RepRap was released. The market price for owning a 3D printer dropped significantly right after these events [5][6]. It is still speculated what caused the drop in prices but the increase in competing FDM based 3D printers is argued to be the largest contributor. The favor for FDM based 3D printers remains as a recent study by HUBS in 2023 revealed that 56% of people used FDM as

their primary method of part manufacturing, the next most popular only being 20% [7]. Thus, the focus of most research including this paper will be focused on FDM based 3D printing.

1.2.2 Analysis of 3D prints

3D prints have various parameters to change how a structure is made. These parameters include layer height, infill, shell thickness, etc. Adjusting these parameters is expected to affect the structures' mechanical properties.

A recent article has indeed shown that the layer height, when varied, can leave significant effects on the tensile strength of a structure, with the strength maximizing at a height of .3 mm [8]. The study was conducted using a varying layer height from .1 to .7 mm and the value for tensile strength was calculated from a measurement of roughness of the structure. The exact calculation made was through an equation relating the ultimate tensile strength to the hardness and a coefficient as stated by Gasko and Rosenberg [9].

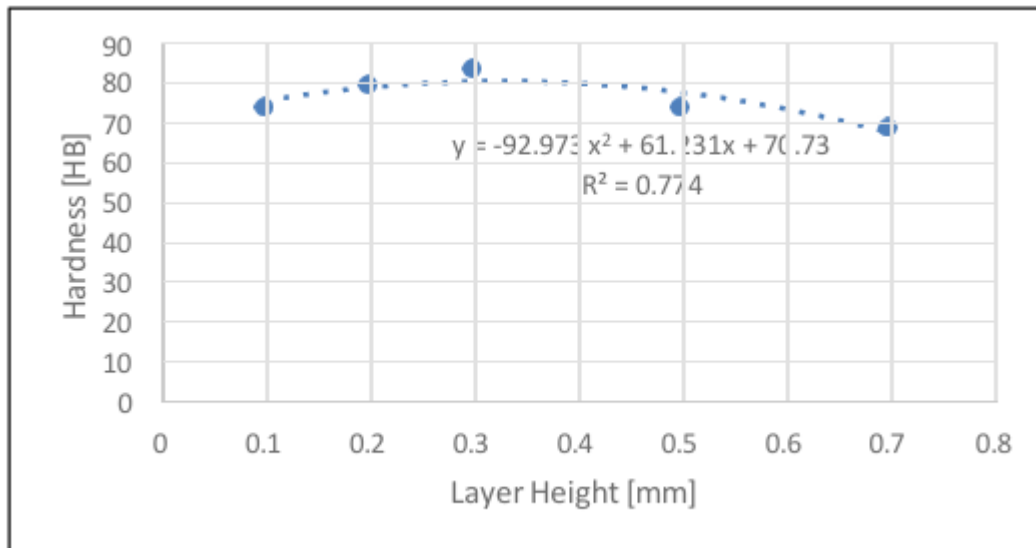


Figure 1.1 – Hardness compared to layer height results by Suprpto et al. [8].

Since the result for maximum tensile strength appears at a height of .3 mm, it can be concluded that too small of a layer height or too large can lead to reduced tensile strength, although further explanations were not made [8].

A significant discovery, made by a team working at the University of Navarra in 2025, has shown that small printing events such as the points of intersection can occur during the printing process that resulted in a 14%-20% error between the experimental and simulated mechanical characteristics with the experimental results showing stronger characteristics and the simulations results showing weaker characteristics [10]. These intersections occur during printed layers when the patterns of the infill overlap during the same layer. Their research was done using a combination of CAD and FEM in Ansys Workbench and using a wavy infill design for their structure. The wavy infill design is the pattern they chose to use for their infill and appears like a grid pattern, but the wavy design replaces the lines with waves. The points of when the waves connect like the grid pattern are the points of intersection mentioned before. Because of the way printing works, points of intersection cause an additional bit of material to build on top of that

point since it does not smoothly print through a previously cooled line and overlap can occur at the connections of infill to the walls of the structure [11]. This makes the structure slightly stronger since the joints appear to have a stronger connection due to the added material. The team studying this error concluded that it is necessary to add correction factors to their simulated values to account for the extra area being added to the structure, which they concluded to be a 25% increase due to intersecting errors and an 8% increase due to the added material in the structure [10]. Although the exact values may change based on infill design, this is a significant development regarding properly simulating the mechanical properties of a 3D printed structure and the assumptions to be made when comparing a simulated structure to the experimental. This also shows the capabilities of 3D printing and the ability to successfully analyze the structure.

Another study in 2020 on the structure of various infill designs for tissue scaffolding tested the ability to properly predict mechanical behaviors using CAD and FEM analysis and was successful [12]. This study is important as it covers yet another parameter of 3D printing, the infill design, and measures their mechanical characteristics and provides further support for the ability to apply FEM analysis to a simulated 3D printed structure. In this case the experimental values matched very closely to the simulated values as compared to the previously mentioned study. This is due to the infill design being printed as scaffolding rather than printed in the same elevation as one another, thus avoiding the errors caused in traditional 3D printing [11] [12]. Concluding this topic, it is not necessarily a negative error. Rather, the error is simply based on proper FEM analysis of a real 3D printed structure.

1.2.3 Typical Errors and Solutions

In a study found by a team in 2023 researching printing in the food industry, it was noted that errors had also occurred around points where the nozzle had to reset its position [13]. This error in the print is called oozing or stringing and is caused when the material from the nozzle leaks during travel points in which there should not be any extrusion [14].

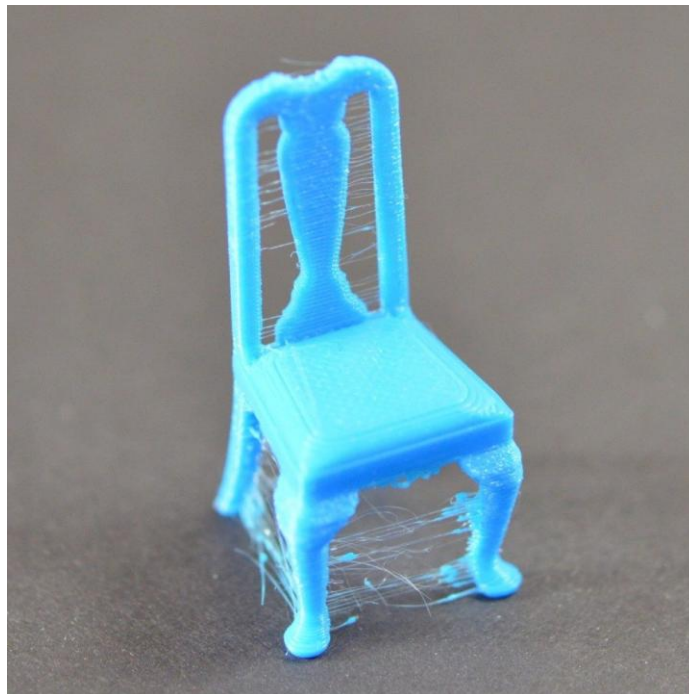


Figure 1.2 – Typical oozing/stringing error on a 3D printed chair [14].

The cause of such errors is mainly due to incorrect temperature settings in either the nozzle or the environment. Since the team was working with a material that had a low melting point it was too difficult to adjust the temperature correctly, thus an appropriate solution to the oozing error was to increase the retraction speed and pull the material back further before it could leak during transport [13]. There already exists a default retraction speed to reduce the effect of oozing, but in this case, it had to be increased further. Solutions that can be made in addition to the retraction speed are to adjust the retraction distance, to ensure the filament does not leak, and to increase the nozzles travel speed as this will reduce time for an error to occur [14][15].

Analyses have also been made in terms of 3D printings using different materials. A study from Sukkur IBA university tested the capabilities and measured multiple physical characteristics of structures made with various materials using FDM, the result of which revealed that PLA is the most ideal material in terms of accuracy and ease of use due to its thermos-capabilities and surface behavior [16]. This result is also reflected in the current popularity of Polylactic Acid (PLA), being one of the most common forms of material used in the use of FDM 3D printing [17]. This study also introduces yet another error that may occur during printing and that is warping that was seen to be very common with the material Acrylonitrile Butadiene Styrene (ABS) [16].

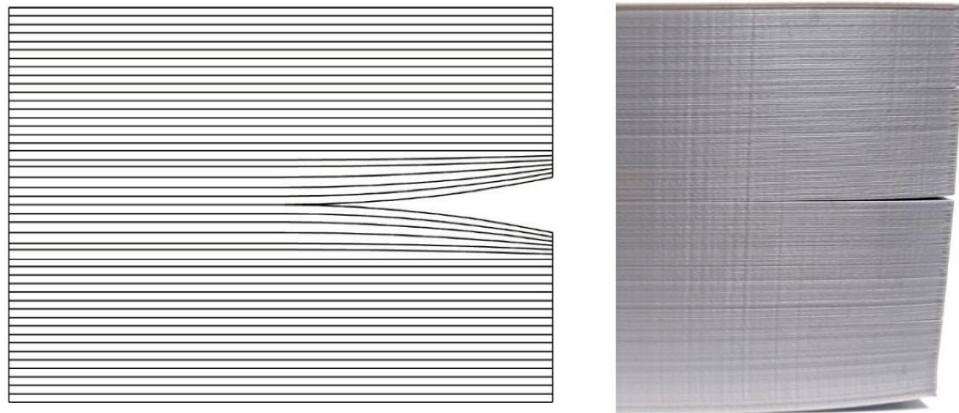


Figure 1.3 – Warping at bottom and middle of structure [19]

Warping occurs due to the extruded material cooling and thus shrinking, lifting the structure off the build plate or causing it to twist and thus altering the structure of the print [18][19]. Warping is more prominent as structures become wider rather than taller but can still crack due to internal stress at a certain level of height, thus it is recommended by Ramian to print with the widest surface applied to the bottom with an applied “brim” to reduce warping [19]. Proper heating of the bed and nozzle also reduces the effects of warping. This is because the difference in temperature between the bed and material may reduce the adhesion between the two.

Infill density is a parameter specific to 3D printing that influences the porosity of the modeled structure. Increasing the density will bring it closer to being equal to a completely solid structure of the material of choice. Theoretically, increased infill density should lead to more strength of the structure, and this is proven in a study by Joana when they measured the strengths of varying densities [20]. A comparison of PLA and tough PLA was also made during this study. PLA tough is a modified form of PLA made to have increased mechanical properties; the one used in this study is developed and sold by Spectrum in Poland [20][21]. The results of their study revealed

that the properties of the tough PLA performed worse than the normal PLA for most of the experiments, only performing better during tests for energy absorption at one to two layers and afterwards being beaten at increased layers [20]. There is no conclusion about the possible reasons as to the tough PLA's performance issues.

1.2.4 Techniques and Innovations

Breakthroughs in techniques to improve printing have also been studied and published. A recent study by Kim et al. analyzes an alternative G-Code [22]. Typically, an infill pattern is generated at the point of converting a model into G-Code and the nozzle position is reset to an origin for each layer of that infill. By using an open-source alternate G-Code like FullControl they were able to create their own infill instructions. FullControl is an open-source custom G-Code created by Dr. Gleadall at Loughborough University to have full control over the printing and splicing process of 3D printing [23]. FullControl offers incredible detail in the design of 3D processing, allowing for specific instructions and settings at every segment of the nozzles pathing and further improving aspects of speed and accuracy during actions such as infill [24]. The method introduced by Kim et al. altered the normal pathing of the nozzle during infills to be adjusted to ideal angles, thus improving its typical time and improving its mechanical characteristics [22]. The results of their study were able to reduce the time to print by 10% to 30% based on increasing infill density and revealed an increase in ultimate tensile strength at around 15% at an infill density of 30%, its additional increase going down as infill density approached 100% at which point the increase in strength was no longer prominent [22]. A combination of the release of the open-source G-Code FullControl and the methods for specific infill instructions shown by Kim and their team allows for an improved method compared to typical 3D printing and opens the door to a wider range of significant improvements to techniques in the future.

Typical movement of the printer head consists of various cartesian based systems, two of which are ideal and known commonly as H-bot or CoreXY [25]. H-bot utilizes a single belt whereas CoreXY uses two that work opposite each other, thus minimizing the error caused by torque in the H-bot system [25][26][27].

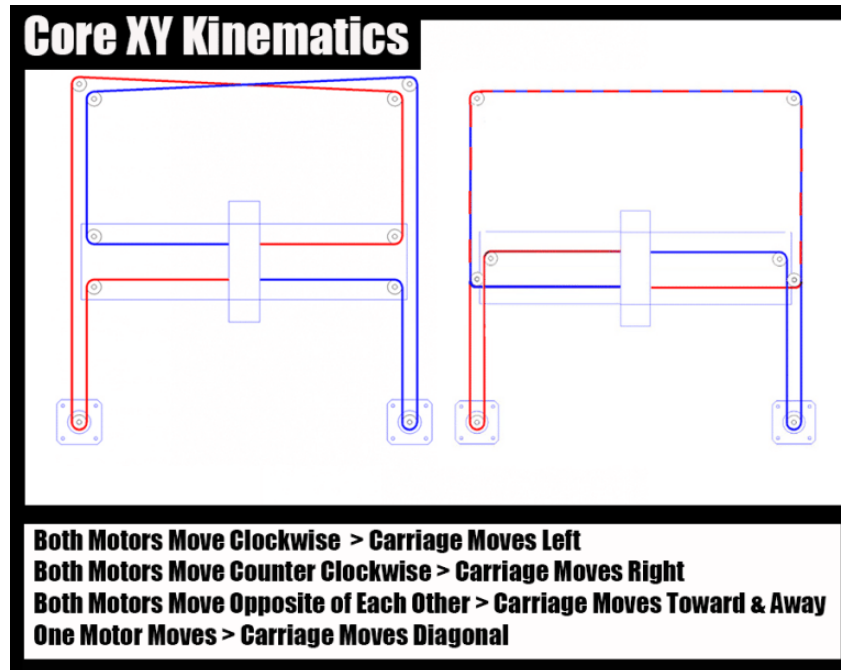


Figure 1.4 – Example of CoreXY kinematics system [28].

Development of a new system that utilizes the compact and efficient design of the H-bot and the dual belt system of the CoreXY was done in 2022, ending in success and deemed the CoreH-bot [29]. The newly realized design can compete with other cartesian based systems according to studies done on the behaviors of the system by Edoardo and his team who were the creators of the new design.

A test on accuracy by Jeong et al. between a high-end dentist's milling machine and a 3D printer was done in Korea [30]. The milling machine used was an Arum 5X-200 which can be purchased for around \$100,000 and the 3D printer used was an unspecified Zenith printer, most of which can be found being sold online for around \$1000 [31][32]. The results for prices were found through public websites and offers not direct to the related companies due to the locations being fixed in Korea. Ignoring the original purpose of the study, the price difference alone shows significance to the introduction of 3D printing into the manufacturing industry. Using RMSs to calculate the difference in error between the Arum and Zenith, the test revealed a significantly lower RMS error in the 3D printed results compared to the results of the milling machine [30].

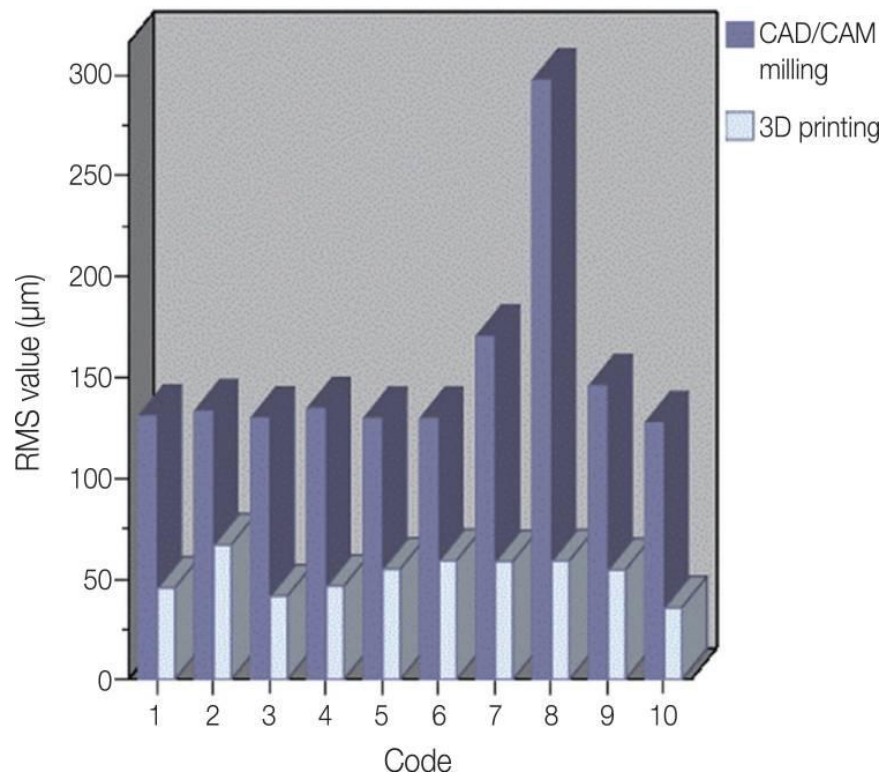


Figure 1.5 – RMS error comparison between Arum 5X-200 and Zenith 3D printer [30].

From the results of their data in Figure 1.5, the difference in RMS error between the miller and 3D printer is of significant value. It can also be concluded that the 3D printer performs more constantly in comparison to the miller.

A new technique studied in 2021 by a team in Poland inverted the direction in which an FDM printer extruded [33]. By placing the printing board above and printing with the extruder pointed upward, they found that the mechanical properties were higher than that of a typical downward facing extruder although very small in difference. The researchers hypothesized that this could be due to the heat convection allowing for a better environment. Further explanation for this can be seen from a previously referenced study regarding the increase in cracking and warping by Ramian, showing that by inverting the printing mechanism it possibly relieves some of the stress of the structure [19].

1.3 Project Proposal

Since 3D printing can be an ideal method to manufacture parts, it would be in our best interest to analyze the capabilities and properties of their print structures. The goal of this project is to analyze the structural properties, such as the static and vibrational properties, of 3D printed parts and verify the effects of:

- Print orientation on natural frequencies
- Infill density on stiffness and dampening
- Anisotropy printing on directional vibration behavior

These varying parameters will be applied to a beam structure of consistent size to properly measure the effects of the parameters. Using the results of the analysis, conclusions will be made on the characteristics of the structures and variable settings to allow ideal techniques for 3D printing in the future.

1.4 Methodology

The timeline of the work for this project will be broken into two separate phases. The purpose of this is to allow focus on both the computational simulations and the experimental measurements of the total analyses. Phase 1 will cover the computational simulations, including the process of studying and modeling the various parameters to be simulated.

1.4.1 Phase 1

The first phase of the project consists of simulations of structures to create reference data in preparation for physical analysis in the second phase. This will be done through a combination of FEM analysis and 3D modeling to create simulations of variable parameters applied to the bar and cylinder models. Creating this analysis will allow for hypothesis' to be made on the characteristics of the 3D printed structures and their capabilities.

A secondary goal of the first phase is to research methods of 3D printing as further preparation for real-world physical analysis. Current options for 3D printing are to utilize a personal station in which there is no restriction of use or to use the public 3D printing stations accommodated by the school. Unfortunately, the accommodation for school is limited to a single print per person per month. This is less than ideal since there will be variable printed structures; thus, a personal station will be prepared and used.

1.4.2 Phase 2

The second phase of the project begins with the physical printing and designing of models with various parameters according to the project goals. These parameters are adjusted within the settings of the 3D printer interface to create various structures. The structures themselves will be rectangular beams of a consistent size to emphasize the effects of the changing parameters on the characteristics.

Once the structures are made, physical analysis can be done by utilizing measuring tools on site of the SJSU campus. These tools will be used to measure frequencies, stiffness, and dampening. Once the analysis is completed, comparisons will be made on the results of the analysis, and the second phase may be concluded with further comparisons, discussions, and conclusions of the analysis and results.

2. Preparation & Theory

2.1 Visualizing of 3D Printed Parameters

The goal of this project is to compare and measure the effects of varying 3D printing settings on the vibrational characteristics of a structure, in this case a beam. The 3D printing software used in this project is Ultimaker Cura 5.10.1. To begin with, a 3D model needs to be imported into Cura. A simple beam model of 150x30x5 mm was created in SolidWorks.

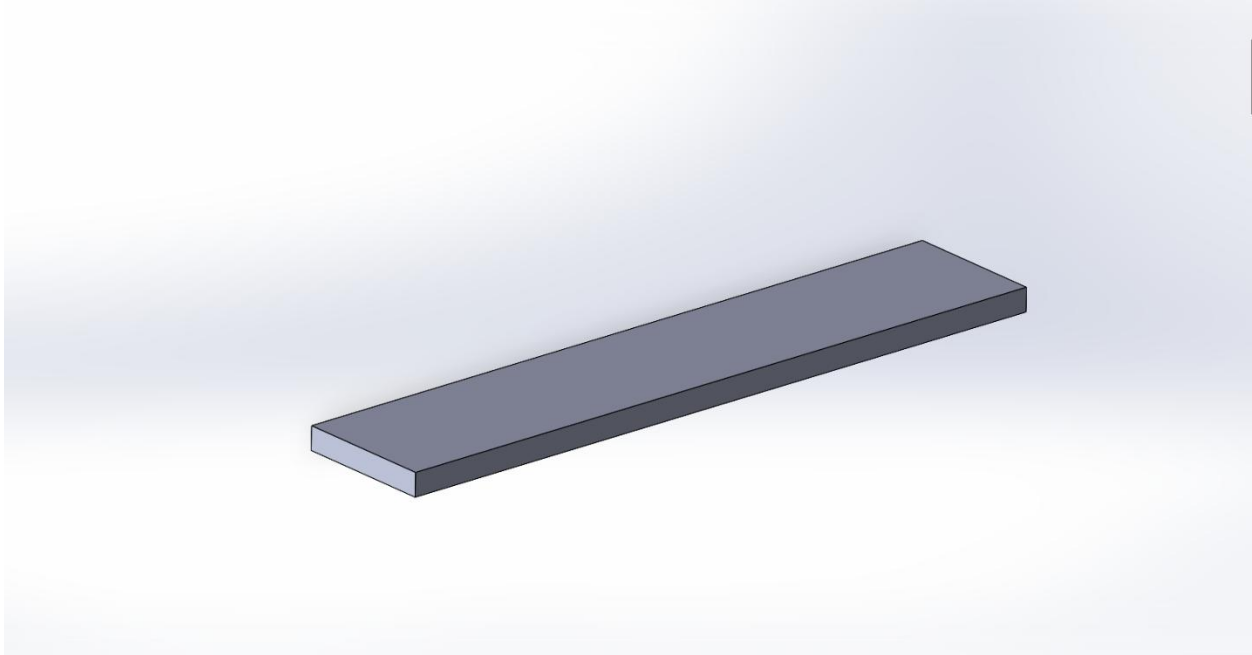


Figure 2.1 – A 150x30x5 mm beam created in SolidWorks.

Once the beam was created in SolidWorks, it was imported into Cura. The file must be saved as an STL (Standard Tessellation Language) file before being imported to Cura. Cura allows for various printing parameters to be changed. This project focuses on the infill density setting and the movement tools to adjust the angle of print and the orientation, thus the infill design will remain as the default grid setting with a 10% minimum infill density throughout the project. Selecting the appropriate settings and clicking splice will create the g-code file in which it can be printed. A preview is available for the file where each layer can be seen allowing for a view of the inside of the structure. These previews are important as they will be used as references when modeling for each specific variable parameter. Aside from the specific parameters mentioned for the project goal, the parameters for the 3D print are left on the default parameters for standard quality. This means that the walls of the structure are .8 mm thick and each layer is printed at .2 mm in height.

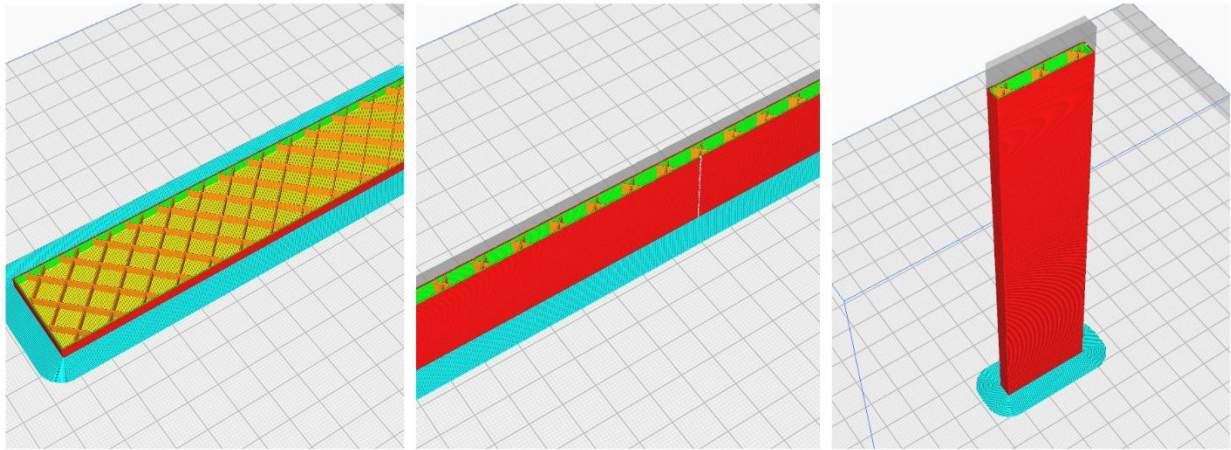


Figure 2.2 – 3D slice preview of various orientations of beam in Cura.

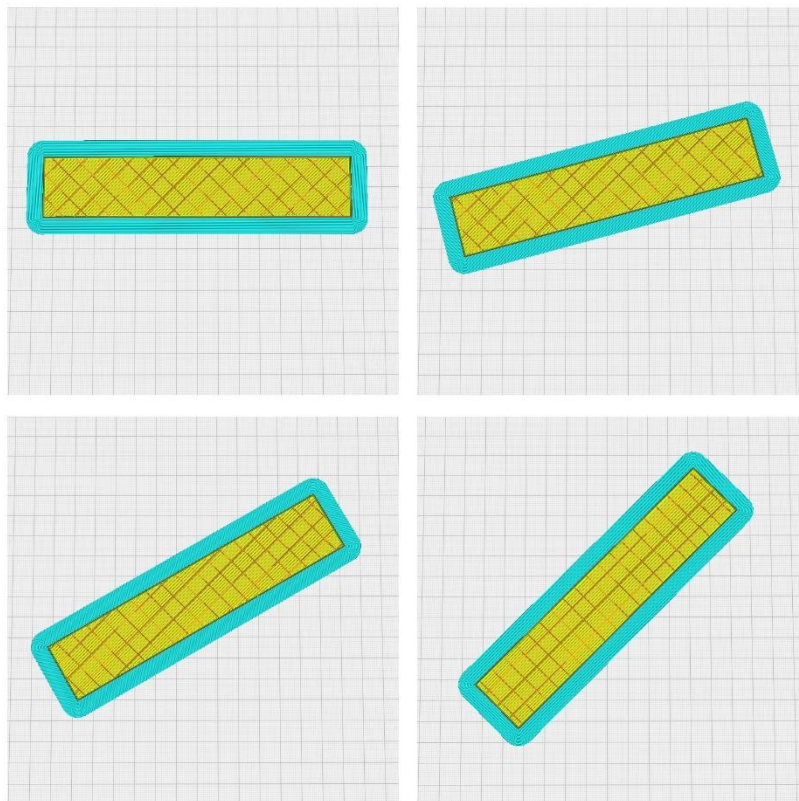


Figure 2.3 – 3D slice preview of variable angles of beam in Cura.

Something interesting to note when viewing the infill of the 3D preview is that the design of the infill does not move with reference to the structure of the beam. This gives insight into the fact that the angle at which a structure is printed may affect the mechanical properties.

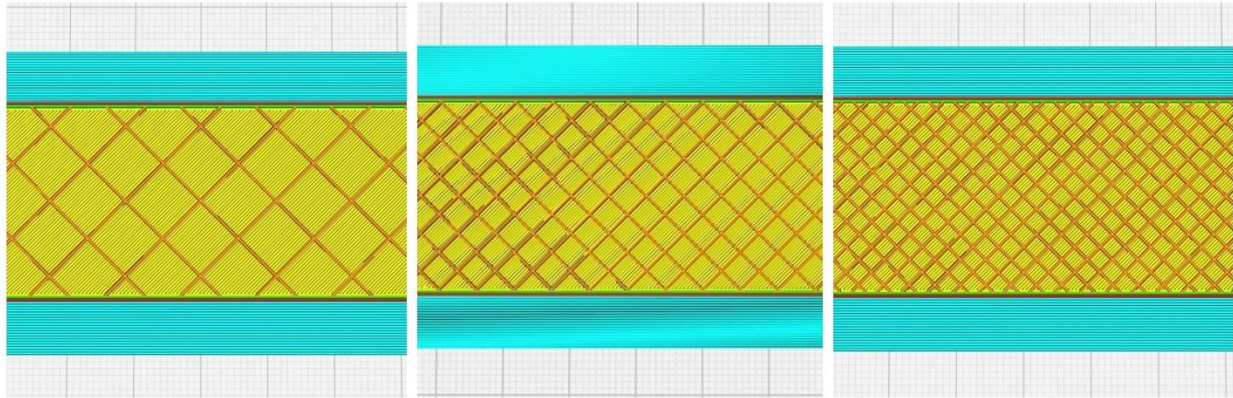


Figure 2.4 – 3D slice preview of variable infill density in Cura.

When viewing the 3D preview of the various infill densities, the increase in density is consistent but also is simplistic. When increasing the infill density, there is no change from the 10% infills position. From 10% to 20%, the lines are simply twice as often with two times the tighter distance between repetition. This remains the same with 30% being equal to three times. This is helpful information for modeling later since details regarding the specific instructions for the software are not public.

The figures shown are sliced to layer 7 to view the infill pattern within the structure. The final print is completely covered by .8 mm of wall on all sides. The cyan colored area represents the brim applied to the print to ensure that warping does not occur.

Summarizing the details of the 3D previews of the various parameters, it is seen that the pattern for infill always originates from the midpoint of the structure. The infill pattern also seems to be in reference to the printing board itself rather than the location or position of the structure. Infill densities also appear to increase linearly based on the infill density in comparison to a 10% infill density. It is still unsure what equations are used to calculate the original infill densities as the specific instructions for Cura's infill density are not public. Parameters not varying in infill density will be given a 10% infill density. Using this set of information, it is possible to begin modeling the 3D previews back in SolidWorks to be used for finite element analysis.

2.2 Modeling Variable Parameters

Using the information gathered from Cura and utilizing the 3D previews as references, the process for modeling the beam with the infill designs included can now begin. Once again, SolidWorks 2025 is the application being used for modeling the structure of the beam and its various parameters. Using the beam previously modeled as a starting point for each modeled parameter, detailed modeling can begin. Since there will be a 10% infill minimum on all designs, it is crucial to be able to accurately model the infill. A technique was used to recreate the infill pattern within SolidWorks. The basics of this method include using a copy of the shelled model and one set of lines in each direction and then combining the solid bodies back together later to complete the grid pattern. The values for the width of the infill lines are set to .4 mm according to the nozzle of the Ender 3 specifications. The widths of the walls, including the roof and flooring, are set to a thickness of .8 mm.

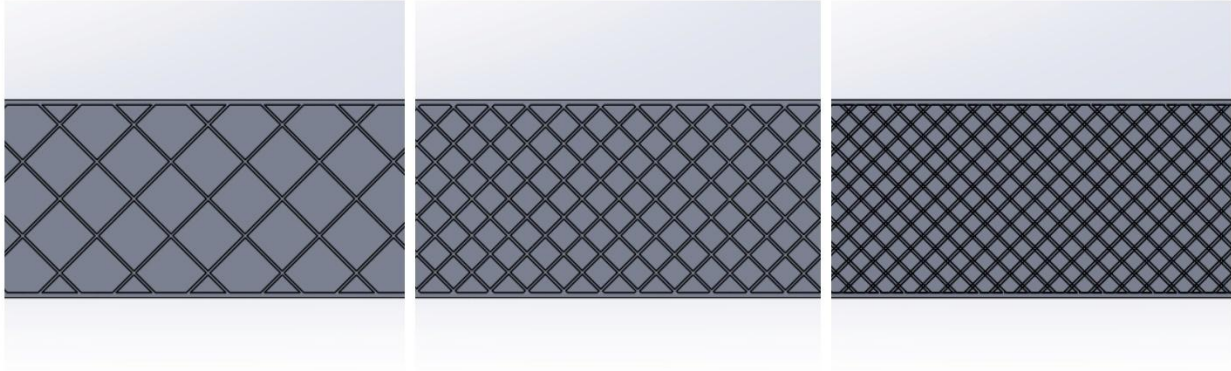


Figure 2.5 – 3D slice of 10% (left), 20% (middle), 30% (right).

Since the pattern always begins at the center of the beam, it can be replicated easily. The density increase by percent directly leads to an increase of the number of lines by double for every 10%. The lines were hand counted to a certain value to prove this theory. The distances between each line were adjusted as closely as possible to resemble the pattern from Cura as their exact measurements and calculations are not available.

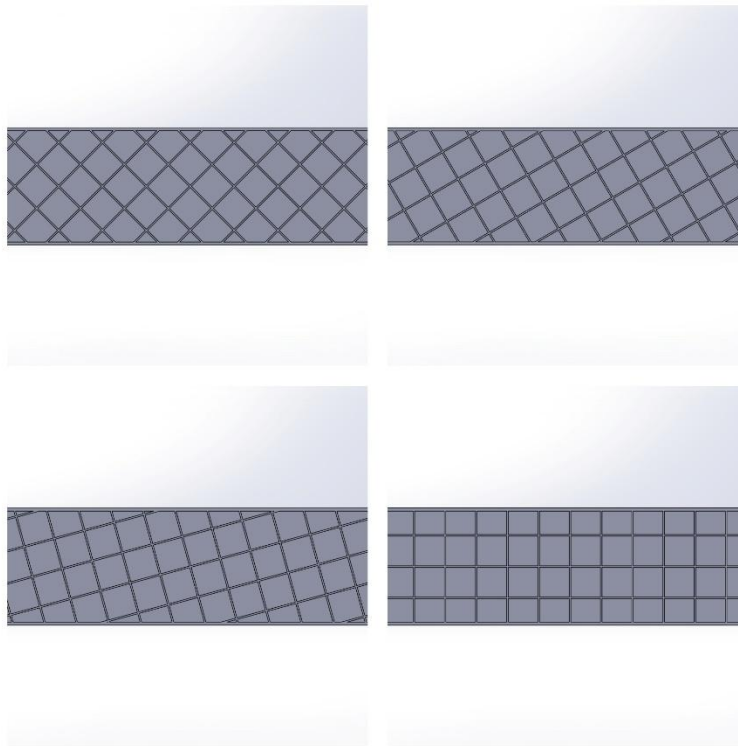


Figure 2.6 – 3D slice of 0° (top left), 15° (top right), 30° (bottom left), and 45° (bottom right) in SolidWorks.

Since the movement of the printing nozzle is omnidirectional, the walls and printing layers are the same despite the angle. The only visible change from changing the angle of the structure is the way the infill pattern is printed. As seen from the Cura preview, the pattern follows the same

change directly as the change in angle of the structure's position, making it easy to recreate when modeling.

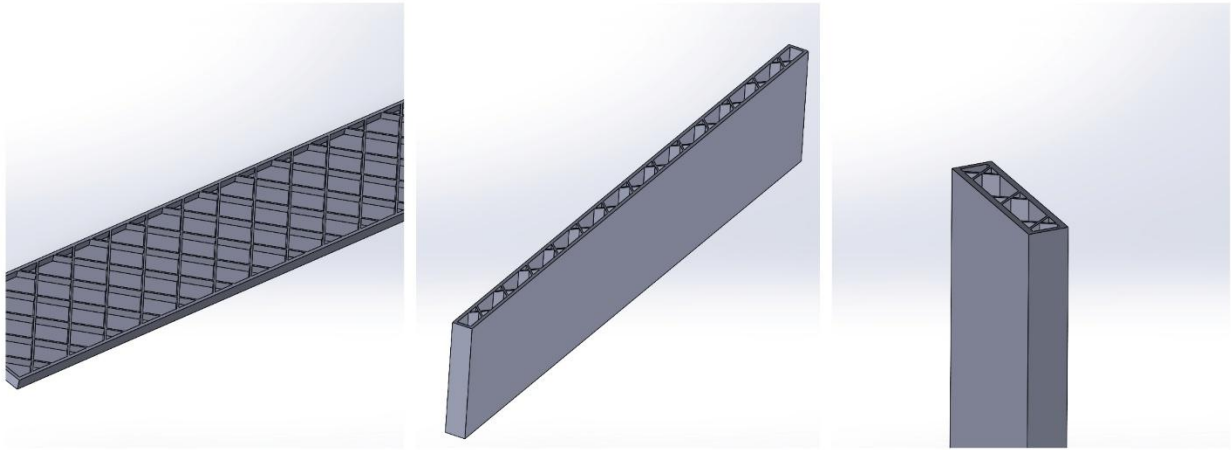


Figure 2.7 – 3D slice of beam in a flat (left), side (middle), and vertical (right) orientation in SolidWorks.

The flat orientation shown in Figure 2.7 is virtually the same as the other 10% infill beams shown for a 0° angle in Figure 2.6 and a 10% infill in Figure 2.5. Changing orientation once again affects the way the infill pattern is printed, which may lead to a difference in mechanical capabilities as expected. Now that each model has been created for the varying parameters, tests can be made on both the printed and 3D model beams.

2.3 Simulation approach

A significant part of this project is the computational simulations that will be paired with the experimental results. The simulations will be conducted with the use of the finite element method/analysis (FEM/FEA). FEM is a method used to simulate real-world interactions of structures. This is done by utilizing advanced computing power to apply equations representative of real physics to small pieces of a structure called “elements”. These elements are then placed into a system of equations to create a solution of reactions for the entire structure. FEA refers to the complete analysis of the results utilizing the finite element method as the method to compute and simulate said results.

The reason for using FEM and FEA for this project is to create a basis of data to compare with when completing the real-world measurements of the same data. The comparison ensures what kind of data to expect from the experimental data and creates further reference on the capabilities of FEM/FEA, for the use of testing 3D printed models.

The accuracy of the results of FEA are limited by the size of the elements used, small elements leading to a more accurate result. Decreasing the size of the elements will take considerably larger computational power depending on how drastic the change is. A technique to avoid this significant increase in computational power is to apply a smaller and more accurate mesh to areas of significance such as corners and points of structural variability.

Another problem that intervenes in the accuracy of the results is the accuracy of the inputs as well. It is necessary that the inputs are completely accounted for and as precise as possible to create results that are truly accurate to real-world interactions. The FEA applications being used for this

project are a combination of Ansys Workbench and Ansys Mechanical. An input required for FEA applications is a model to perform analysis upon. As stated before, inputs need to be precise and therefore so does the model. Further details regarding the analysis of the 3D models created in SolidWorks will be discussed in the results for FEA later in the report.

The expected results for the analysis are that there will be an increase in mechanical strength for increasing infill density. The change and orientation and angle should also provide unique results based on the difference in pattern.

2.4 Printing Setup

A necessary step to completing this project is to obtain and correctly apply a 3D printing system. The options for public 3D printing locations are limited as productions are set per person. A personal 3D printing station was acquired for the purpose of this project for its ideal location and convenience. The 3D printer used for this project is an Ender 3 currently sold commercially by Creality for \$189. The printer utilizes FDM printing which is the specific target of this project. It has a printing zone of 220x220x250 mm, which is ideal to fit the entirety of the beam in its various orientations and angles. The nozzle size is .4 mm in diameter, providing enough precision to complete the project ideally. Adjustments made to create an ideal printing area are fine-tuned through human precision and vary significantly between products and locations and thus are not necessary to record. The nozzle and bed temperatures are set to 200° C and 60° C respectively. All other settings for the system are left at default values.



Figure 2.8 – Ender 3 3D printing setup.

Test prints were done to ensure that the printing setup was fit to carry on with the project. These tests include bed level prints to ensure that the printer is flat and the well-known “Benchy” boat test. The previously mentioned application “Cura” has a setting that applies the Ender 3 specifications to its slicing configuration. The SolidWorks models were also modeled with these same specifications in mind.

2.4.1 3D Printed Beams

3D prints are created layer by layer onto a heated build plate and extruded through a heated nozzle with a width of .4 mm. The nozzle moves through a belt moving in the X direction while a motor also moves the entire belt up in down in the Z direction. The build plate moves through a motor and belt moving it in the Y directions. This means that the system is moving with 3 separate systems of motors and belts.

Beams are printed through the setup described previously. The beams are printed and cleaned to maintain a clean part. This includes cutting off extra printed layers placed to ensure that the beam is printed correctly, such as the brim. A small line is visible along the wall of the 3D prints. This is due to the extruder beginning its print at a specific position at each layer printed. This is unavoidable in FEM printing, but the resulting blemishes are also removed in post printing clean up.

3. Setup & Results of FEM

3.1 FEM Setup

As stated before, the application used for FEM analysis is Ansys 2025 R2 Workbench and Mechanical. The license used is the free version under student applications. Because this is a student license, there are limits placed on the number of elements allowed for analysis and meshing. This is why the study for infill density goes up to 30% as any density further will surpass the limit of the license.

3.1.1 Ansys Workbench

The first step before opening Ansys Workbench is to properly format the SolidWorks files so that it can be accepted into Ansys. The two options for this are to save them as an IGES file or a STEP file. Initially the IGES file was used, but at higher infill densities it incorrectly read the infill density as an inverted surface and saving each hole as a separate part. This caused significantly higher demand from the computer and made meshing within the limit of the student license impossible. Thus, the STEP file was used. Using the STEP file saved the beam as a singular body and detailed the infill density correctly.

Once the files are saved, simulation systems can be made for analysis. Beginning with a modal system, since the project is based on vibrational results, a new material needs to be added with the characteristics of PLA. This can be done by entering the engineering data page seen in Figure 3.1.



Figure 3.1 – Basic modal analysis system in Ansys Workbench 2025.

An empty library has been created to be used as a container for the new material. A custom material is added into the new library and the library is saved before the new material can be added into the modal analysis system. The material is labeled as PLA and uses custom mechanical values listed below provided by Tunca et al [34]. PLA was once contained within the Ansys materials library in older versions but does not appear by default in the 2025 R2 version.

Table 3.1 – Mechanical properties of PLA (polyactic acid) [34].

Property	Value	Units
Density	1250	kg/m ³
Young's Modulus	3.45E+09	Pa
Poisson's Ratio	.39	
Bulk Modulus	5.2273E+09	Pa
Shear Modulus	1.241E+09	Pa

Once the material is added to the system, the models containing the various parameters are added to their own separate systems to be worked on afterwards. The values added to the custom material are necessary for vibrational analysis.

The specific variable parameter STEP file is imported into the geometry input as seen in Figure 3.1. These Workbench procedures are applied to all other instances of variable parameters. The rest of the analysis is completed in Ansys Mechanical through editing the Model input of the modal analysis system.

3.1.2 Ansys Mechanical

The first step to creating the system is to apply a mesh to the model. The mesh is what defines the elements of the model and is affected by physics simulator. Elements are adjustable to create an efficient mesh. A smaller mesh will mean that the elements will be smaller. The mesh size is set to 2 millimeters. This is the limit for which the student license can allow on the most mesh intensive structure, the 30% infill beam. This size is more than enough to capture accurate results for the analysis. A mesh analysis shows that the difference in data between mesh sizes decreases significantly as the element size gets smaller. When the difference in results for frequencies reaches below 1% is typically a point when the result is deemed accurate. The table below shows the results of the mesh analysis.

Table 3.2 – Percent difference in frequency mesh analysis for a 10% infill beam.

	Element Size in Meters (m)				
	1 to .1	.1 to .01	.01 to .005	.005 to .002	.002 to .001
Mode 1	2.67	4.49	0.13	0.37	0.14
Mode 2	2.25	2.03	0.14	0.41	0.13
Mode 3	15.54	19.27	0.41	0.73	0.21
Mode 4	6.41	7.06	0.95	1.17	0.41
Mode 5	19.57	23.19	0.75	1.24	0.33
Mode 6	6.76	4.40	0.21	0.40	0.14

From the table, we see that the difference in data from 2 millimeters to 1 millimeter is not significant. Technically, a 5-millimeter or 1-centimeter element size would also suffice as an accurate mesh. A 2-millimeter mesh size was still chosen to be as accurate as possible since the tools for analysis are limited. The figure below better presents the difference between decrease in mesh sizes.

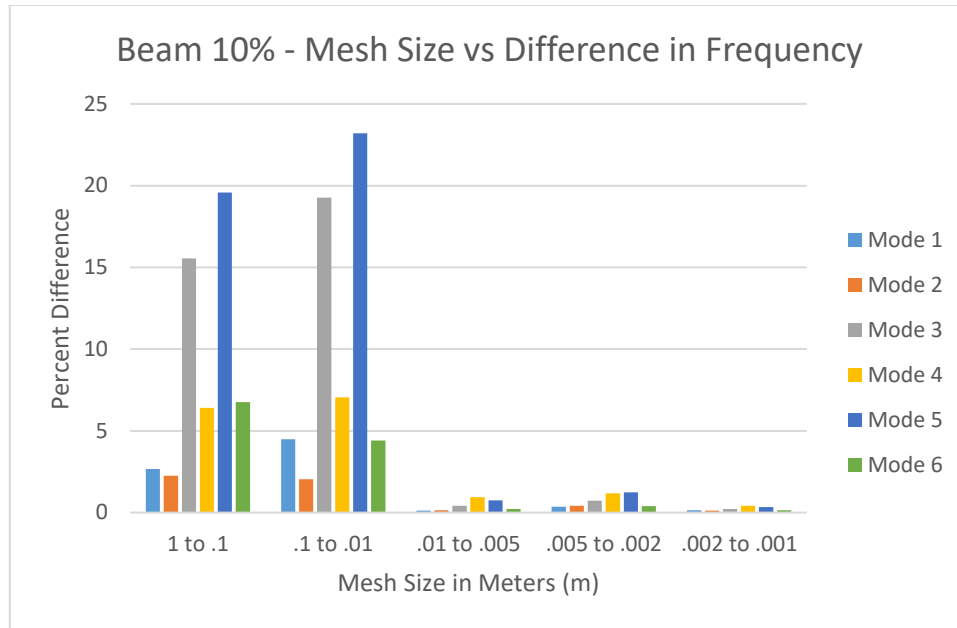


Figure 3.2 – Mesh size vs difference in frequency for a 10% infill beam.

The reason for the range of infill density variability being from 10% to 30% is due to the limited elements allowed for the student version of Ansys 2025. The infill densities create significantly more elements due to the many pores in the infill. Unfortunately, this is unavoidable even when adjusting the mesh size to create less elements.

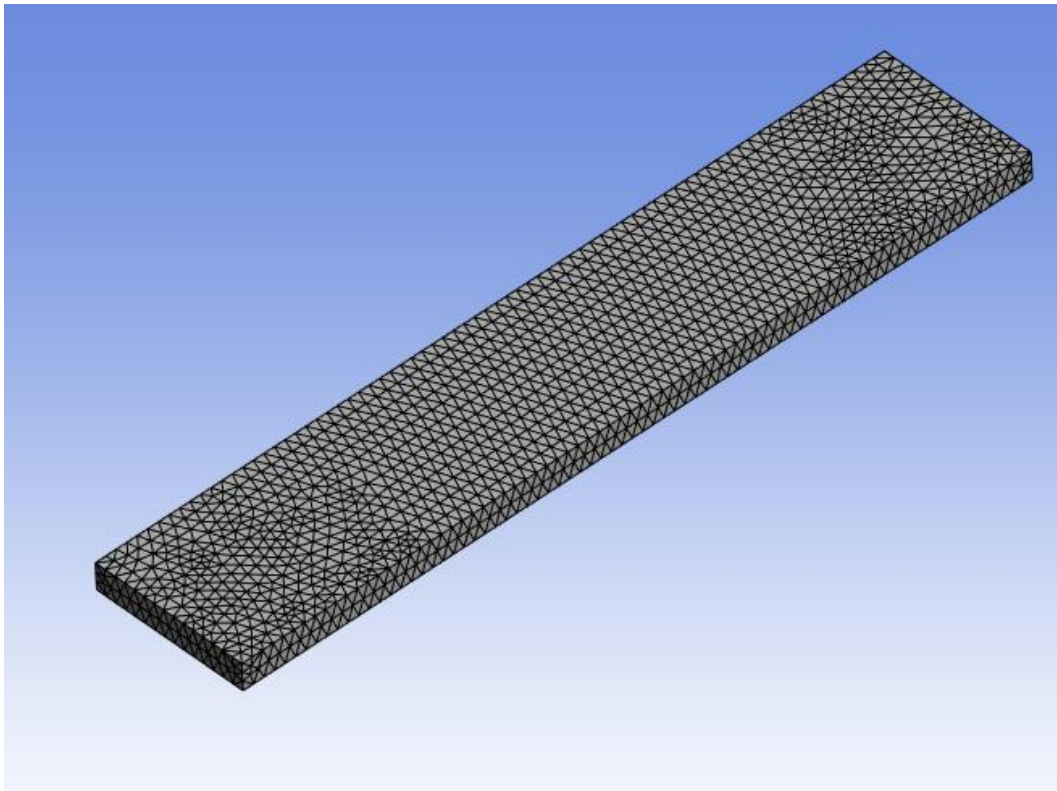


Figure 3.3 – .002 m size mesh of 30% infill density beam.

After a mesh is applied to the beams, the parameters of the system and analysis can be created. A fixed support is applied to the end of all beams in the same position. Damping is also turned on for cases involved with variable infill density since it is turned off by default. The system is given a constant structural damping of 2% to simulate typical structural damping. Structural damping simulated damping effects that occur within the structure itself due to micro friction. The effects are typically negligible but nonetheless included. The value comes from the damping ratio of a typical hard plastic, which PLA is the biodegradable alternative of. This is to properly simulate vibrational characteristics of the beam to test the effects of infill density on the system. The modes that are analyzed from the beam represent vibrational characteristics in multiple directions. The total modes being analyzed are 6 total modes. This is because almost all necessary modes important to being analyzed are within the 6 modes which are also considered to be the vibrational body modes. This is also a reason for applying the fixed support to one end of the beam. Not doing so would create values close to zero for all modes since the beam would have no reaction if left in free space.

3.2 FEM Results

The results of the analysis give the natural frequencies of the various modes. The six modes analyzed are the vibrational body modes of the beam. The modes are of two types, bending and rotational. Mode 4 represents torsion about the y-axis, specifically for this analysis. Modes 1, 3, and 5 represent bending movements in the x-direction. Modes 2 and 6 represent the bending movements in the z-direction. The results are given visualized results. These show the deformation of the beam with a range of deformation included in the resulting visualizer.

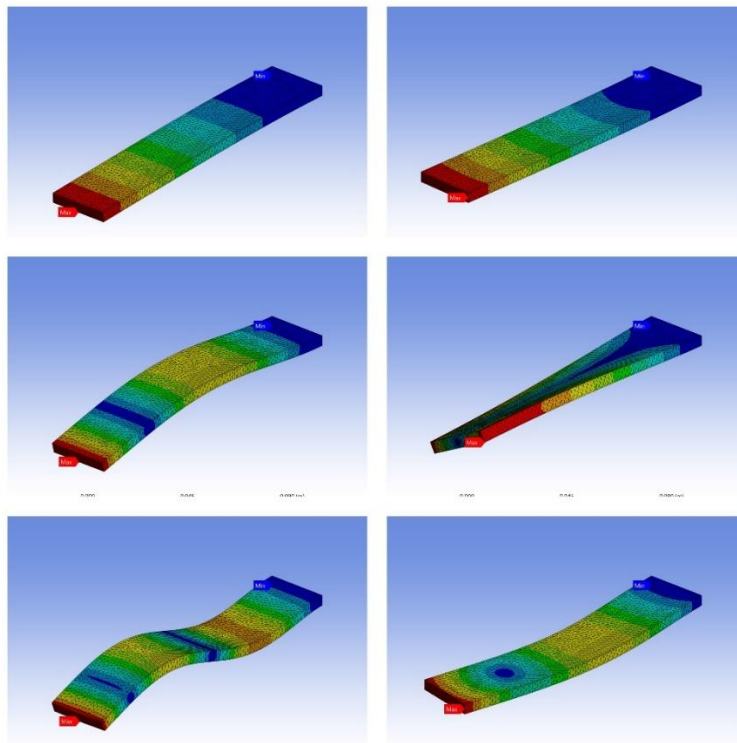


Figure 3.4 – Deformation visualization for modes 1-6 (top-left to bottom-right) for a 10% infill beam.

3.2.1 Variable Orientation Results

The results for frequencies in hertz and other measured results for each mode of varying orientations parameter are recorded in the tables below. The results for the 10% infill beam with no other adjustment will be used as the baseline comparison for all varied parameters.

Table 3.3 – Natural frequency in Hertz (Hz) for different printing orientations.

Mode	Natural Frequencies (Hz)		
	Flat	Side	Vertical
1	77.40	77.274	77.62
2	348.82	349.87	369.43
3	469.94	461.55	471.82
4	640.34	637.56	619.25
5	1259.5	1208.3	1266.1
6	1851.8	1843.8	1826.2

The flat orientation in the orientation tables is the data collected from the basic 10% infill beam. The frequencies are clearly affected by the printing orientation but by a slight margin. This is still expected since this is a representation of a clean model with zero FDM characteristics such as micro-indents between each layer, which would lead to more serious changes.

Table 3.4 – Max total displacement in millimeters (mm) for different printing orientations.

Mode	Max Total Displacement (mm)		
	Flat	Side	Vertical
1	18.18	18.2	17.95
2	17.99	18.04	17.72
3	17.56	17.52	17.36
4	21.31	21.36	20.62
5	17.13	17.02	16.94
6	17.28	17.31	20.22

3.2.2 Variable Infill Density Results

It is well known for it to be difficult to measure dampening of a structure in FEM. Finding the damping coefficient of a structure is typically done using an accelerometer or similar equipment. The tables below are the result of a dampened system utilizing a .02 or 2% damping based on mass. FEM results still give us insight into the general characteristics and allow for comparisons to be made. Results of significance from this analysis include the damp frequency, stability, and maximum total deformation.

Table 3.5 – Damped frequency in Hertz (Hz) for different infill density.

Mode	Damped Frequencies (Hz)		
	10%	20%	30%
1	77.40	73.48	70.55
2	348.84	332.86	323.36
3	469.96	451.79	435.8
4	640.37	624.42	609.31
5	1259.6	1233.3	1197.9
6	1851.8	1787.4	1747.9

Table 3.6 – Max total displacement in millimeters (mm) for different infill density.

Mode	Max Total Displacement (mm)		
	10%	20%	30%
1	18.05	17.04	16.02
2	17.96	16.86	16.02
3	17.58	16.64	15.89
4	21.29	20.33	19.29
5	17.00	16.36	15.61
6	17.25	16.18	15.61

Table 3.7 – Stability in Hertz (Hz) for different infill density.

Mode	Stability (Hz)		
	10%	20%	30%
1	-0.77398	-0.73472	-0.70541
2	-3.488	-3.3283	-3.2333
3	-4.6991	-4.5175	-4.3575
4	-6.4031	-6.2436	-6.0925
5	-12.595	-12.332	-11.978
6	-18.517	-17.872	-17.477

The stability measurement of each mode ensures that the system is being analyzed properly. The stability is recorded as a frequency response and represents the real portion of a complex response related to damping. If a measured stability were to be positive, it would mean that the system is unstable, and the natural frequencies would also be recorded as a negative value. The negative stability values show that the system is dynamically stable which is the correct response. Recording the values also allows for further comparisons of the systems.

3.2.3 Variable Angle Results

The change in angles represents the anisotropic effects of 3D printing. From the hypothesis made before, there should be noticeable effects on the vibrational characteristics as the angle continuously changes. The range for varying degrees goes from 0 degrees to 45 degrees. Going further than this leads to similar results as previous degrees but mirrored. Removing the unnecessary additional angles saves time and material without hindering the results of the project and data collection.

Table 3.8 – Natural frequency in Hertz (Hz) for different angles.

Mode	Natural Frequencies (Hz)			
	0°	15°	30°	45°
1	77.40	77.489	77.72	78.003
2	348.82	351.	354.71	353.57
3	469.94	470.39	471.74	473.22
4	640.34	639.37	637.1	640.13
5	1259.5	1260.6	1263.9	1266.7
6	1851.8	1854.1	1854.9	1845.7

Table 3.9 – Maximum total displacement in (mm) for different angles.

Mode	Max Total Displacement (mm)			
	0°	15°	30°	45°
1	18.18	18.19	18.19	18.25
2	17.99	17.99	17.97	18.03
3	17.56	17.58	17.57	17.54
4	21.31	21.41	21.37	21.56
5	17.13	17.09	17.10	17.02
6	17.28	17.33	17.23	17.15

Once again, the 10% infill beam design is used as the 0-degree data point. There are no additional parameters changed to the structure.

3.3 FEM Summary

The results of FEM are values from vibrational modal analysis. The geometry used consists of the beam shape and the changing infill within the beam. The geometry does not include details regarding the micro-indentations between print layers. This means that the FEM results are best understood as an analysis of how the variable parameters affect the vibrational properties through the change in infill. Results from the experimental analysis will give greater insight to the detailed effects of these parameters.

The change in orientation causes the direction of the infill to change since the infill design is unaffected by position and orientation and remains in the same position. When the beam is printed on its side, when reoriented it would appear as though the infill were printed sideways when compared to the flat position. The same applies to the vertical position. As hypothesized, there is indeed an effect on the vibrational characteristics, but these effects are only a factor due to the infill. The main factor behind the hypothesis was the idea that the adhesion between layers may cause significant change to the properties based on orientation. Thus, experimental results will reveal further significance of orientation on vibrational characteristics.

Variable density results proved significant and were expected. FEM analysis results are limited in terms of specific values such as damping and stiffness. This is solved in the experimental phase. The results of FEM still give clear results of the effects of increasing density, showing a decrease in frequency and max deformation as the infill density increases. Typically, a higher frequency means an increase in stiffness and decrease in deformation. This gives insight into the

possibility that the increase in infill density increases the mass significantly more than increases the stiffness of the structure. Further discussion will explain this result.

Measurements for the change in angles are useful to once again identify the effects of infill patterns and printing techniques. It also provides further information regarding how orientation can affect vibrational characteristics. Understandably, the results of the change in angles lead to noticeable but small differences in the vibrational characteristics. There is a small change in mass due to how the infill is placed within the structure which is a factor to consider when analyzing the results of the simulation.

4. Setup & Results of Modal Impact Analysis

4.1 Modal Impact Setup

The method of experimental analysis used for this project is the modal impact method. The modal impact method utilizes multiple tools to stimulate, measure, and calculate vibrational characteristics. Instruments required for modal impact analysis include an impact hammer and accelerometers. The application used for data acquisition is a custom-made impact analysis application created through LabVIEW. Modal impact analysis was done in SJSU's Engineering Building inside of the Aerospace Structures Lab. A clamp is placed on a table and tightened on one end of each beam to simulate the same boundary conditions as done in the FEA. Figure 4.1 shows an example of the full experimental set-up.



Figure 4.1 – Clamped 3D printed beam with accelerometers.

4.1.1 Modal Impact Analysis Theory

Modal impact analysis is a method of vibrational analysis that is simple to use and prepare. Modal impact analysis uses a tool called an impact hammer to stimulate the vibrational modes of the structure. The hammer provides an instantaneous force to excite all modes within a large frequency. The tighter the impulse, the more the modes there are that are excited. Realistically, the impact hammer is not capable of creating a completely instant impact. This means that in some cases, the impact cannot excite certain modes beyond a level of frequency. To fix this, there are a multitude of adjustments to be made. There are a variety of hammers with different weights and tips. The adjustment in weight allows the hammer to create a meaningful impact on large structures such as boats or propellers. Smaller hammers are also meant for small components such as circuit boards or processors, the lighter weight allowing for a more precise hit. The tips of the hammers

are also adjustable. Tips generally span from a very soft tip consisting of rubber to a hard tip made of plastic or metal. These arrangements of tips allow for higher frequency excitations while using harder tips. If specific frequencies are being experimented with, then the tip is crucial to acquiring the correct range of modes.

A key step to acquiring promising data is to avoid double-hits. A double hit occurs when the hammer strikes a structure twice or more, due to human error. This can occur when the hammer bounces multiple times on the structure when hit. The figure below shows an ideal instantaneous impact with no double-hits. A double impact would show multiple peaks in the impact graph spread throughout the time frame of the graph.

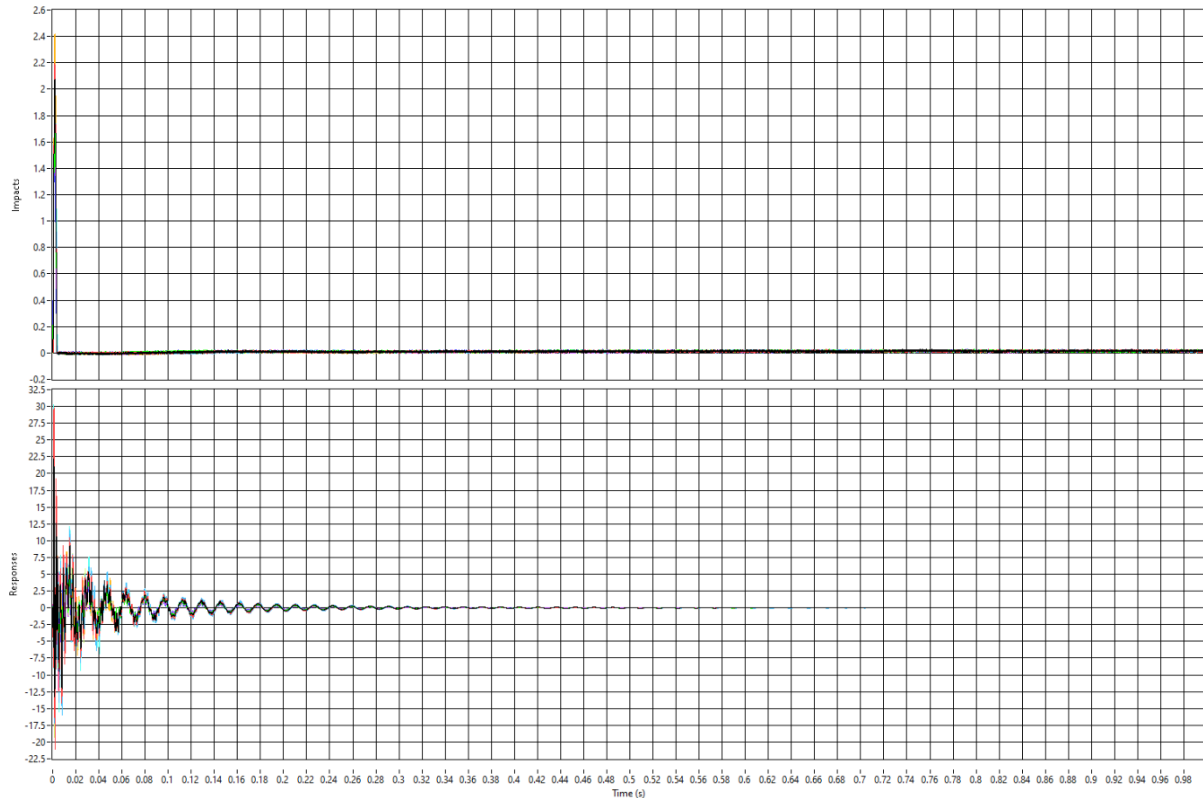


Figure 4.2 – Impact data as a function of time with impact(above) and response (below).

The application used for data acquisition typically produces graphed results of coherence, magnitude, and phase. The magnitude and phase are both a part of the FRF or Frequency Response Function. The FRF can also be output as a real and imaginary set of values although for this experiment it is presented as a magnitude and phase. Coherence is a representation of the effectiveness between the impact and the response. This means that it is a measurement of how much of the response of the system is due to the impact rather than outside noise. Coherence is measured from 0 to 1 with 1 being coherent and 0 being distorted. Ideal results should have the coherence being near 1 for most of the analyzed frequency. Points at which the coherence may be low are at low magnitudes which are typically the nodes of the system that produce little vibrations.

4.1.2 Impact Hammer Specifications

The only hammer currently available for modal analysis in the Aerospace Structures Lab is the PCB-086C03. This model is meant for small structures such as impellers to slightly larger

structures such as panels or frames. Although a smaller hammer would be more optimal, the PCB-086C03 structural functioning range still includes the structures created in this paper. Table 4.1 contains the specifications of the impact hammer.

Table 4.1 – PCB-086C03 performance specifications.

	English	SI
Sensitivity	10 mV/lbf	2.25 mV/N
Measurement Range	±500 lbf pk	±2224 N pk
Resonant Frequency	≥22 kHz	≥22 kHz
Non-Linearity	≤1 %	≤1 %

4.1.3 Accelerometer Specifications

The accelerometers available in the lab are PCB-352A24. These are typical accelerometers and are fully capable of performing this experiment. Table 4.2 contains the specifications of the accelerometers.

Table 4.2 – PCB-352A24 performance specifications.

	English	SI
Sensitivity (±10 %)	100 mV/g	10.2 mV/(m/s ²)
Measurement Range	±50 g pk	±490 m/s ² pk
Frequency Range (±5 %)	1.0 to 8000 Hz	1.0 to 8000 Hz
Frequency Range (±10 %)	0.8 to 10000 Hz	0.8 to 10000 Hz
Frequency Range (±3 dB)	0.4 to 12000 Hz	0.4 to 12000 Hz
Resonant Frequency	≥30 kHz	≥30 kHz
Broadband Resolution (1)	0.0002 g rms	0.002 m/s ² rms
Non-Linearity	≤1 %	≤1 %
Transverse Sensitivity	≤5 %	≤5 %

4.1.4 Driving Point Survey

Before collecting data, it is necessary to conduct a driving point survey. The purpose of a driving point survey is to find the optimal location to create the impact. The optimal location should be able to excite as many modes as possible or at the very least, the modes that are being analyzed. To conduct a driving point survey, an impact location on the structure is tested as how a normal analysis was to be performed. The results are then compared to those that were taken from when a different location was to be impacted. Repeating this practice along the structure will show at which location excited the most modes, thus giving the ideal location to perform analysis. Figure 4.3 shows the locations at which the test was performed.

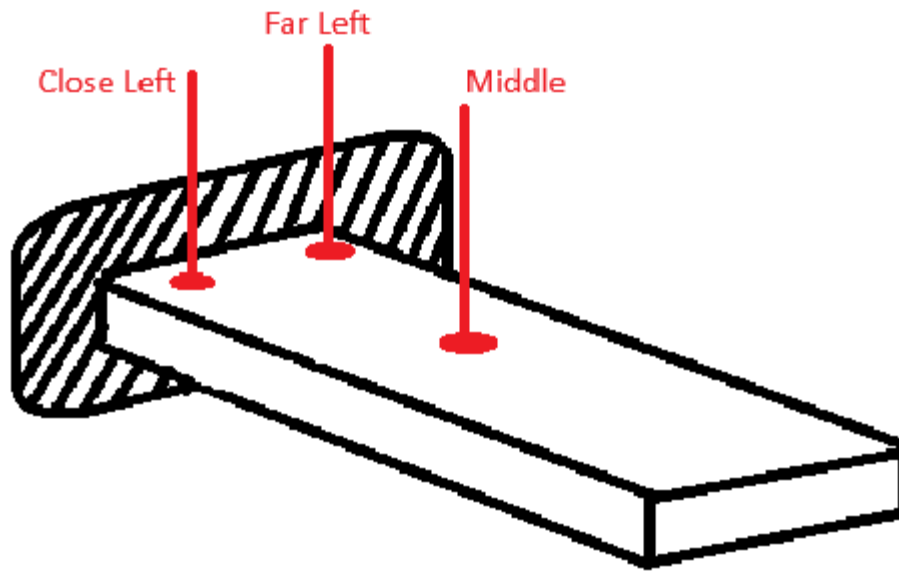


Figure 4.3 – Visual representation of data point survey across a beam clamped on the left.

These locations for the data point survey were chosen due to the inability to acquire data at any points lower than the middle location. This is due to the difficulty with the mass of the hammer causing more momentum than the structure can handle for it to create meaningful vibrations. Instead of impacting in an instant, the structure experiences significant bend and thus the results become unsuitable. This can be seen in Figure 4.4. These graphs show hypothetical FRF results when impacting from different locations. Ideal results should show smooth peaks at distinguishable locations. The middle location's results were poor and significantly distorted, with the close-left and far-left providing clearer data. In the end, the close-left location was chosen since it was able to give a slightly better reading of modes than the far-left location.

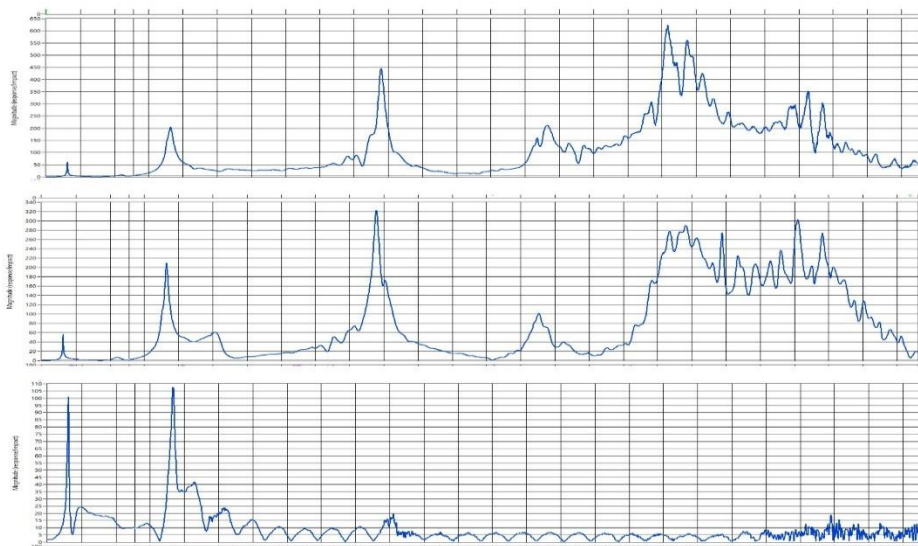


Figure 4.4 – Data point survey at close-left (top), far-left(middle), and middle (bottom).

4.1.5 Data Import

Data collected from LabView's acquisition is saved as a set of files. These files include the impact results saved in the form of a TDMS file and the FRF results saved as a UFF (universal file format) file. These are files typically used in data acquisition as ways to easily categorize and organize data.

TDMS and UFF files cannot be read by normal means. A specific software or code is designed to read these files to properly display the organized data. Methods to view these files include excel add-ins, LabView applications, and MATLAB code. The method used for this project was MATLAB for its ease of use and previous experience.

Using MATLAB, two key functions were used to read the files containing data. To read a TDMS file, "tdmsread" is used. This is a function already integrated within MATLAB. To read a UFF file, a custom function by Thomas Emmert called "UFF File Reading and Writing" was downloaded from MATLAB's file exchange [35]. This download contains the function "readuff", allowing for the ability to read the organized UFF file and the details of category. This includes the units and labels used for the data.

The data collected from the FRF is recorded as a complex response with a real and imaginary component against frequency in Hertz in the x-axis. The data is also recorded as a separate set of data for each accelerometer. The results shown in Figure 4.4 and in LabView are already averaged and converted into magnitude format. This process is done manually in MATLAB onto the raw data. The data must be averaged as real and imaginary components before being converted into magnitude values. Processing the data in the incorrect order results in data that incorrectly measures phase.

The key results that are important to this project are the location of natural frequencies for modes and the damping of each mode. The natural frequencies can be found at the location of peaks in the magnitude response. The first six peaks represent the first six modes of the structure. Damping is calculated using the half power method [36]. This method uses the width of each peak at a power of 50% or -3 dB from the peak of each natural frequency. The magnitude is converted into decibels using the MATLAB function "mag2db()" and the damping factor Q is then found at the location below 3 dB from the peak using equation (1). The damping factor is then converted to damping ratio ζ through a conversion ratio (2).

$$Q = \frac{\omega_n}{\omega_2 - \omega_1} \quad (1)$$

$$\zeta = \frac{1}{2Q} \quad (2)$$

Calculations and acquisitions for this method are done by manually viewing data points at each key location. At certain modes that have natural frequencies close to each other for the half power method, the peaks are isolated and curve fitting is used to properly use the half power method.

4.2 Modal Impact Results

The results of the data acquisition give us three graphs. Coherence in green is a measure of how accurate data is. The maximum value for coherence is 1. Generally, if the coherence is around 1 at the point of natural frequency, then the data can be considered good. It is common for the coherency to appear low moments before approaching the natural frequency of modes. The blue graph represents the Magnitude of the FRF. The magnitude is measured by the response over the impact. Phase at the bottom represents the time shift between input and output waves. The important result to this project is the magnitude, as it signifies the natural frequencies at the locations of peaks that appear. The tables following each figure represent the data for manually acquired natural frequencies and damping ratios.

4.2.1 Varying Infill Density Results

The results for the infill density are as shown in Figures 4.5-4.7. The results of the infill densities, aside from 30% infill density, lack a natural frequency peak for what appears to be mode 5. The results despite this are correct. This is confirmed by the coherence, meaning that the data collection itself was clear.

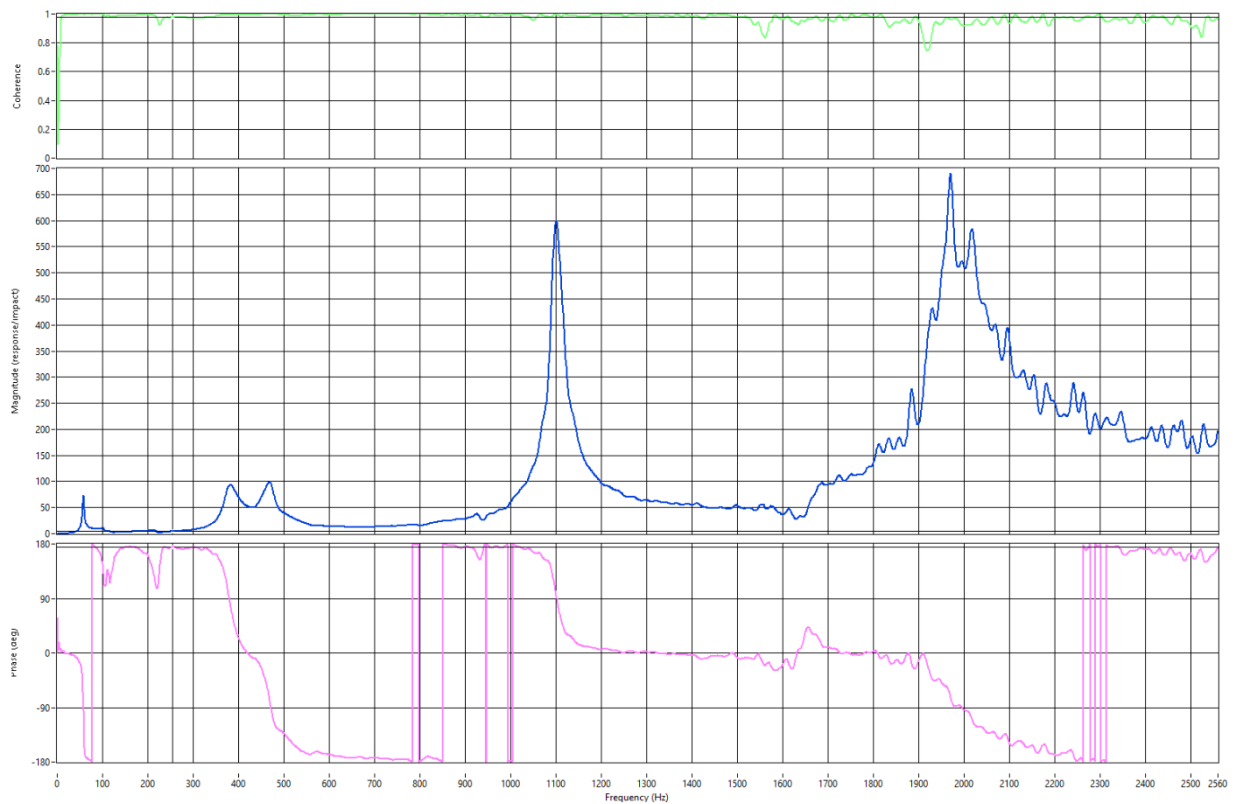


Figure 4.5 – FRF results of 10% infill beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.3 – Natural frequency and damping ratios for modes 1-6 of a 10% infill beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	59	383	474	1102	-	1971
Damping Ratio	.0271	.0392	.0369	.0122	-	.0658

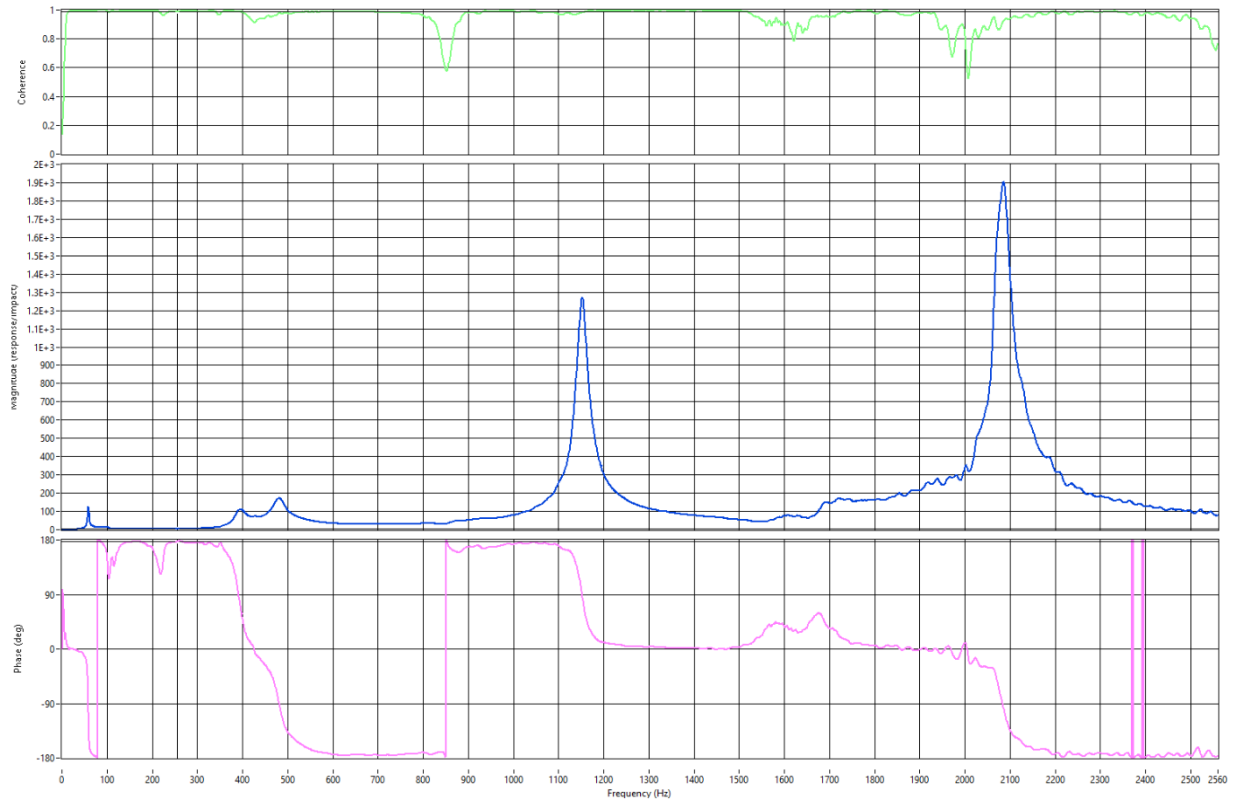


Figure 4.6 – FRF results of 20% infill beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.4 – Natural frequency and damping ratios for modes 1-6 of a 20% infill beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	60	395	488	1153	-	2072
Damping Ratio	.0213	.0316	.0446	.0101	-	.0076

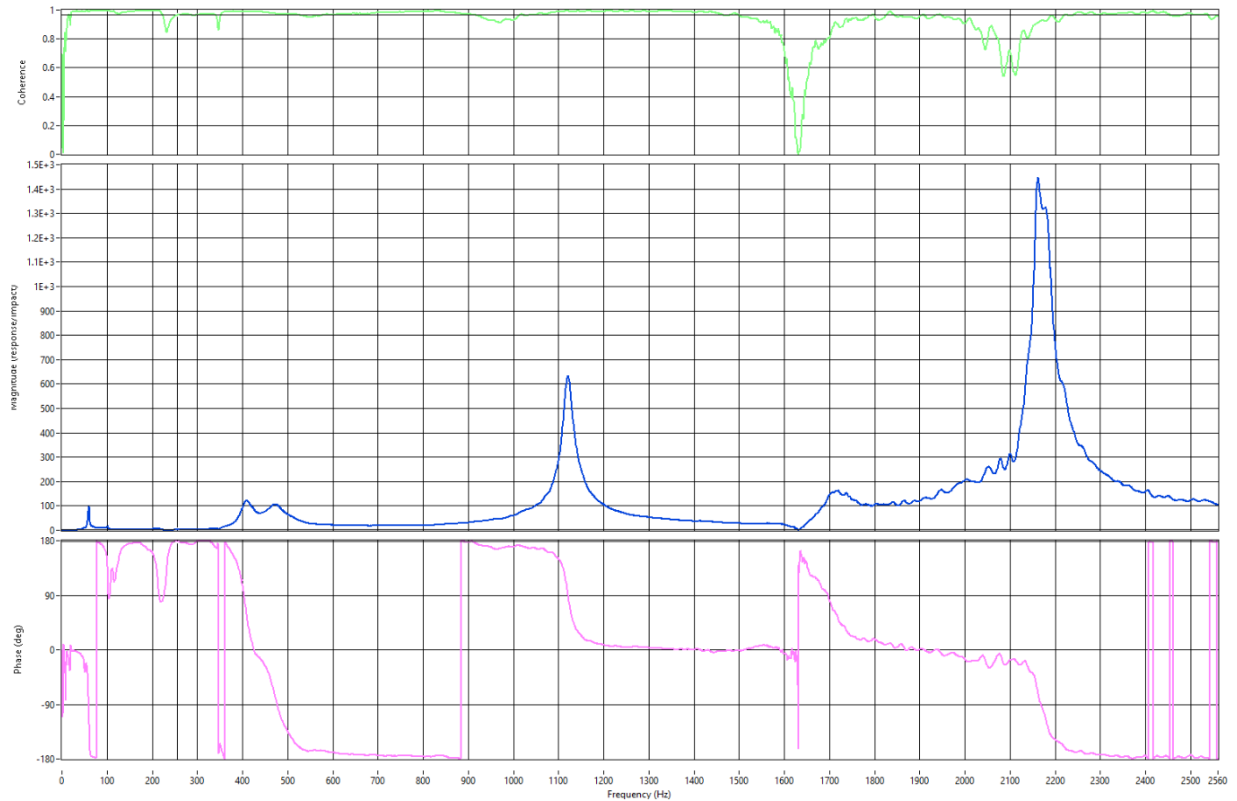


Figure 4.7 – FRF results of 30% infill beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.5 – Natural frequency and damping ratios for modes 1-6 of a 30% infill beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	61	409	481	1122	1727	2170
Damping Ratio	.0172	.0266	.0642	.0099	.0197	.0091

4.2.2 Varying Degrees Results

The results for the varying degrees are shown in Figures 4.8-4.10. Once again, a clear peak of natural frequency is missing for the fifth mode, most likely due to the placement of accelerometers discussed later. The coherence drops at locations before the natural frequencies are semi-normal as the structure approaches its natural frequency. The drops in coherence can be seen where the typical mode 5 should have appeared, the magnitude however does not give a distinct result except for a 30-degree angle.

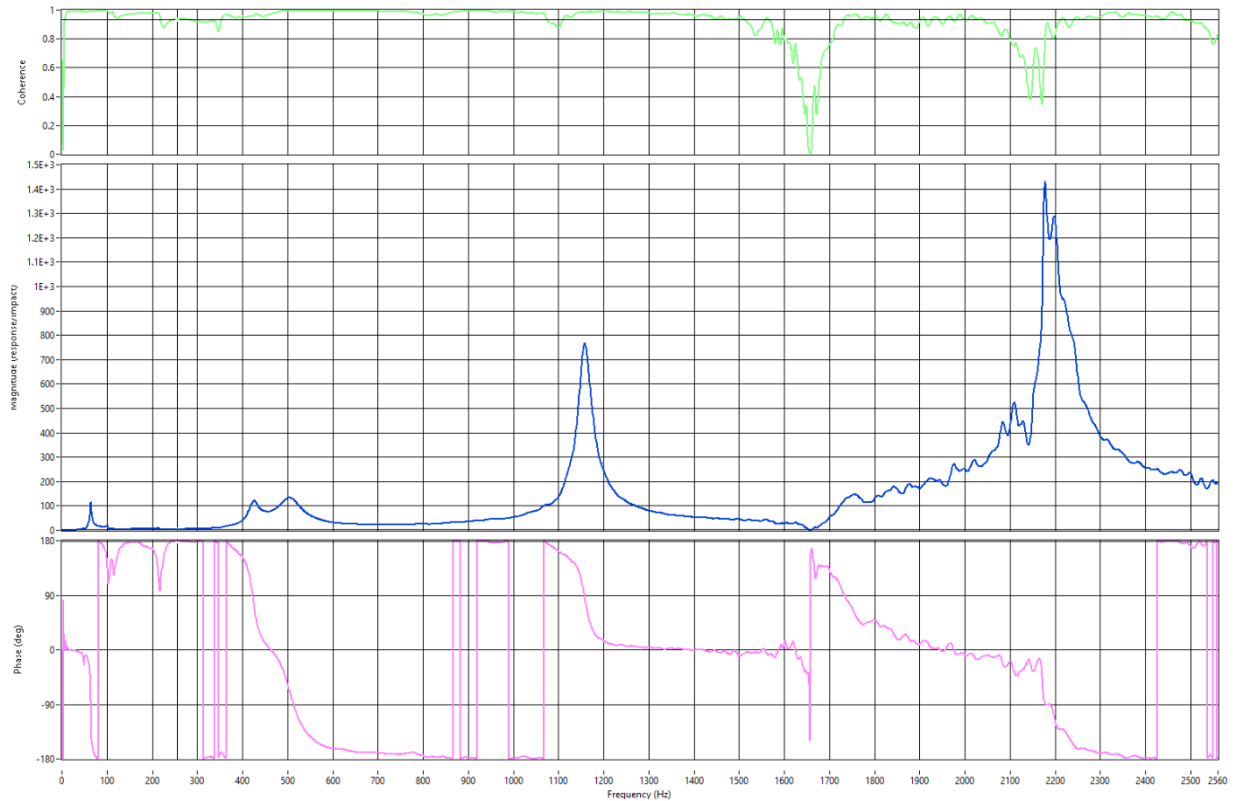


Figure 4.8 – FRF results of 15° beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.6 – Natural frequency and damping ratios for modes 1-6 of a 15° beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	66	426	517	1159	-	2178
Damping Ratio	.0307	.0257	.0865	.0118	-	.0076

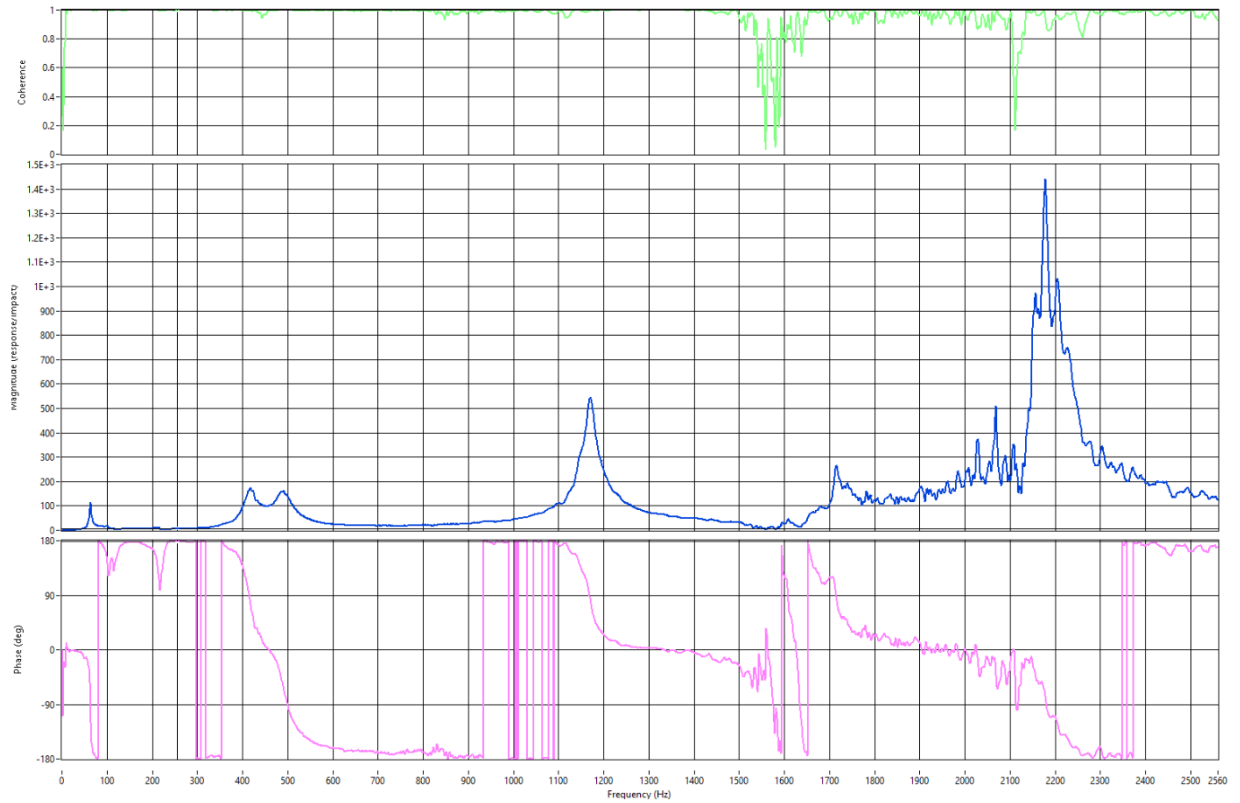


Figure 4.9 – FRF results of 30° beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.7 – Natural frequency and damping ratios for modes 1-6 of a 30° beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	64	418	494	1172	1717	2179
Damping Ratio	.0273	.0281	.0464	.0107	.0048	.0037

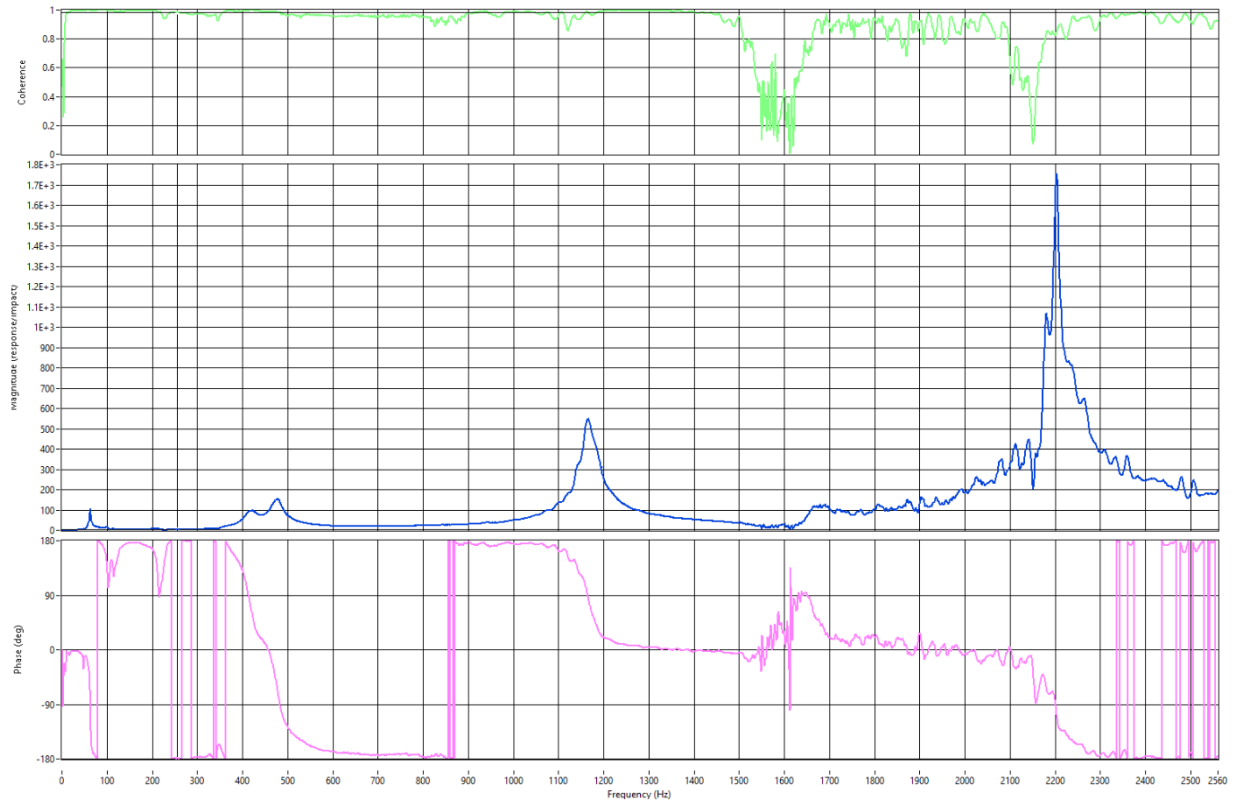


Figure 4.10 – FRF results of 45° beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.8 – Natural frequency and damping ratios for modes 1-6 of a 45° beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	64	418	482	1166	-	2204
Damping Ratio	.0215	.0374	.0283	.0144	-	.0033

4.2.3 Varying Orientation Results

The results for the orientations are as shown in Figures 4.11 and 4.12. The orientation data has less coherent data, although clear peaks are still able to be seen. The side results fall off at later frequencies. The peaks that are clear and within coherence are recorded within the tables following the figures. The vertical results in Figure 4.12 once again show a missing natural frequency for the fifth mode.

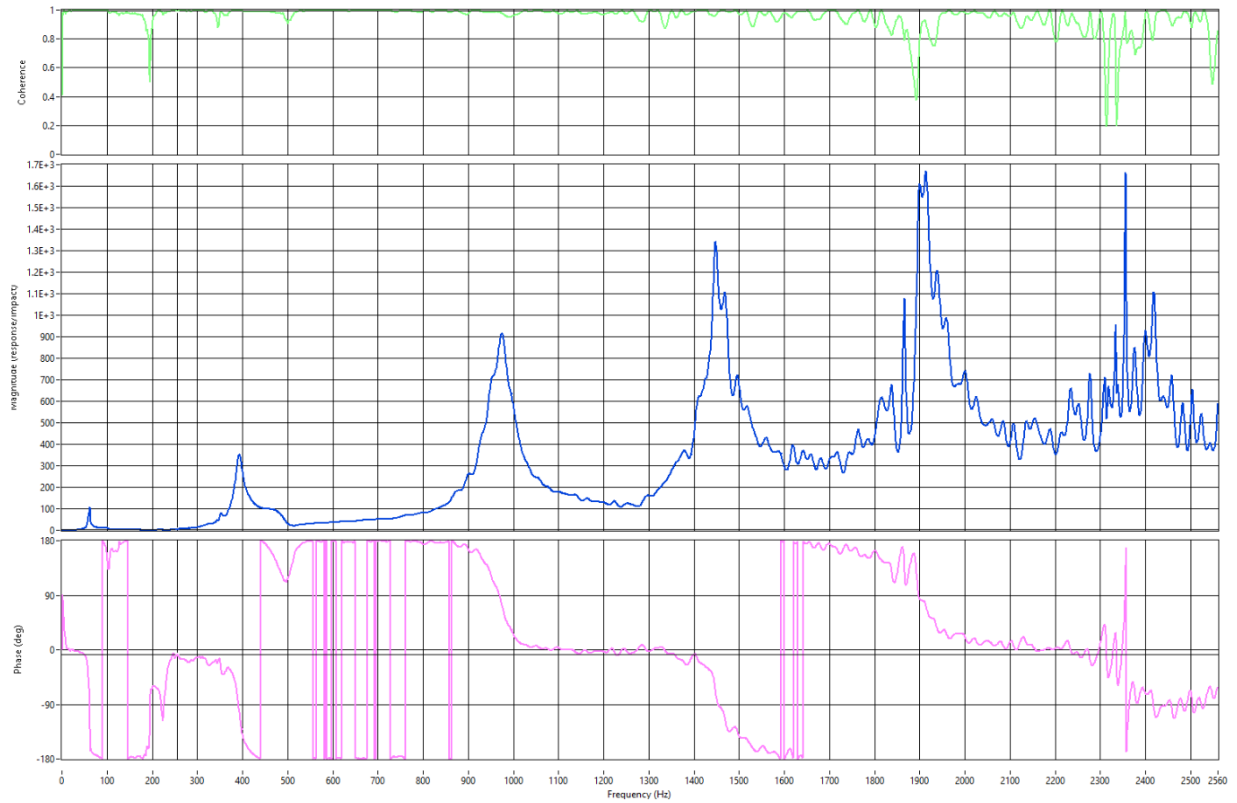


Figure 4.11 – FRF results of side printed beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.9 – Natural frequency and damping ratios for modes 1-6 of a side printed beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	63	393	489	977	1449	1910
Damping Ratio	.0222	.0223	.0449	.0243	.0068	.0087

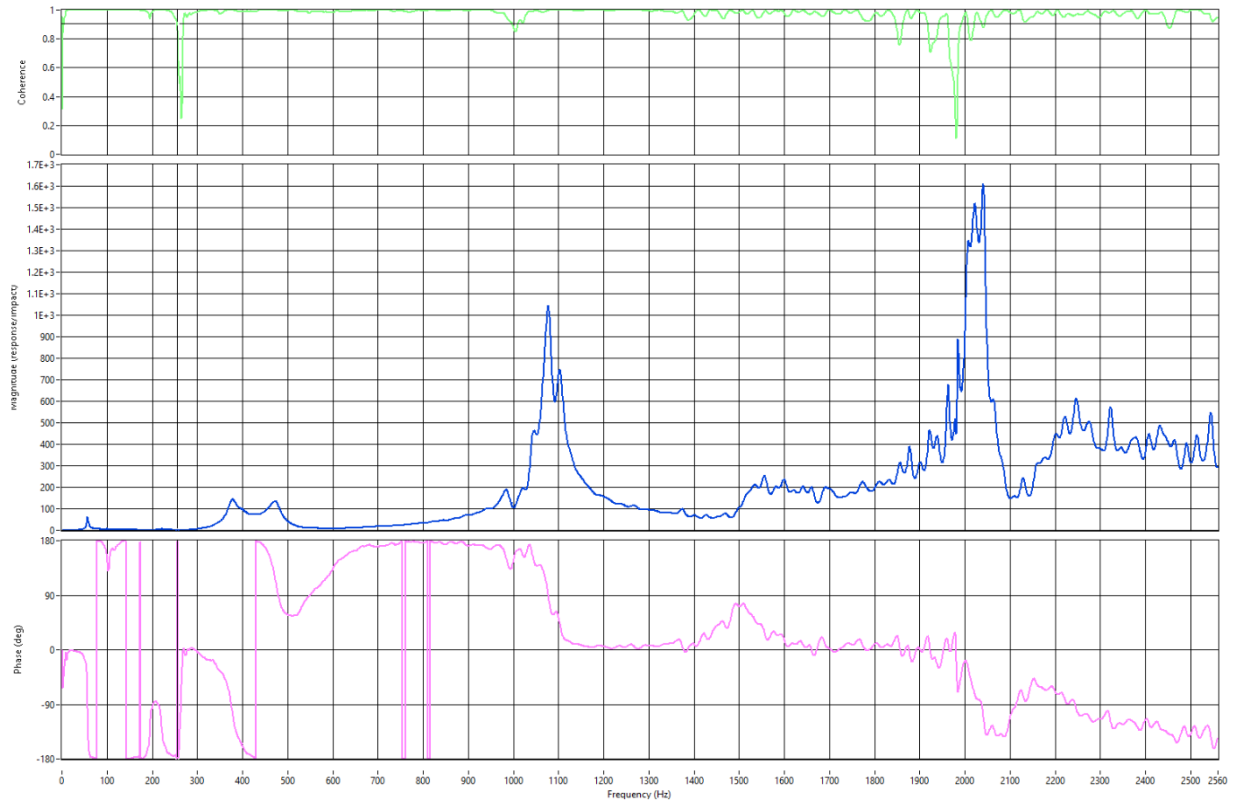


Figure 4.12 – FRF results of vertical printed beam with Coherence (top), Magnitude (middle), and Phase (bottom).

Table 4.10 – Natural frequency and damping ratios for modes 1-6 of a vertical printed beam.

Modes	1	2	3	4	5	6
Natural Frequency (Hz)	58	379	473	1078	-	2025
Damping Ratio	.0284	.0350	.0322	.0087	-	.0098

5. Discussion & Comparison

Using the data collected, comparison can be made between the varying parameters. Results are compared between their respective varying parameters by the natural frequencies and damping coefficients. From the comparisons, conclusions can be drawn based on the patterns.

Table 5.1 – Comparison of experimental natural frequencies (Hz) for varying infill densities.

Mode	Frequencies (Hz)		
	10% infill	20% infill	30% infill
1	59	60	61
2	383	395	409
3	474	488	481
4	1102	1153	1122
5	-	-	1727
6	1971	2072	2170

Table 5.1 compares the natural frequencies of the results obtained from varying infill densities. From the table, the frequency tends to increase consistently depending on which mode is being focused on. When comparing the 10% infill to either of the increased infill densities, the high infill densities have a higher natural frequency. This is to be expected, as the greater infill densities should create a stiffer structure. Although the 30% infill density beam does not have a higher natural frequency in modes 3 and 4, it still has greater frequencies compared to the base 10% beam. Further studies and tests can confirm whether the discrepancy is due to print quality.

Table 5.2 – Comparison of experimental natural frequencies (Hz) for varying printing angles.

Mode	Frequencies (Hz)		
	15°	30°	45°
1	66	64	64
2	426	418	418
3	517	494	482
4	1159	1172	1166
5	-	1717	-
6	2178	2179	2204

Table 5.2 compares the results of natural frequencies of varying print angles. Since all beams aside from the varying infill densities have a base infill density of 10%, the 10% infill density results can be used as a neutral comparison for a print angle of 0°. Using this information, we see that the angled prints all have a higher natural frequency for every mode. The reason for this could be due to the way printed layers are able to fuse when printed at an angle. Another reason for this can be due to the adjusted infill pattern within the structure adding better stiffness for angled prints. The first three modes show a decrease in natural frequencies as the angle increases to 45°, whereas modes 4 and 6 show a general trend of a higher frequency at a higher angle of print.

Table 5.3 – Comparison of experimental natural frequencies (Hz) for varying orientations.

Mode	Frequency (Hz)		
	Flat	Side	Vertical
1	59	63	58
2	383	393	379
3	474	489	473
4	1102	977	1078
5	-	1449	-
6	1971	1910	2025

Comparisons between the print orientations use the 10% infill data as the flat default orientation since the since all orientations use a 10% infill density. For modes 1 to 3, the vertical orientation has the lowest natural frequency whereas the side orientation has the highest. Mode 4 has the flat orientation as the highest natural frequency and the side orientation as the lowest. The side natural frequency is the lowest for mode 6 with the vertical being the highest. Once again, results for mode 5 are not discernable from the FRF response for the flat and vertical orientations.

Table 5.4 – Comparison of damping coefficients for varying infill densities.

Mode	Damping Coefficients		
	10% infill	20% infill	30% infill
1	0.0271	0.0213	0.0172
2	0.0392	0.0316	0.0266
3	0.0369	0.0446	0.0642
4	0.0122	0.0101	0.0099
5	-	-	0.0197
6	0.0658	0.0076	0.0091

Trends can be found when comparing the damping coefficients of varying infill density beams. Modes 1, 2, 4, and 6 experience a consistent decrease for an increasing infill density. On the other hand, mode 3 has an increase in damping coefficient with increasing density. The decrease in damping coefficients seen in mode 6 appears significantly between the densities of 10% and 20%, dropping to nearly a tenth of the base 10% infill density damping coefficient value.

Table 5.5 – Comparison of damping coefficients for varying printing angles.

Mode	Damping Coefficients		
	15°	30°	45°
1	0.0307	0.0273	0.0215
2	0.0257	0.0281	0.0374
3	0.0865	0.0464	0.0283
4	0.0118	0.0107	0.0144
5	-	0.0048	-
6	0.0076	0.0037	0.0033

Table 5.5 shows multiple trends of increasing and decreasing coefficients. Modes 1,3, and 6 show a decreasing damping coefficient at higher angles. Mode 2 experiences increased damping

when increasing the angle of print. Meanwhile, mode 4 has mixed results. These results show the unique effects of the printing angle on the structures vibrational modes. More prints with an increased number of angle variables can confirm results and possibly give detail on the trend of damping for mode 4.

Table 5.6 – Comparison of damping coefficients for varying orientations.

Mode	Damping Coefficients		
	Flat	Side	Vertical
1	0.0271	0.0222	0.0284
2	0.0392	0.0223	0.035
3	0.0369	0.0449	0.0322
4	0.0122	0.0243	0.0087
5	-	0.0068	-
6	0.0658	0.0087	0.0098

There are some signs of a trend when comparing results of the damping coefficients for varying orientations. The side orientation appears to have comparably lower damping coefficients when compared to the other orientations for modes 1 and 2. For modes 3 and 4, the side orientation has a much higher damping compared to the others. For these first four modes, the side and vertical orientations share similar coefficients in comparison to the side results. Mode 5 once again has missing data for the flat and vertical orientation. The damping coefficient for the flat orientation appears to be significantly higher than the side and vertical orientations for Mode 6.

What was seen in some results was a missing fifth mode natural frequency peak. It was previously thought that the reason for this was due to the location of the modal impact. However, the cause of the missing mode was because of the placement of the accelerometers. As seen in Figure 5.1, one of the accelerometers was able to acquire data for mode 5 whereas the other had no reaction. This is because the accelerometer happened to be placed on the fifth mode's node of oscillation. This means that the accelerometer could not experience any significant vibrations, and the results of that accelerometer canceled out the results of the other when averaged together.

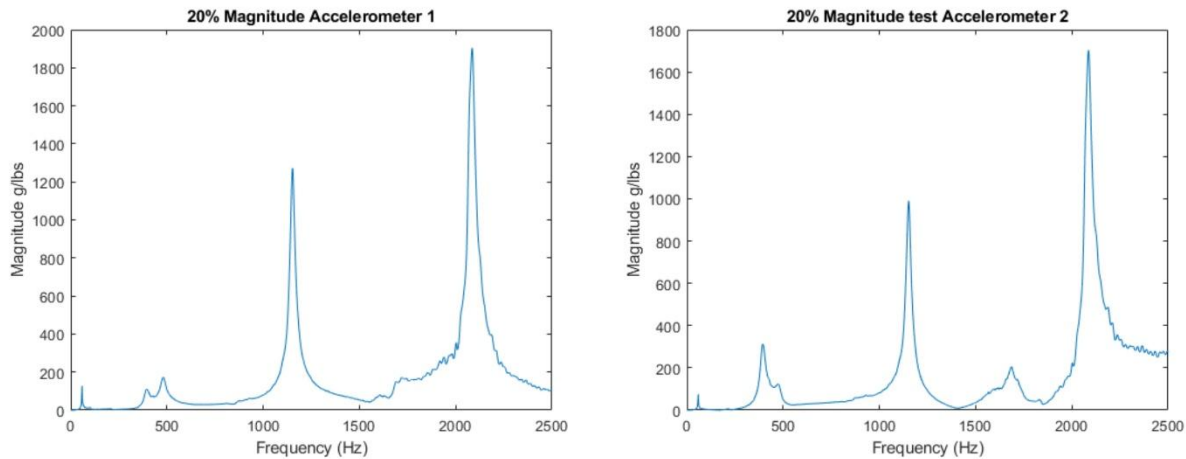


Figure 5.1 – Comparison of accelerometer results for 20% infill beam.

The data on the left in Figure 5.1 represents the accelerometer placed near the third quarter of the beam from the fixed point while the data on the right represents the accelerometer at the tip of the beam. Using multiple accelerometers allows for better data distribution, but in this an accelerometer happened to be placed on a node. With only two accelerometers, the average result can be heavily influenced. Further increased amounts of accelerometers at unique locations can better average the natural frequencies of the system.

Results were ideal but limited due to limitations in equipment and constraints caused by the size of the 3D printed structures. Since the printer used had a maximum of 220x220x250 printing zone, it was difficult to fit a structure any larger than what was already designed. Because the structure was smaller, there is greater difficulty in data acquisition with the limited equipment. Limitations in software also made it difficult to test varying parameters to greater detail. Using the student license limits the number of elements and nodes allowed for simulations, thus the density could only reach 30%. Despite this, the data collection was overall coherent aside from the missing mode reactions. The change in natural frequencies is also smaller than expected, thus it would be beneficial to reduce the hertz increment for a detailed change in natural frequencies. Ideally, a larger structure should be tested with more accelerometers to create a better average. Increasing the range of the varying parameters could also lead to further conclusions on the effects on vibrational characteristics.

Table 5.7 – Comparison of FEM and experimental 10% infill beam natural frequencies.

		Natural Frequencies (Hz)		
		10% infill	20% infill	30% infill
Mode 1	Experimental	59	60	61
	FEM	77.40	73.48	70.55
Mode 2	Experimental	383	395	409
	FEM	348.84	332.86	323.36
Mode 3	Experimental	474	488	481
	FEM	469.96	451.79	435.8
Mode 4	Experimental	1102	1153	1122
	FEM	640.37	624.42	609.31
Mode 5	Experimental	-	-	1727
	FEM	1259.6	1233.3	1197.9
Mode 6	Experimental	1971	2072	2170
	FEM	1851.8	1787.4	1747.9

When comparing the FEM results to the experimental results, we find that the trends appear opposite to each other. The FEM results show a decrease in natural frequency with increasing density whereas the experimental results show that the frequency increases instead. These results can both be argued to be correct as typically an increase in mass would lead to a lower natural frequency, which is why the FEM results make sense as the mass and frequency have an inverse relationship. However, other factors such as stiffness and shape also influence the natural frequency which gives insight into the reason for the difference between the results. Thus, it can be concluded that the 3D printed structure's stiffness and microstructure have a greater influence on the natural frequency than just the increased mass as simulated in the FEM analysis.

6. Conclusion

Summarizing this paper, vibrational analysis was done on varying parameters of 3D printing specific to FDM. These parameters included infill density, angle of print, and face orientation. FEM analysis was done on the various beam designs as a foundation of data. Models were created using SolidWorks 2025 and FEM analysis was done through a combination of Ansys Workbench and Mechanical. Results of the FEM analysis were accurate as proven by the mesh analysis in Table 3.2 and Figure 3.2. FEM results are based purely on the structure of the varying parameters, which in this case only truly affect the infill pattern and density.

It was found that the infill pattern, particularly for Ultimaker Cura, is set with respect to the printing zone rather than the model. Thus, the overall infill pattern and mass was affected by varying parameters. For varying orientations, the infill pattern would stay in place. This made the infill pattern print in varying orientations following the respective orientation. FEM results also showed that increased infill densities led to a decrease in natural frequency and displacement. It is hypothesized that the increase in mass had significant effects on the natural frequency within the simulation. Varying angles generally showed a small increase in natural frequencies as the angles grew from 0 to 45 degrees.

Following the FEM analysis, modal impact analysis was done on printed beams of the modeled structures. A driving point survey was done to find the best point of impact for modal analysis. A total of two accelerometers were available for testing and an impact hammer, both previously specified. A custom coded application from LabVIEW was used for data acquisition. It was found that increasing the infill density generally led to an increase in natural frequencies and a decrease in damping apart from mode 3. Increasing the infill density further or adjusting the increment of density would reveal better trends regarding this data. Varying angle prints show that there is a general increase in natural frequency at increasing angles for modes 1 to 3 and decreasing natural frequencies for increasing angles for modes 4 and 6. Modes 1,3, and 6 show a decreasing damping coefficient at higher angles. On the other hand, mode 2 increases in damping with greater angles. Orientation parameters reveal that the side orientation has a greater natural frequency for modes 1 to 3, while having the lowest for modes 4 and 6. The side orientation and default flat orientation show similar natural frequencies until mode 6, where the vertical print has a noticeably higher natural frequency. For damping, the side orientation has the highest damping for modes 1 and 2 and the lowest for modes 3 and 4. The side and vertical orientations once again have similar damping coefficients for the first four modes. Mode 6 shows that the default flat orientation has the highest damping by a significant amount.

Overall, results show that a stiffer system generally comes from a higher infill density and a slightly angled print. The results of the infill density for experimental results compared to the FEM results give insight into the effectiveness of the stiffness and microstructure on the natural frequency. Possible tests on the material used can also be done to ensure that the material characteristics properly match in the FEM analysis. Increasing angles past 15 degrees show decreasing effects of the increased natural frequency but still increase the natural frequency when compared to the default print 10% infill print. Orientation results are best designed for specific needs depending on the objective of the structure and shape.

Changes can be made to improve the results of the tests. Because of the limited resources and time constraints, depth of data is limited. This leaves room for further research with greater increments of variation. Improvements in the design of the project could be using a larger printer to create larger structures. Using a full license for Ansys could allow for FEM analysis of higher

infill densities, although there was no limit to the experimental infill density. A variety of hammers could allow for a wider range of options to create clearer data. Increased numbers of accelerometer placed at different locations would create a better average for the FRF responses. Furthermore, the natural frequency was recorded with data increments of 1. Decreasing the increment size to a smaller value could give more detailed results for comparisons as the change in natural frequencies is smaller than initially expected. These improvements would correct some of the issues found data collection and results. Despite the limited resources, data collection was smooth, and coherence was accurate for the range of data collected. The project was able to fulfill its purpose and research in the future can be built upon this data for further conclusions.

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