Final Year Honours Project

AUTOMATED DESIGN OPTIMISATION OF 3D-PRINTED MULTIMATERIAL STRUCTURES

Supervised by Dr. John Cater and Emilio Calius

Kevin Zhong
kzho956 374918950
Department of Engineering Science

August 3, 2018

Abstract

Abstract goes here

Acknowledgements

Acknowledgements goes here.

Contents

List of Figures

1 Introduction

1.1 Background

- Exploiting hetereogeneity to obtain unique responses from structures
- Difficult in subtractive manufacturing, additive manufacturing technologies can allow for this to be exploited as multimaterial 3d printing is now available. Allows for a more top-down design approach: begin with a desired bulk behavioural response and modify a structure's material distribution to reflect this
- Particularly useful in field of vibrations - as tuning vibrational response of structures is often an ad-hoc process. Additional mass added to already assembled structures to tune vibrational responses - sub-optimal.
- With the advent of commercially available multimaterial 3d printing technologies; time is now ripe to explore the potential for addressing this issue. Focus on making the workflow "stream-lined" or automated. I.e. automated, requiring minimal effort from engineers to design

1.2 Project Scope

- Analyse a fixed-free cantilever structure - due to its ubiquity across multiple engineering disciplines.
- Natural frequencies tuning - try and enforce uniformity. Motivation is simplicity and produces adequete spacing between modes and reduce chance of vibrational coupling. Will require numerical eigenvalue solver.
- Topology is decided a-priori. Intention is to modify internal material distribution to achieve desired response.
- We want to parallelise the workflow
- Combined workflow of numerical solver, optimisation techniques and experimental validation

2 Methodology

2.1 Overview

A rough, placeholder sketch of the workflow.

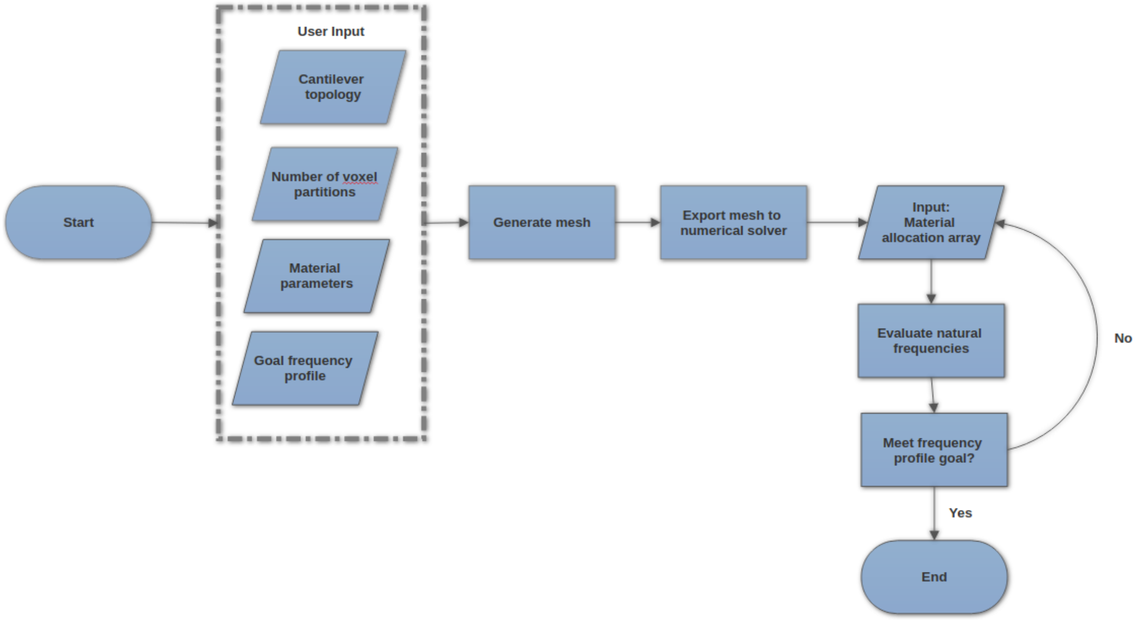


Figure 1: Placeholder figure

- "Goal frequency profile" is intentionally kept general due to flexibility of objective function.
- Updating material allocation array requires optimisation tools
- At end, solutions will then be 3D printed and validated through experimental testing

2.2 Vibrational Analysis

- Begin with pre-amble on elementary Euler-Bernoulli beam theory. Homogeneous solutions. State governing equations, governing parameters, existing analytic solutions
- Explain the types of modes encountered: bending in-plane, bending out-of-plane and torsional.
- Moving to multimaterial problem -> $E(x, y, z)$, $\rho(x, y, z)$ heterogeneity makes things near impossible to treat analytically.
-

2.3 Modeling Multi-material Structures

- Selection of TWO materials readily available in additive manufacturing. Substantially different material properties for wide range of responses in solutions. Easier to deal with; problem becomes a binary decision making process

- Use cartesian voxel structure - fits nicely for a rectangular prism cantilever. Decision on overall cantilever topology, and number of voxels to use must be decided a priori. (Parametric study on a suitable number of voxels can be conducted????)
- Either material is assigned to each of the voxels. One is stiff, one is flexible ideally. Analogy is to think of the flex material as being blocks of “inclusions” inside the host structure that is the stiff material.
- Geometry generation, meshing, and partitioning done using Salome.

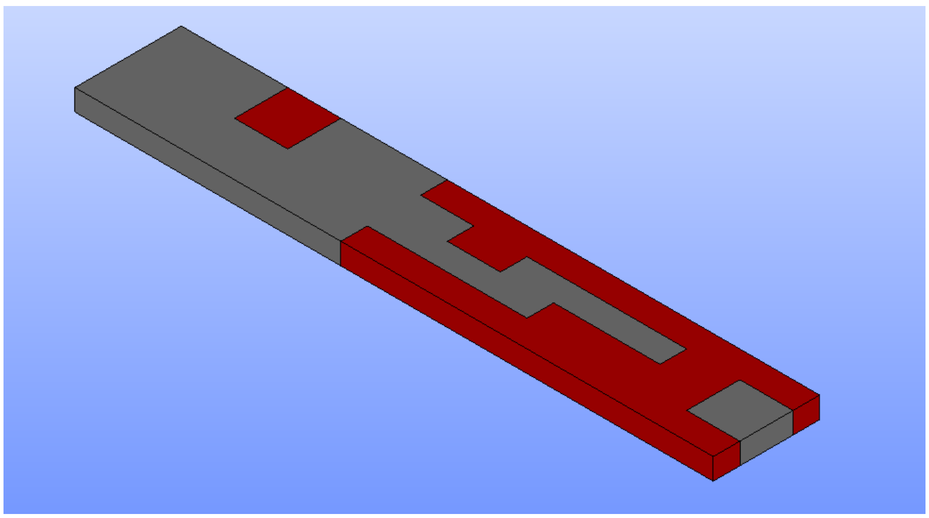


Figure 2: Placeholder figure. Can probably generate a fancier voxel distribution for illustration. E.g. multiple voxel layers.

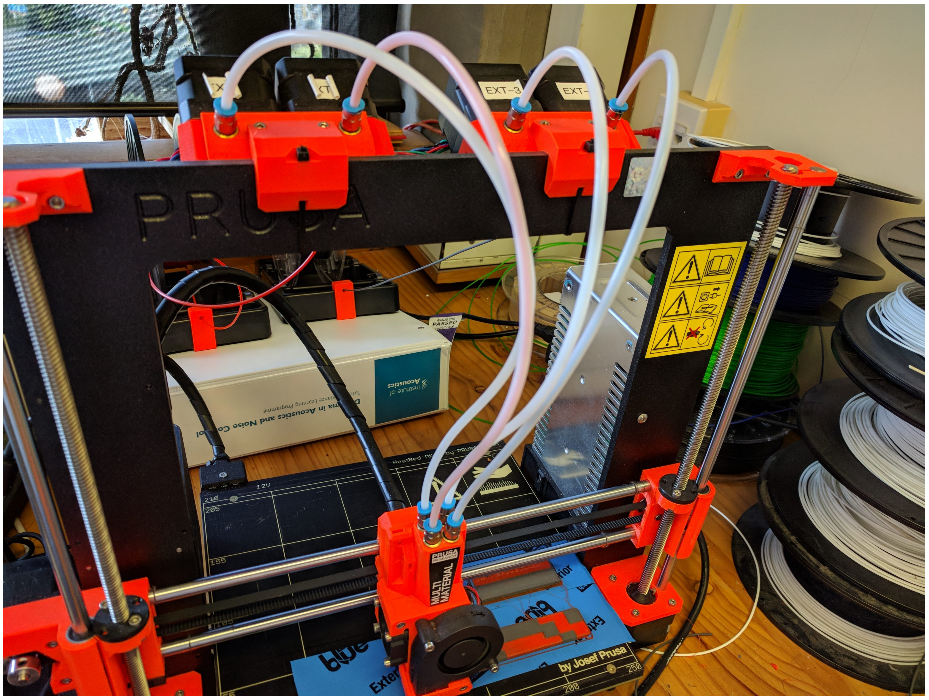


Figure 3: Snapshot of filament-based, multimaterial-capable 3d printer. 4 seperate filament extruders in tubes, all capable of being used to print a single structure.

2.4 Numerical Solver

- Modeling of multimaterial problem is approached using numerical techniques
- Problem of finding natural frequencies is reduced to finding the eigenvalues of a linear system
- Requirements in software: eigenvalue solver, open-source and lightweight for parallelisation
- Preliminary investigations in solve times and verification using homogeneous analyic solutions using different mesh settings. Cubic mesh elements for simplicity. Sweetspot found with linear mesh with roughly $h/dx = 3$. I.e. 3 mesh elements through thickness of cantilever. 100L x 2H x 20W geometry tested:

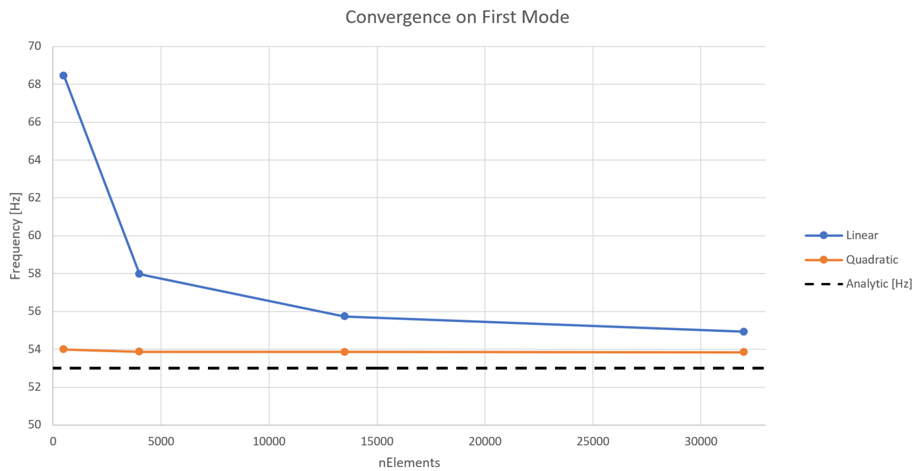


Figure 4: Convergence testing on homogeneous solutions. Comparing linear and quadratic elements to analytic solution for first natural frequency.

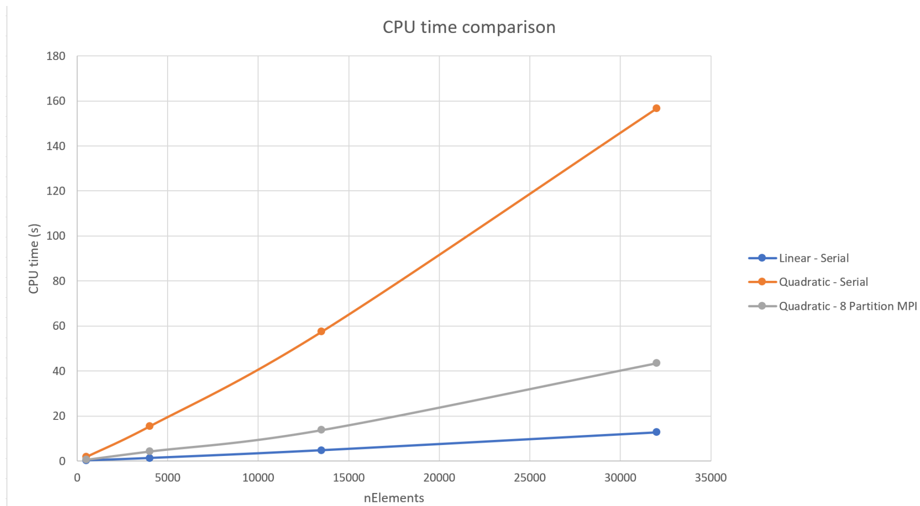


Figure 5: CPU time comparison for selection of mesh grids. Used MPI partitioning on quadratic meshes to observe any potential speed-uponvergence testing on homogeneous solutions. Comparing linear and quadratic elements to analytic solution for first natural frequency.s.

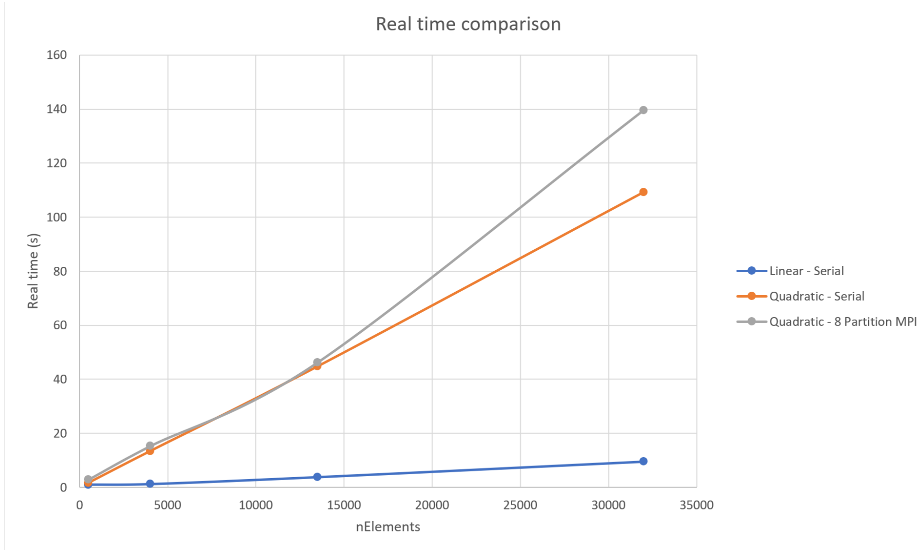


Figure 6: Comparison of real time elapsed to solve.

2.5 Scaling

- Investigate effects of scaling dimensions of geometry by some scale factor, whilst maintaining identical voxel distribution
- Frequencies inverely proprtional to scaling factor

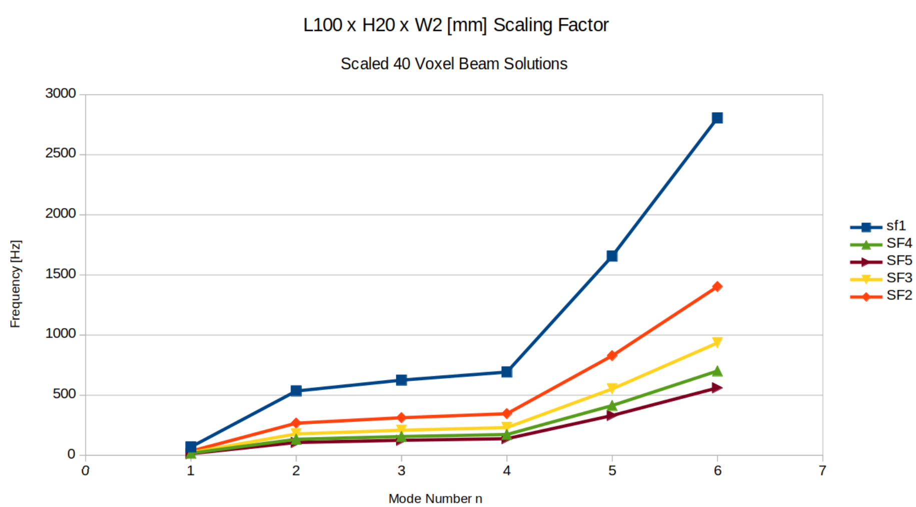


Figure 7: Scale factor effects on numerical solutions

2.6 Printing Samples

- Filament based 3d printer (relies on fused deposition modeling).
- Multiple filaments, multiple filament extruders, SINGLE nozzle

- Filament is heated and extruded through the nozzle as a viscous solid and printed onto a heatbed
- Flex and steelfill used - two substantially different material properties
- Very sensitive to printer settings. Ad-hoc tuning required. Main issues are stringyness of material, delamination and minor air bubble formation
- Main variables of interest are: heatbed temperature, nozzle temperature, speed, volumetric flowrate, z-axis height offset
- Printed as fibrous, laminate structure. Only rectilinear and concentric patterning available for 100% infill density. Resulting printed specimen is probably quasi-isotropic at best
- Require exporting beam solutions in .STL format file compatible with the 3D printer software. Done using a matrix/host structure for one file, and inclusions in another file
- May be worthwhile to mix up fibre orientations for quasi-isotropic laminate structure. I.e. $N = 4$ quasi-isotropic laminate

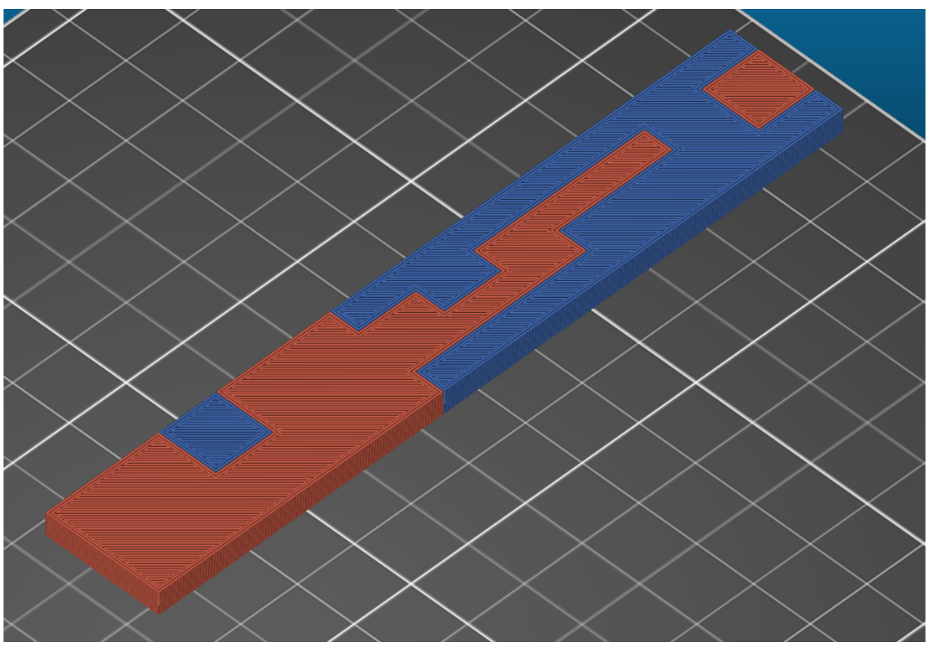


Figure 8: Preview of printed layers. ±45 degree fibre orientations each consecutibe layer. "Rectilinear" fill pattern.

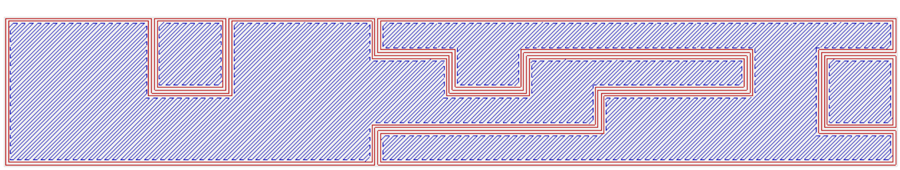


Figure 9: 2D view of preivous figure

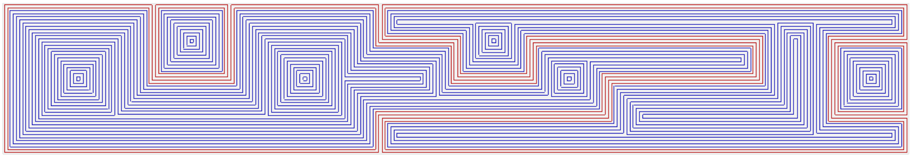


Figure 10: Another possible fibre orientation for 100% infill density. However, it is not possible to use this fibre orientation for every single layer.

2.7 Validation

2.7.1 Experimental Setup

- Preliminary testing with aluminium slab
- Spectral estimation using Room EQ Wizard (REW). Real time analyser functionality allows for real time acquisition of signal
- Workflow: Pluck cantilever. Laser doppler vibrometer makes non-contact measurements of surface velocity as a voltage. Signal goes through analogue to digital convert / pre-amplifier with USB interface into computer. Signal enters computer and is processed using REW.

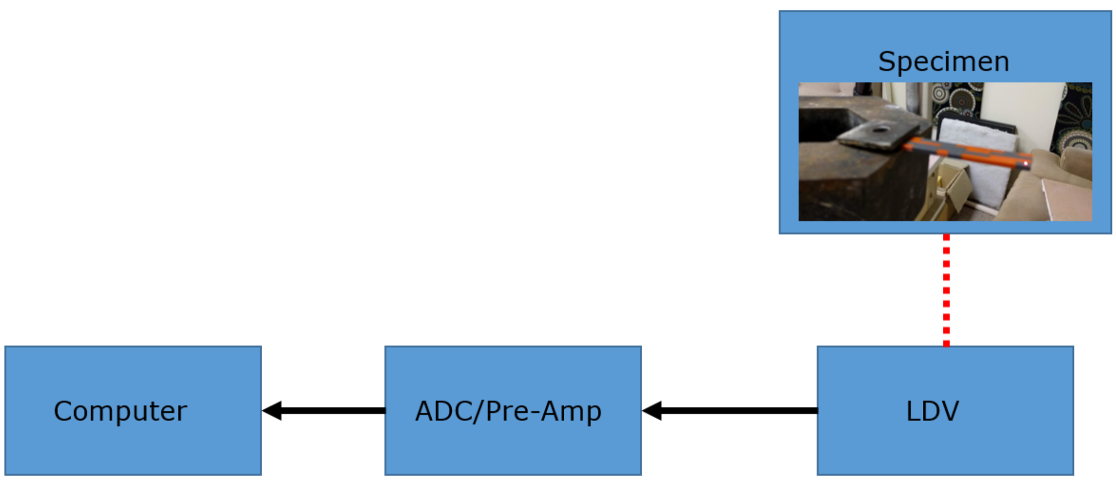


Figure 11: Experimental workflow

Figure 12: Example of how experiment was set up. Missing G-clamp for fixing sample.

2.7.2 Testing

- Did preliminary testing using this method with aluminium sample, agreement was excellent

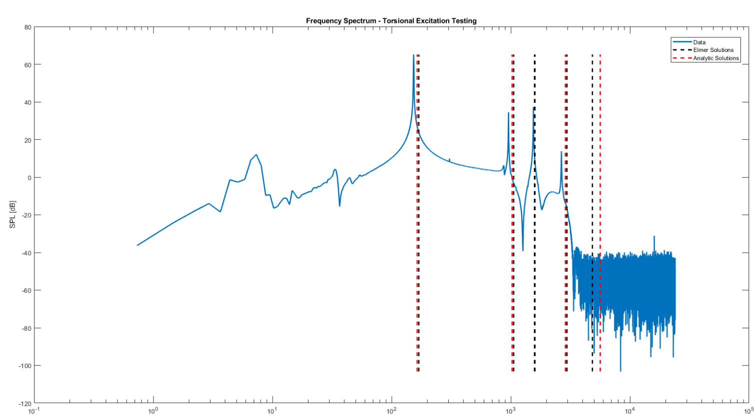


Figure 13: Freq. spectrum of aluminium sample. Compared with analytic solutions where available, and Elmer's numerical solutions.

- Printed homogeneous samples to obtain estimates of E and ρ, because provided technical datasheets likely unreliable
- Laminate sample also printed, as a preliminary step before attempting to solve for voxelised beam solutions

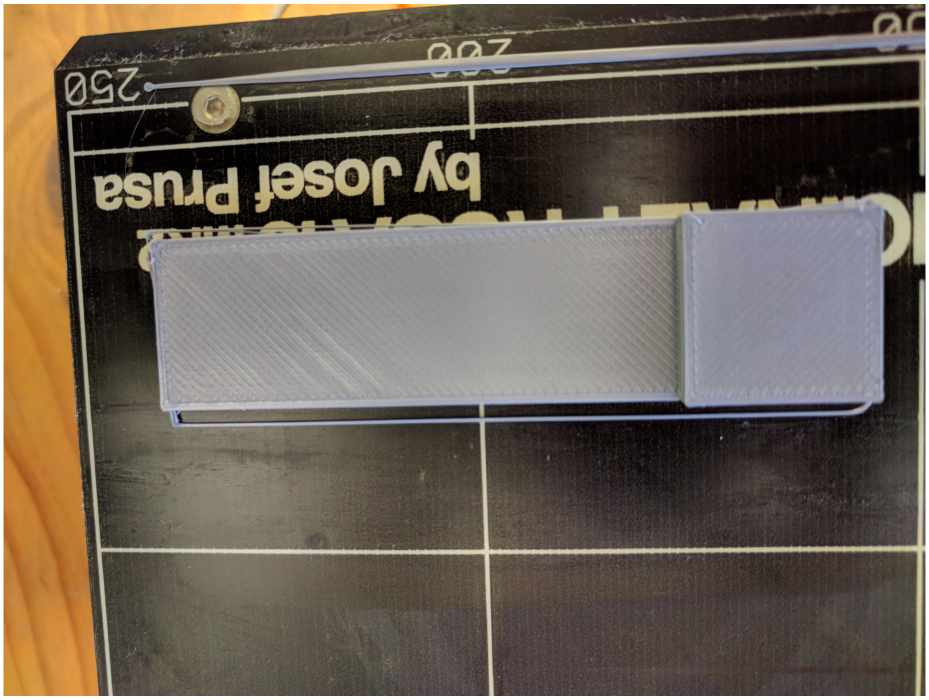


Figure 14: Homogeneous PLA print

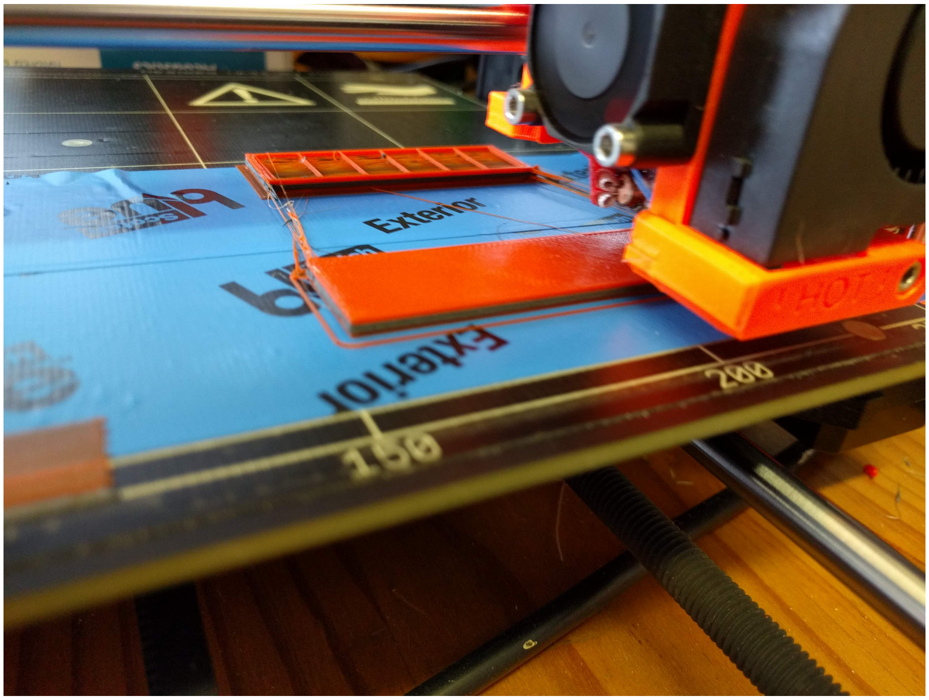


Figure 15: Laminate structure

3 Results and Discussion

- Homogeneous sample testing - frequency spectrums used to obtain estimation for E by fitting value of E to analytic solution for first natural frequency. ρ estimated using mass scale.

- Used these material parameter estimates as inputs into the 4 layer laminate model in Elmer. Compared with experimental results, but peaks did not line up with Elmer predictions

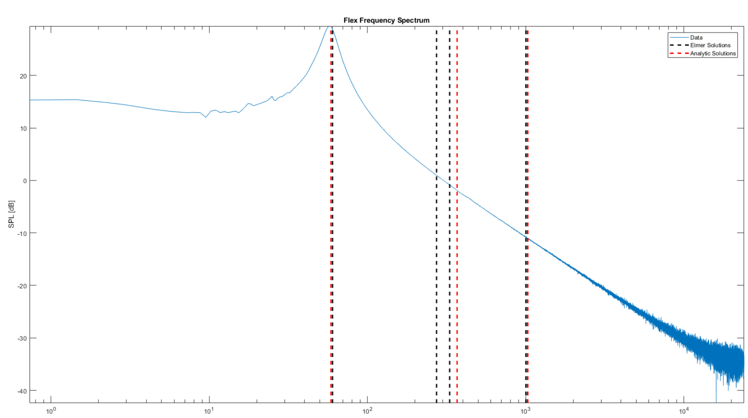


Figure 16: Frequency spectrum for flex

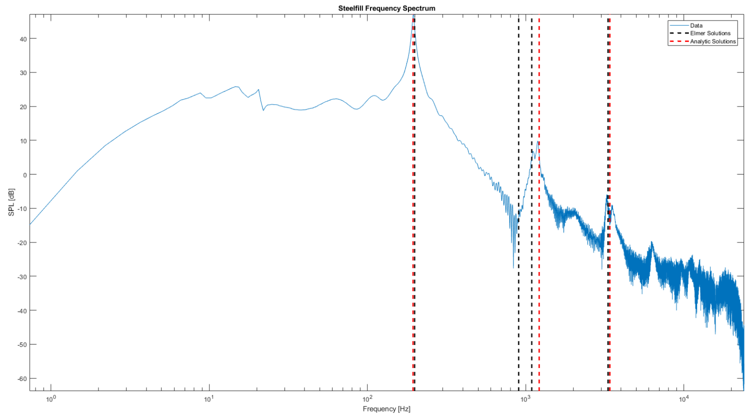


Figure 17: Freq. spectrum for Steelfill

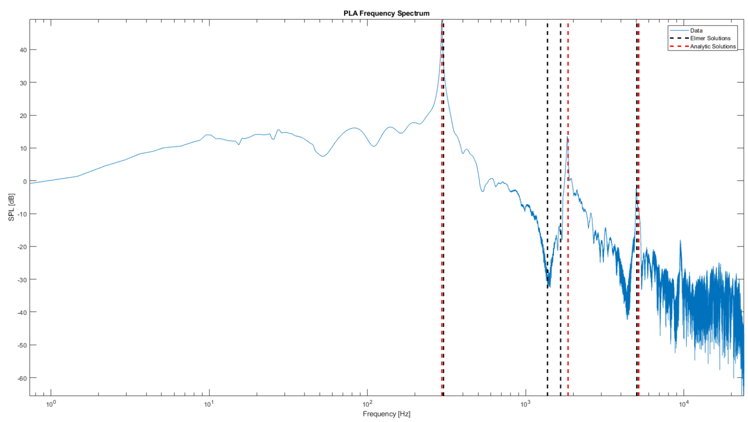


Figure 18: Freq. spectrum for generic PLA.

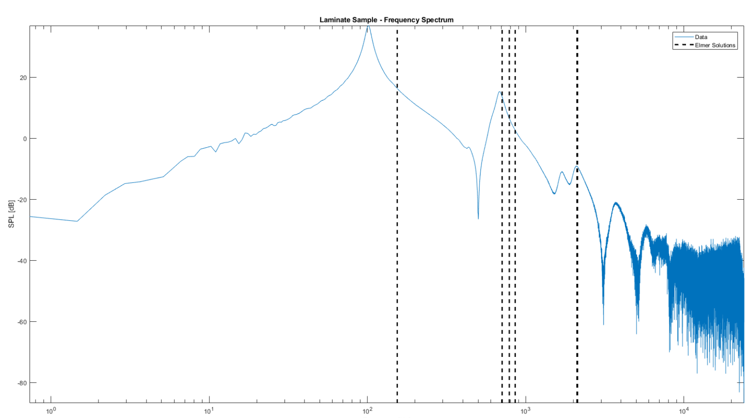
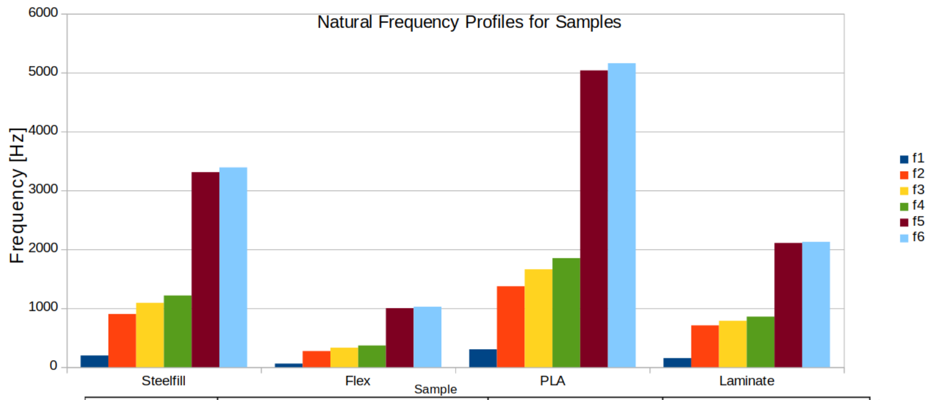


Figure 19: Freq spectrum of laminate specimen

	Natural Frequencies [Hz]					
Material	f1	f2	f3	f4	f5	f6
Steelfill	199	903	1092	1217	3311	3391
Flex	60	273	331	369	1003	1027
PLA	302	1374	1662	1852	5038	5161
Laminate	154	710	788	858	2109	2127



Material	Young’s Modulus [Mpa]	Density [kg/m3]	E/ρ [m^2/s^2]
Steelfill	3450	2950	1.17E+06
Flex	115	1070	1.07E+05
PLA	3250	1200	2.71E+06

Figure 20: Summary of material parameters and natural frequency profiles of specimens

Main difficulties were:

- Potential harmonic responses of specimens
- Difficult for laser to focus onto flex surface due to dispersion
- Was observed that the laminate specimen may have exhibited “internal” resonance between its layers before producing its bulk resonant response. During real-time acquisition, the freq. respose spectrum for the laminate would have a delay before producing the "expected" frequency spectrum from plucking

3.1 Voxel Beam Testing

- Using hill-climbing methods, a variety of voxel beam solutions were generated; each taking roughly 10 to 15 minutes to obtain
- Note that additional clamping block was also printed to help with testing
- Voxel beams yet to be tested

```
Natural frequencies:
1: 55.47 Hz
2: 146.82 Hz
3: 277.71 Hz
4: 434.75 Hz
5: 613.59 Hz
6: 760.65 Hz
```

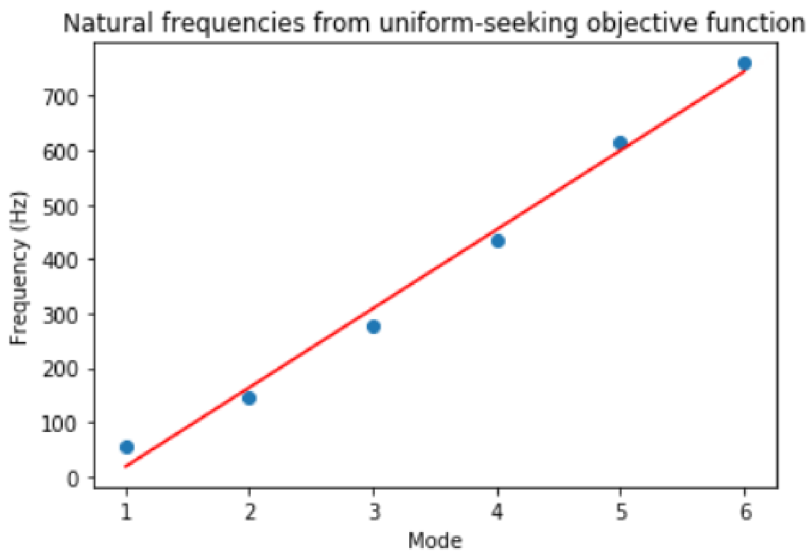


Figure 21: Sample solution obtained - Steelfill + flex in 40 voxel beam

Figure 22: 40 voxel solution above

4 Conclusions

Conclusion goes here.

5 Future Work

- Printing/generating extra "backup" solutions for redundancy
- Experimental validation of voxel beam solutions
- Varying voxel heights

1 Appendix A