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Mechanical Characterization of 3D Printed Hydrogel Lattices

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Topic: Mechanical Characterization of 3D Printed Hydrogel Lattices

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Abstract

White matter brain tissue is largely inaccessible and is therefore difficult to mechanically characterize although this would be useful in understanding injuries and injury prevention. Thus, soft gels and 3D bioprinted materials allow for the estimation of the mechanical properties of brain tissue through non-invasive means. Through previous studies, it is determined that brain tissue is inherently anisotropic. To properly model it, the use of anisotropic cubic, diamond, and vintile type lattice 10 x 10 x 10 cm cube structures were used in compression testing to determine the elastic modulus of each lattice type in each of its orientations. Each lattice was scaled by 2 times in its X-direction and remined the same in its Y and Z directions. It was found that anisotropy in the material produces greater overall stiffness in the lattice structure, although more testing is needed to verify the results of this original study.

Introduction

Traumatic brain injury (TBI) is an injury caused by external force to the head or body which disrupts normal brain function. TBI results in death in thousands of people each year, and was diagnosed in 2.9 million emergency department visits, hospitalizations, and deaths in 2014 [1]. While there are qualitative studies that have been completed to characterize these types of brain injuries from a practical point of view, there is little research being done to characterize TBIs quantitatively. This is since brain tissue is largely inaccessible. Common imaging techniques have been developed such as EEG, PET, and MRI that allow the investigator to understand brain functionalities on a visual basis, but these non-invasive procedures do not extract the mechanical properties of brain tissue. Thus, the mechanical characterization of soft gels and 3D bio printed materials allows for the accurate estimation and characterization of white matter brain tissue through non-invasive means.

Through previous study, it is determined that brain tissue is structurally anisotropic through traditional magnetic resonance elastography (MRE) methods. However, there is a need to experimentally determine the validity of these studies and mechanically characterize brain tissue mimicking substances on a tangible basis. This study uses 3D bioprinting methods to create 3D soft anisotropic material to mimic the mechanical properties of the brain through the investigation of various unit celled lattice structures.

There are three main unit celled lattice structures investigated in this study: cubic, diamond, and vintile type structures. The visualization of these three lattice structures is shown in Figure 1.

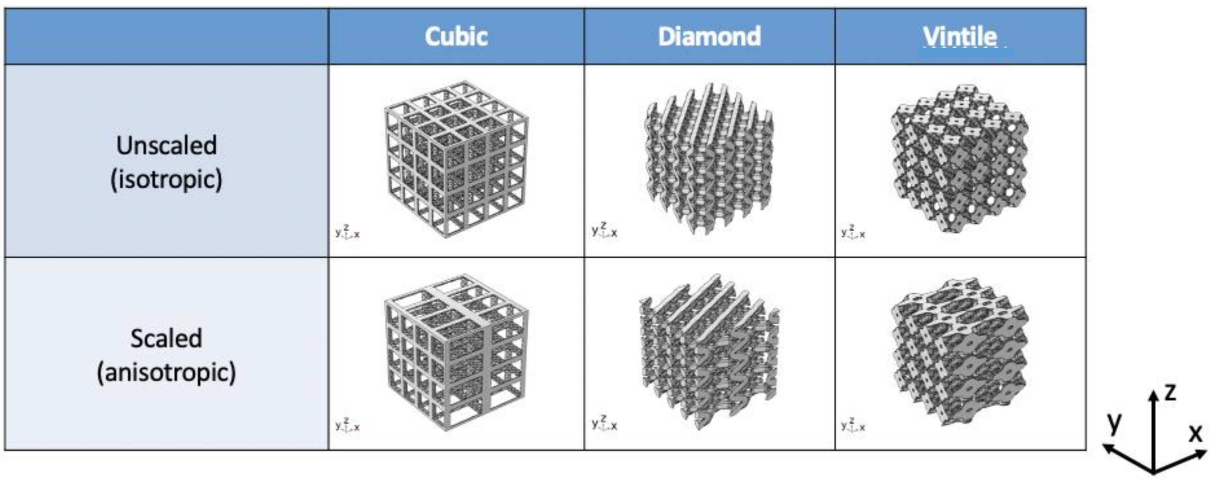

Figure 1: Isotropic and Anisotropic Cubic, Diamond, and Vintile Lattice Structures

As visible in Figure 1, the internal structure of each lattice structure differs, and each encompass differing amounts of space and shapes within the overall structure. Furthermore, these lattice types are scaled in a single dimension to introduce anisotropy in the material. This is easily seen in Figure 1, as the scaled lattices appear “stretched” and non-uniform in the x-dimension.

One of the mechanical properties of the structures of interest is the Young’s Modulus of each material in their specific orientation. This mechanical property describes the tensile or compressive stiffness of a material when a force is applied to it lengthwise. It describes the ratio between the compressive stress and axial strain a material undergoes when experiencing elastic deformation. A visualization of the Young’s Modulus on a stress-strain curve is shown in Figure 2.

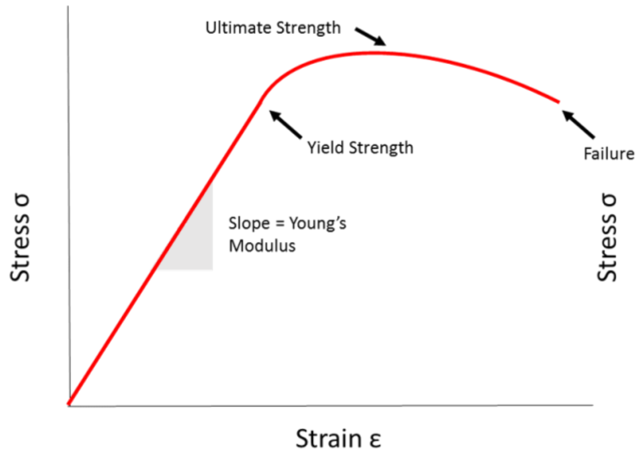

Figure 2: Stress-Strain Curve [2]

As shown visually and described, when a material undergoes compression it experiences a change in length, which is shown in Figure 3. These parameters can then be used to mathematically define Young's Modulus in Equation 1.

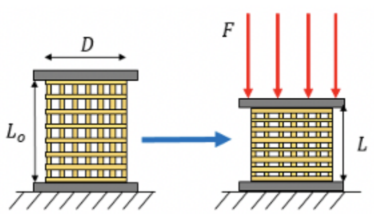

Figure 3: Compressed Material

$$E = \frac{\sigma}{\varepsilon} = \frac{-F/A_o}{(L-L_o)/L_o} \qquad (1)$$

In Eqn 1, $E\ \left[\frac{N}{m^2}\right]$ is the Young's Modulus of the sample $\sigma\ [\frac{N}{m^2}]$ is the stress applied to the lattice sample, $\varepsilon\ [\frac{mm}{mm}]$ is the axial strain applied to the sample, $F\ [N]$ is the force applied to the sample (shown in Fig 3), $A_o\ [m^2]$ is the cross-sectional area of the sample, $L_o\ [m]$ is the initial length of the sample (shown in Fig 3), and $L\ [m]$ is the final length of the sample (shown in Fig 3). This study will complete an extensive analysis of the elastic material properties of both isotropic and anisotropic cubic, vintile, and diamond lattice structures to better determine their mechanical properties relating to stiffness.

Methods

All lattice structures were designed using CAD software, and printed using photo-printing in PEGDA hydrogel by Bayly Lab members. All tested lattice structures, print date, test date, and strut diameter are shown in Table 1.

Table 1: Sample type, test date(s), and other special notes[1]

Sample Type	Test Date (1)	Test Date (2)	Other Notes
Cubic Isotropic	03/08/22	03/22/22	Good print. Symmetric in all orientations
Diamond Isotropic	03/08/22	03/22/22	Did not fully adhere to build plate during Printing. Y-Orientation is slanted.
Vintile Isotropic	03/08/22	03/22/22	Did not fully adhere to build plate during printing. Not uniform.
Cubic Anisotropic	04/19/22	N/A	Good print. Symmetric in all orientations.
Diamond Anisotropic	04/19/22	N/A	Good print. Symmetric in all orientations.
Vintile Anisotropic	04/19/22	N/A	Good print. Symmetric in all orientations.

[1] The experimenter listed in this report did not print samples, so key details of their specifications must be found by Maggie Ruding and Daniel Yoon of the Bayly Lab

All samples were kept refrigerated and hydrated in deionized water with added food coloring up until their compression testing, and were replaced in their hydration between tests. Furthermore, all samples were compressed in three orientations: the X, Y, and Z directions.

Compression of each sample took place on the ElectroForce 3200 available in the Washington University MEMS SIG Lab, pictured in Figure 4.

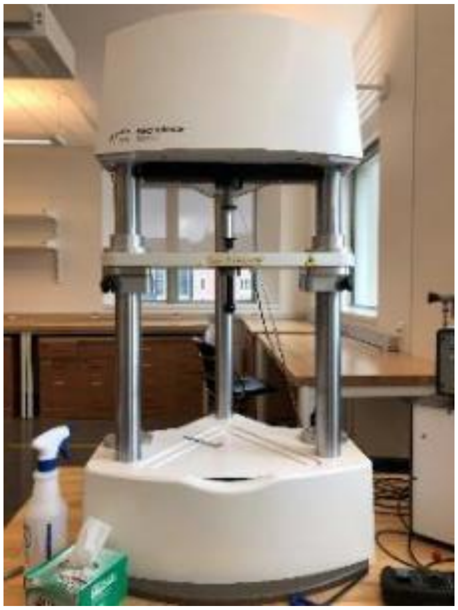

Figure 4: ElectroForce 3200

Using the ElectroForce 3200 with 45N load cell and accompanying WinTest software, each lattice structure was compressed with a pre-load of -0.02 N before testing began. This value was chosen because it allowed the experimenter to visually determine compressive contact between the ElectroForce 3200 and sample without causing any visible buckling. Furthermore, each sample was compressed to approximately 10% strain. The exact strain level experienced by each sample depends on their specific dimensions, however a strain rate of 10% was applied to each sample assuming they are each a perfect 10 cm x 10 cm x 10 cm cube. Furthermore, the rate at which axial strain was applied to each sample was 1 mm/s.

Lastly, all samples were marked on each of their orientations with a differently colored Sharpie pen in order for the experimenter to keep track of their orientations. Blue denoted the X-direction, red denoted the Y-direction, and black denoted the Z-direction. The X-direction was determined to be the scaled orientation of each anisotropic lattice structure.

After compression testing of each lattice structure was completed in each orientation, MATLAB was used to extract the stress, strain, and Young's Modulus calculations from the raw data outputted by the WinTest software (which includes Force and Displacement as the relevant measurements). The details of the MATLAB is shown in Appendix A.

Due to time constraints, the Cubic, Diamond, and Vintile Isotropic lattices were tested twice (approximately two weeks apart), and the Cubic, Diamond, and Vintile Anisotropic lattices were tested once.

Results/Discussion

Figure 5 below shows the Young's Modulus results of the initial testing of the Isotropic, Cubic, Diamond, and Vintile lattice structures.

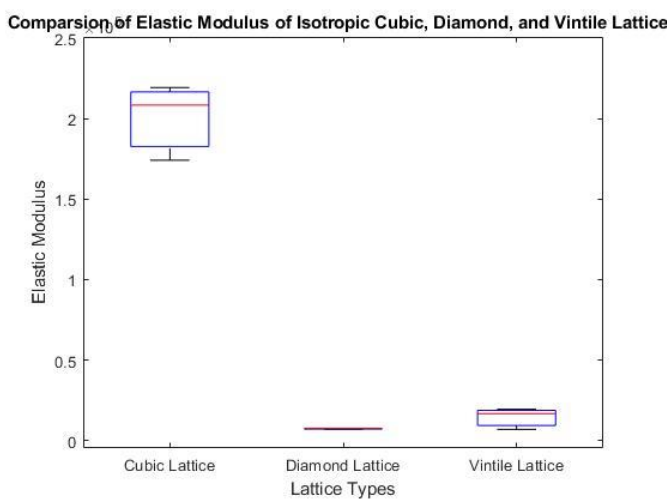

Figure 5: Comparison of Elastic Modulus of Isotropic Cubic, Diamond, and Vintile Lattice Structures

In Figure 5, the results are formatted as a standard boxplot, with the red line representing the median, the top and bottom blue lines of each box plot representing the third and first quartile of the data, respectively, and the black lines representing the maximum and minimum of the data set. It is determined from this analysis that the initial found Elastic Modulus of the Isotropic Cubic lattice is approximately $2.1x10^5\ N/m^2$, while that of the Isotropic Diamond and Vintile lattices are approximately

$0.2x10^5 N/m^2$. Initially, it is shown that the Isotropic Cubic lattice is stiffer than the Isotropic Diamond and Vintile lattice structures. Furthermore, the small distribution in these box plots shows that these samples do indeed obtain isotropic properties, as they have similar elastic moduli in all orientations.

When these same samples were tested again approximately two weeks later, similar results were found, shown in Figure 6.

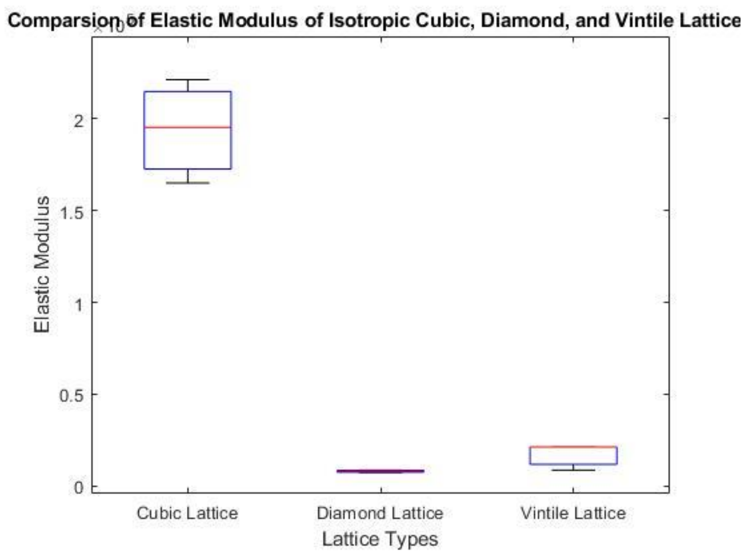

Figure 6: Comparison of Elastic Modulus of Isotropic Cubic, Diamond, and Vintile Lattice Structures

The median elastic modulus of each isotropic lattice structure is nearly identical to its median determined two weeks prior. Thus, it is initially shown in this study that there is no time-dependent property of the stiffness of isotropic cubic, diamond, or vintile lattice structures. However, more testing is needed to definitively determine the results of this initial study.

Anisotropic/scaled samples of each of these lattice structures were also tested, and their elastic moduli varied from the results previously shared in this report, as shown in Figure 7.

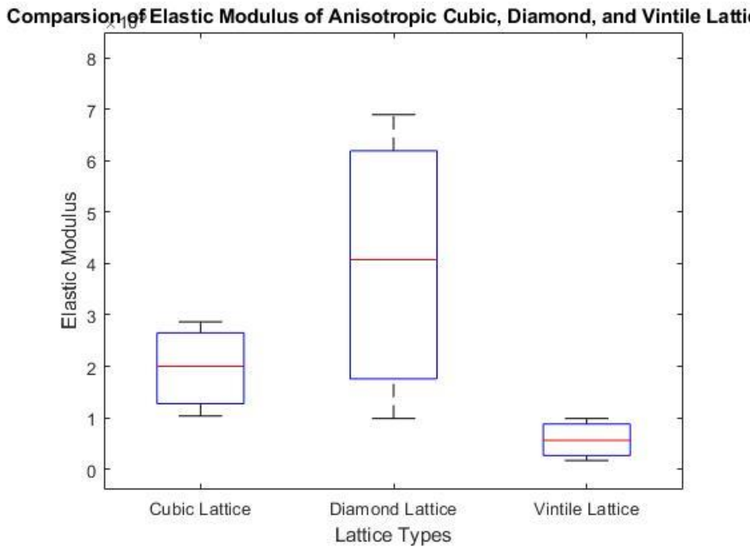

Figure 7: Comparison of Elastic Modulus of Anisotropic Cubic, Diamond, and Vintile Lattice Structures

While the cubic lattice structure reports a similar median elastic modulus to its isotropic counterpart (approximately $2x10^5 N/m^2$), the diamond and vintile lattice structures both show stiffer properties. The median anisotropic diamond lattice elastic modulus is approximately $4.1x10^5 N/m^2$ while that of the anisotropic vintile lattice is approximately $0.8x10^5 N/m^2$. Furthermore, there is no single common orientation in the lattice structures that proved to be the stiffest, which inconclusively shows the effect of scaling on the stiffness of a single orientation of a lattice structure. However, it overall appears that the introduced anisotropy to the 3D printed lattice structures introduces greater stiffness than in their isotropic counterparts.

Conclusion

This study determined the mechanical stiffness of 3D bio printed isotropic and anisotropic cubic, diamond, and vintile lattice structures. While this study included a small sample size, it was initially shown that anisotropy in the lattice structures introduced some variability in their stiffness configurations in comparison with their isotropic counterparts. Some sources of error in this study include imperfect prints that introduce variability in the sample size and structure as well as unknown precise dimensions of each print (their dimensions were assumed based on print specifications). Another source of error includes the limited number of samples included in this study. Further experimentation is needed to verify the results of this study.

References

[1] Peterson, Alexis B, and Hong Zhou. *Traumatic Brain Injury-Related Hospitalizations and Deaths by Age Group, Sex, and Mechanism of Injury*. CDC, 2017.

[2] *Investment Casting Strength*. https://www.remet.com/en/insights/investment-casting-strength-part-2/.

[3] Abate, Kalayu Mekonen, et al. "Design, Optimization, and Validation of Mechanical Properties of Different Cellular Structures for Biomedical Application." *The International Journal of Advanced Manufacturing Technology*, vol. 106, no. 3-4, 2019, pp. 1253–1265., https://doi.org/10.1007/s00170-019-04671-5.

[4] Munford, Maxwell, et al. "Prediction of Anisotropic Mechanical Properties for Lattice Structures." *Additive Manufacturing*, vol. 32, 2020, p. 101041., https://doi.org/10.1016/j.addma.2020.101041.

PVB update to AM / MR matlab

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2022 0307

Locate NEW Directory

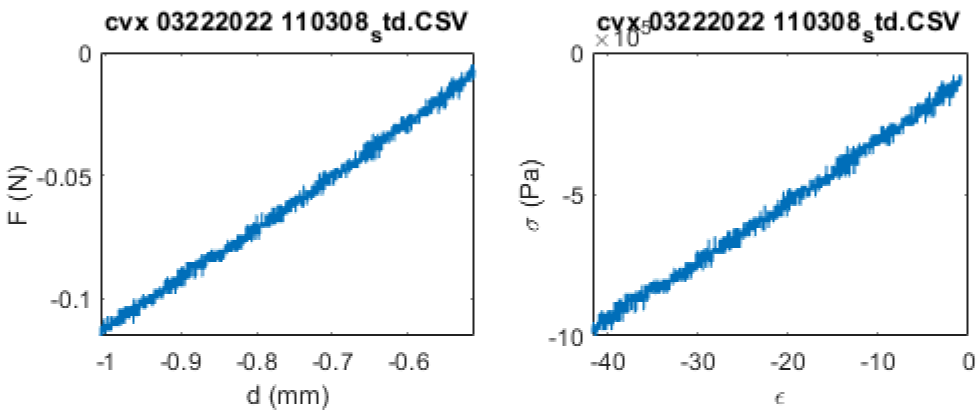
```
clear all
close all

% Compression
% Z: is brainlab, uncomment the correct directory
% Maggie data
% directory = 'Z:\Electroforce_data\maggie_data\sb3c_data\compression';
 %change to folder w/ data
% Annie data
%directory = 'Z:\Electroforce_data\annie_data\Comp\20220303\CC'; %change to
 folder w/ data
%directory = 'Z:\Electroforce_data\annie_data\Comp\20220303\CD'; %change to
 folder w/ data
%directory = 'Z:\Electroforce_data\annie_data\Comp\20220308\CV'; %change to
 folder w/ data
directory = 'Z:\Electroforce_data\annie_data\Comp\20220322\CV'; %change to
 folder w/ data

cd(directory);
addpath(directory,'-begin');
mfileDir = 'Z:\Electroforce_data\Electroforce_mfiles'; %where this file is
 saved
addpath(mfileDir,'-begin')
% find list of files
d = dir;
k = length(dir);
klen = k-2;

leg = strings(klen,1);
% define data range
midrange = 51:2500;       % samples in mid-range - CHANGE AS NEEDED
```

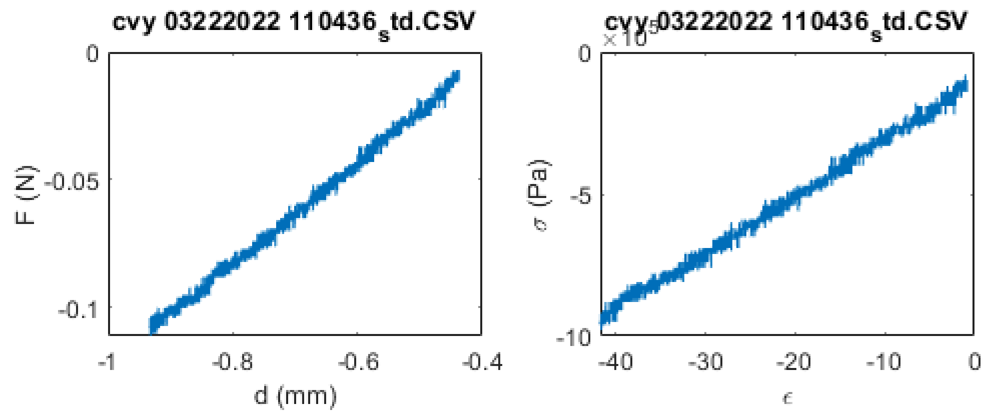
Gather data from excel files

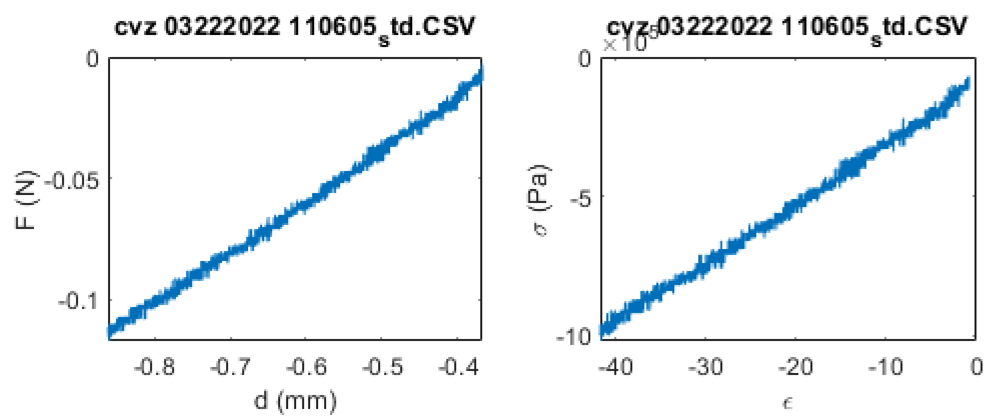
```
STRAIN = cell(klen,1);
```

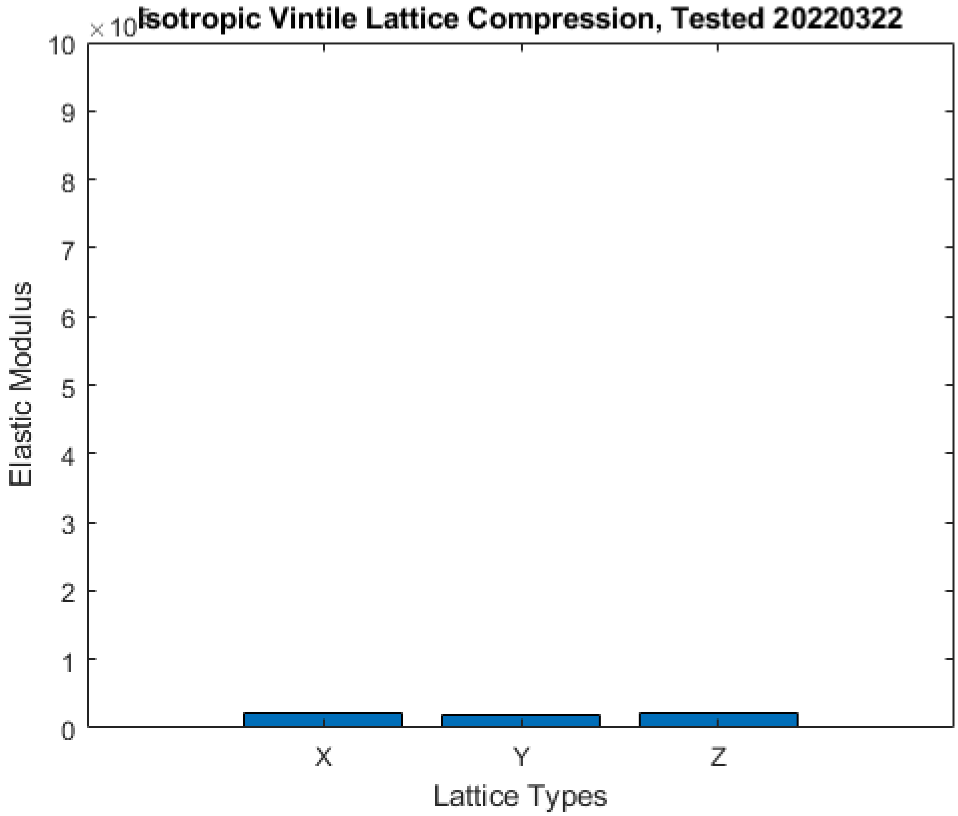
```
STRESS = cell(klen,1);

for i = 1:klen
    ii = i+2;
    currD = d(ii).name;
    %     fname = currD + '.CSV';
    num2str = string(i);
    leg(i) = num2str + ': ' + currD;

    load = xlsread(currD,'D42:D3006'); % input file name and file column
    disp = xlsread(currD,'C42:C3006');

    width = xlsread(currD, 'I2:I2');
    if isempty(width), width = 0.01; end;       % 10 mm cube

    thickness = width;
    area = width*thickness; % cross-sectional area
    length = width;


    stress = load(midrange)/area;      %stress in mid-range Mpa
    stress = stress.*1000; %kPa
    strain = (disp(midrange)-disp(1))/length;

    p = polyfit(strain,stress,1);
    slope = p(1);
    intercept = p(2);


    figure(100+i),
    subplot(2,2,1)
    plot(disp,load),title(d(ii).name),xlabel('d (mm)'),ylabel('F (N)')
    subplot(2,2,2)

 plot(strain,stress),title(d(ii).name),xlabel('{\epsilon}'),ylabel('{\sigma}
 (Pa)')

    E(i) = slope;
    STRAIN{i} = strain;
    STRESS{i} = stress;

end
%
% E_box = [E(1), E(4), E(6);
%          E(2), E(5), E(7);
%          E(3), E(6), E(9);];

figure(300)
bar(E)
xlabel('Lattice Types')
ylabel('Elastic Modulus')
ylim([0, 10E5])
title('Isotropic Vintile Lattice Compression, Tested 20220322')
xticklabels({'X','Y','Z'})
```

```
% figure(200)
% boxplot(E_box)
% xlabel('Lattice Types')
% ylabel('Elastic Modulus')
% title('Comparsion of Elastic Modulus of Isotropic Cubic, Diamond, and
 Vintile Lattices')
% xticklabels({'Cubic Lattice', 'Diamond Lattice', 'Vintile Lattice'})
```




cvy 03222022 110436std.CSV
F (N)
0
-0.05
-0.1
-1
-0.8
-0.6
-0.4
d (mm)
cvy 03222022 110436std.CSV
σ (Pa)
0
-5
-10
-40
-30
-20
-10
0
ϵ


cvz 03222022 110605std.CSV
F (N)
0
-0.05
-0.1
-0.8
-0.7
-0.6
-0.5
-0.4
d (mm)
cvz 03222022 110605std.CSV
σ (Pa)
0
-5
-10
-40
-30
-20
-10
0
ϵ



Published with MATLAB® R2021b