FINITE ELEMENT ANALYSIS SIMULATION FOR ANTERIOR CRUCIATE LIGAMENT SCAFFOLDS

```
% Let's first import the data
FEA_data = readtable("Downloads/stress_strain_acl_vs_pcl_plga.csv")
```

```
Warning: Column headers from the file were modified to make them valid MATLAB identifiers
before creating variable names for the table. The original column headers are saved in the
VariableDescriptions property.
Set 'VariableNamingRule' to 'preserve' to use the original column headers as table variable names.
FEA_data = 100×7 table
```

...

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
1	'Native ACL'	0	0	150	0.4500
2	'Native ACL'	0.6122	0.9184	150	0.4500
3	'Native ACL'	1.2245	1.8367	150	0.4500
4	'Native ACL'	1.8367	2.7551	150	0.4500
5	'Native ACL'	2.4490	3.6735	150	0.4500
6	'Native ACL'	3.0612	4.5918	150	0.4500
7	'Native ACL'	3.6735	5.5102	150	0.4500
8	'Native ACL'	4.2857	6.4286	150	0.4500
9	'Native ACL'	4.8980	7.3469	150	0.4500
10	'Native ACL'	5.5102	8.2653	150	0.4500
11	'Native ACL'	6.1224	9.1837	150	0.4500
12	'Native ACL'	6.7347	10.1020	150	0.4500
13	'Native ACL'	7.3469	11.0204	150	0.4500
14	'Native ACL'	7.9592	11.9388	150	0.4500
15	'Native ACL'	8.5714	12.8571	150	0.4500
16	'Native ACL'	9.1837	13.7755	150	0.4500
17	'Native ACL'	9.7959	14.6939	150	0.4500
18	'Native ACL'	10.4082	15.6122	150	0.4500
19	'Native ACL'	11.0204	16.5306	150	0.4500
20	'Native ACL'	11.6327	17.4490	150	0.4500
21	'Native ACL'	12.2449	18.3673	150	0.4500
22	'Native ACL'	12.8571	19.2857	150	0.4500
23	'Native ACL'	13.4694	20.2041	150	0.4500
24	'Native ACL'	14.0816	21.1224	150	0.4500
25	'Native ACL'	14.6939	22.0408	150	0.4500

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
26	'Native ACL'	15.3061	22.9592	150	0.4500
27	'Native ACL'	15.9184	23.8776	150	0.4500
28	'Native ACL'	16.5306	24.7959	150	0.4500
29	'Native ACL'	17.1429	25.7143	150	0.4500
30	'Native ACL'	17.7551	26.6327	150	0.4500
31	'Native ACL'	18.3673	27.5510	150	0.4500
32	'Native ACL'	18.9796	28.4694	150	0.4500
33	'Native ACL'	19.5918	29.3878	150	0.4500
34	'Native ACL'	20.2041	30.3061	150	0.4500
35	'Native ACL'	20.8163	31.2245	150	0.4500
36	'Native ACL'	21.4286	32.1429	150	0.4500
37	'Native ACL'	22.0408	33.0612	150	0.4500
38	'Native ACL'	22.6531	33.9796	150	0.4500
39	'Native ACL'	23.2653	34.8980	150	0.4500
40	'Native ACL'	23.8776	35.8163	150	0.4500
41	'Native ACL'	24.4898	36.7347	150	0.4500
42	'Native ACL'	25.1020	37.6531	150	0.4500
43	'Native ACL'	25.7143	38.5714	150	0.4500
44	'Native ACL'	26.3265	39.4898	150	0.4500
45	'Native ACL'	26.9388	40.4082	150	0.4500
46	'Native ACL'	27.5510	41.3265	150	0.4500
47	'Native ACL'	28.1633	42.2449	150	0.4500
48	'Native ACL'	28.7755	43.1633	150	0.4500
49	'Native ACL'	29.3878	44.0816	150	0.4500
50	'Native ACL'	30	45	150	0.4500
51	'PCL/PLGA (3:1)'	0	0	35	0.4000
52	'PCL/PLGA (3:1)'	1.0204	0.3571	35	0.4000
53	'PCL/PLGA (3:1)'	2.0408	0.7143	35	0.4000
54	'PCL/PLGA (3:1)'	3.0612	1.0714	35	0.4000
55	'PCL/PLGA (3:1)'	4.0816	1.4286	35	0.4000
56	'PCL/PLGA (3:1)'	5.1020	1.7857	35	0.4000
57	'PCL/PLGA (3:1)'	6.1224	2.1429	35	0.4000
58	'PCL/PLGA (3:1)'	7.1429	2.5000	35	0.4000

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
59	'PCL/PLGA (3:1)'	8.1633	2.8571	35	0.4000
60	'PCL/PLGA (3:1)'	9.1837	3.2143	35	0.4000
61	'PCL/PLGA (3:1)'	10.2041	3.5714	35	0.4000
62	'PCL/PLGA (3:1)'	11.2245	3.9286	35	0.4000
63	'PCL/PLGA (3:1)'	12.2449	4.2857	35	0.4000
64	'PCL/PLGA (3:1)'	13.2653	4.6429	35	0.4000
65	'PCL/PLGA (3:1)'	14.2857	5	35	0.4000
66	'PCL/PLGA (3:1)'	15.3061	5.3571	35	0.4000
67	'PCL/PLGA (3:1)'	16.3265	5.7143	35	0.4000
68	'PCL/PLGA (3:1)'	17.3469	6.0714	35	0.4000
69	'PCL/PLGA (3:1)'	18.3673	6.4286	35	0.4000
70	'PCL/PLGA (3:1)'	19.3878	6.7857	35	0.4000
71	'PCL/PLGA (3:1)'	20.4082	7.1429	35	0.4000
72	'PCL/PLGA (3:1)'	21.4286	7.5000	35	0.4000
73	'PCL/PLGA (3:1)'	22.4490	7.8571	35	0.4000
74	'PCL/PLGA (3:1)'	23.4694	8.2143	35	0.4000
75	'PCL/PLGA (3:1)'	24.4898	8.5714	35	0.4000
76	'PCL/PLGA (3:1)'	25.5102	8.9286	35	0.4000
77	'PCL/PLGA (3:1)'	26.5306	9.2857	35	0.4000
78	'PCL/PLGA (3:1)'	27.5510	9.6429	35	0.4000
79	'PCL/PLGA (3:1)'	28.5714	10	35	0.4000
80	'PCL/PLGA (3:1)'	29.5918	10.3571	35	0.4000
81	'PCL/PLGA (3:1)'	30.6122	10.7143	35	0.4000
82	'PCL/PLGA (3:1)'	31.6327	11.0714	35	0.4000
83	'PCL/PLGA (3:1)'	32.6531	11.4286	35	0.4000
84	'PCL/PLGA (3:1)'	33.6735	11.7857	35	0.4000
85	'PCL/PLGA (3:1)'	34.6939	12.1429	35	0.4000
86	'PCL/PLGA (3:1)'	35.7143	12.5000	35	0.4000
87	'PCL/PLGA (3:1)'	36.7347	12.8571	35	0.4000
88	'PCL/PLGA (3:1)'	37.7551	13.2143	35	0.4000
89	'PCL/PLGA (3:1)'	38.7755	13.5714	35	0.4000
90	'PCL/PLGA (3:1)'	39.7959	13.9286	35	0.4000
91	'PCL/PLGA (3:1)'	40.8163	14.2857	35	0.4000

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
92	'PCL/PLGA (3:1)'	41.8367	14.6429	35	0.4000
93	'PCL/PLGA (3:1)'	42.8571	15	35	0.4000
94	'PCL/PLGA (3:1)'	43.8776	15.3571	35	0.4000
95	'PCL/PLGA (3:1)'	44.8980	15.7143	35	0.4000
96	'PCL/PLGA (3:1)'	45.9184	16.0714	35	0.4000
97	'PCL/PLGA (3:1)'	46.9388	16.4286	35	0.4000
98	'PCL/PLGA (3:1)'	47.9592	16.7857	35	0.4000
99	'PCL/PLGA (3:1)'	48.9796	17.1429	35	0.4000
100	'PCL/PLGA (3:1)'	50	17.5000	35	0.4000

```
% Let's inspect the data
% Check for missing values
disp('Checking for missing values:');
```

```
Checking for missing values:
```

```
any_missing = any(ismissing(FEA_data));
disp(any_missing);
```

```
   0   0   0   0   0   0   0
```

```
% Summary statistics for stress and strain
disp('Summary statistics for stress and strain:');
```

```
Summary statistics for stress and strain:
```

```
% Standardize column names
FEA_data.Properties.VariableNames =
strrep(FEA_data.Properties.VariableNames, '_x__x_', '');
% Use correct column names after checking
summary(FEA_data(:, ["Strain___", "Stress_MPa_"]))
```

```
100×2 table

Variables:

    Strain___: double (Strain (%))
    Stress_MPa_: double (Stress (MPa))

Statistics for applicable variables:

                   NumMissing     Min       Median       Max        Mean          Std

    Strain___          0           0        18.6735       50       20.0000       13.1981
    Stress_MPa_        0           0        12.6786       45       15.6250       12.2419
```

```
% Check for negative or inconsistent values
if any(FEA_data.("Strain___") < 0) || any(FEA_data.("Stress_MPa_") < 0)
    disp('Warning: There are negative values in strain or stress columns.');
else
```

```
    disp('No negative values found in strain or stress columns.');
end
```

```
No negative values found in strain or stress columns.
```

```
% Let's extract relevant data for each material
acl_data = FEA_data(strcmp(FEA_data.Material, 'Native ACL'), :);
pcl_plga_data = FEA_data(strcmp(FEA_data.Material, 'PCL/PLGA (3:1)'), :);
acl_data
```

acl_data = 50×7 table

...

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
1	'Native ACL'	0	0	150	0.4500
2	'Native ACL'	0.6122	0.9184	150	0.4500
3	'Native ACL'	1.2245	1.8367	150	0.4500
4	'Native ACL'	1.8367	2.7551	150	0.4500
5	'Native ACL'	2.4490	3.6735	150	0.4500
6	'Native ACL'	3.0612	4.5918	150	0.4500
7	'Native ACL'	3.6735	5.5102	150	0.4500
8	'Native ACL'	4.2857	6.4286	150	0.4500
9	'Native ACL'	4.8980	7.3469	150	0.4500
10	'Native ACL'	5.5102	8.2653	150	0.4500
11	'Native ACL'	6.1224	9.1837	150	0.4500
12	'Native ACL'	6.7347	10.1020	150	0.4500
13	'Native ACL'	7.3469	11.0204	150	0.4500
14	'Native ACL'	7.9592	11.9388	150	0.4500
15	'Native ACL'	8.5714	12.8571	150	0.4500
16	'Native ACL'	9.1837	13.7755	150	0.4500
17	'Native ACL'	9.7959	14.6939	150	0.4500
18	'Native ACL'	10.4082	15.6122	150	0.4500
19	'Native ACL'	11.0204	16.5306	150	0.4500
20	'Native ACL'	11.6327	17.4490	150	0.4500
21	'Native ACL'	12.2449	18.3673	150	0.4500
22	'Native ACL'	12.8571	19.2857	150	0.4500
23	'Native ACL'	13.4694	20.2041	150	0.4500
24	'Native ACL'	14.0816	21.1224	150	0.4500
25	'Native ACL'	14.6939	22.0408	150	0.4500
26	'Native ACL'	15.3061	22.9592	150	0.4500

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
27	'Native ACL'	15.9184	23.8776	150	0.4500
28	'Native ACL'	16.5306	24.7959	150	0.4500
29	'Native ACL'	17.1429	25.7143	150	0.4500
30	'Native ACL'	17.7551	26.6327	150	0.4500
31	'Native ACL'	18.3673	27.5510	150	0.4500
32	'Native ACL'	18.9796	28.4694	150	0.4500
33	'Native ACL'	19.5918	29.3878	150	0.4500
34	'Native ACL'	20.2041	30.3061	150	0.4500
35	'Native ACL'	20.8163	31.2245	150	0.4500
36	'Native ACL'	21.4286	32.1429	150	0.4500
37	'Native ACL'	22.0408	33.0612	150	0.4500
38	'Native ACL'	22.6531	33.9796	150	0.4500
39	'Native ACL'	23.2653	34.8980	150	0.4500
40	'Native ACL'	23.8776	35.8163	150	0.4500
41	'Native ACL'	24.4898	36.7347	150	0.4500
42	'Native ACL'	25.1020	37.6531	150	0.4500
43	'Native ACL'	25.7143	38.5714	150	0.4500
44	'Native ACL'	26.3265	39.4898	150	0.4500
45	'Native ACL'	26.9388	40.4082	150	0.4500
46	'Native ACL'	27.5510	41.3265	150	0.4500
47	'Native ACL'	28.1633	42.2449	150	0.4500
48	'Native ACL'	28.7755	43.1633	150	0.4500
49	'Native ACL'	29.3878	44.0816	150	0.4500
50	'Native ACL'	30	45	150	0.4500

```
pcl_plga_data
```

pcl_plga_data = 50×7 table

...

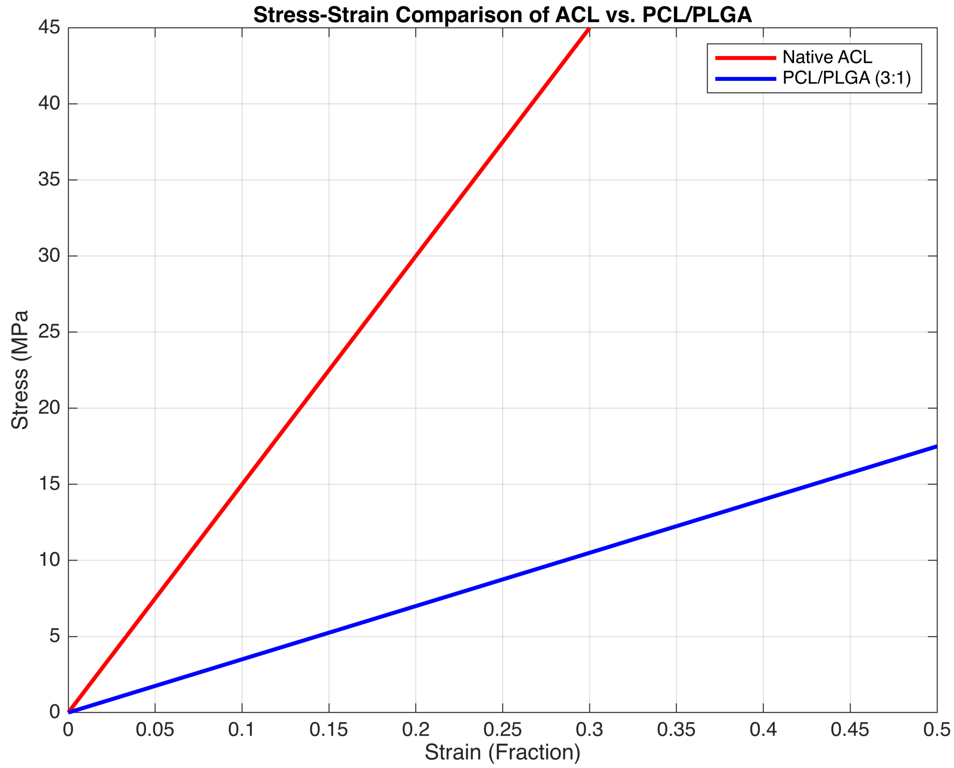
	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
1	'PCL/PLGA (3:1)'	0	0	35	0.4000
2	'PCL/PLGA (3:1)'	1.0204	0.3571	35	0.4000
3	'PCL/PLGA (3:1)'	2.0408	0.7143	35	0.4000
4	'PCL/PLGA (3:1)'	3.0612	1.0714	35	0.4000
5	'PCL/PLGA (3:1)'	4.0816	1.4286	35	0.4000

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
6	'PCL/PLGA (3:1)'	5.1020	1.7857	35	0.4000
7	'PCL/PLGA (3:1)'	6.1224	2.1429	35	0.4000
8	'PCL/PLGA (3:1)'	7.1429	2.5000	35	0.4000
9	'PCL/PLGA (3:1)'	8.1633	2.8571	35	0.4000
10	'PCL/PLGA (3:1)'	9.1837	3.2143	35	0.4000
11	'PCL/PLGA (3:1)'	10.2041	3.5714	35	0.4000
12	'PCL/PLGA (3:1)'	11.2245	3.9286	35	0.4000
13	'PCL/PLGA (3:1)'	12.2449	4.2857	35	0.4000
14	'PCL/PLGA (3:1)'	13.2653	4.6429	35	0.4000
15	'PCL/PLGA (3:1)'	14.2857	5	35	0.4000
16	'PCL/PLGA (3:1)'	15.3061	5.3571	35	0.4000
17	'PCL/PLGA (3:1)'	16.3265	5.7143	35	0.4000
18	'PCL/PLGA (3:1)'	17.3469	6.0714	35	0.4000
19	'PCL/PLGA (3:1)'	18.3673	6.4286	35	0.4000
20	'PCL/PLGA (3:1)'	19.3878	6.7857	35	0.4000
21	'PCL/PLGA (3:1)'	20.4082	7.1429	35	0.4000
22	'PCL/PLGA (3:1)'	21.4286	7.5000	35	0.4000
23	'PCL/PLGA (3:1)'	22.4490	7.8571	35	0.4000
24	'PCL/PLGA (3:1)'	23.4694	8.2143	35	0.4000
25	'PCL/PLGA (3:1)'	24.4898	8.5714	35	0.4000
26	'PCL/PLGA (3:1)'	25.5102	8.9286	35	0.4000
27	'PCL/PLGA (3:1)'	26.5306	9.2857	35	0.4000
28	'PCL/PLGA (3:1)'	27.5510	9.6429	35	0.4000
29	'PCL/PLGA (3:1)'	28.5714	10	35	0.4000
30	'PCL/PLGA (3:1)'	29.5918	10.3571	35	0.4000
31	'PCL/PLGA (3:1)'	30.6122	10.7143	35	0.4000
32	'PCL/PLGA (3:1)'	31.6327	11.0714	35	0.4000
33	'PCL/PLGA (3:1)'	32.6531	11.4286	35	0.4000
34	'PCL/PLGA (3:1)'	33.6735	11.7857	35	0.4000
35	'PCL/PLGA (3:1)'	34.6939	12.1429	35	0.4000
36	'PCL/PLGA (3:1)'	35.7143	12.5000	35	0.4000
37	'PCL/PLGA (3:1)'	36.7347	12.8571	35	0.4000
38	'PCL/PLGA (3:1)'	37.7551	13.2143	35	0.4000

	Material	Strain___	Stress_MPa_	Young_sModulus_MPa_	Poisson_sRatio
39	'PCL/PLGA (3:1)'	38.7755	13.5714	35	0.4000
40	'PCL/PLGA (3:1)'	39.7959	13.9286	35	0.4000
41	'PCL/PLGA (3:1)'	40.8163	14.2857	35	0.4000
42	'PCL/PLGA (3:1)'	41.8367	14.6429	35	0.4000
43	'PCL/PLGA (3:1)'	42.8571	15	35	0.4000
44	'PCL/PLGA (3:1)'	43.8776	15.3571	35	0.4000
45	'PCL/PLGA (3:1)'	44.8980	15.7143	35	0.4000
46	'PCL/PLGA (3:1)'	45.9184	16.0714	35	0.4000
47	'PCL/PLGA (3:1)'	46.9388	16.4286	35	0.4000
48	'PCL/PLGA (3:1)'	47.9592	16.7857	35	0.4000
49	'PCL/PLGA (3:1)'	48.9796	17.1429	35	0.4000
50	'PCL/PLGA (3:1)'	50	17.5000	35	0.4000

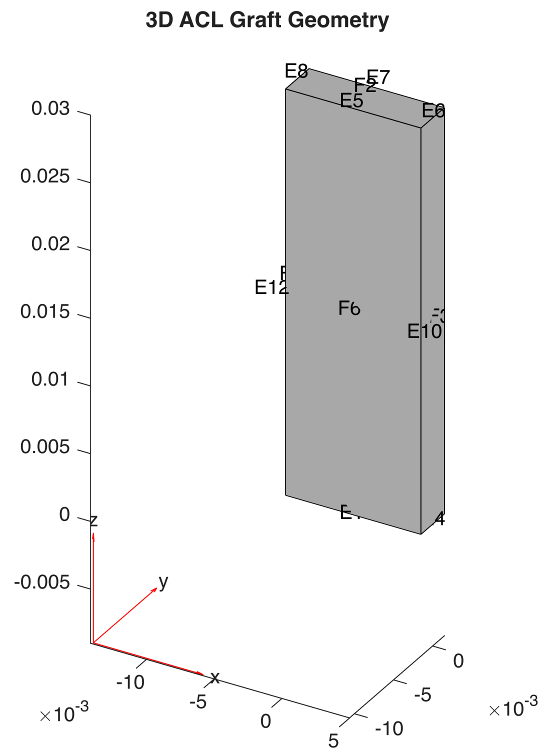
```
% Define strain and stress vectors
strain_acl = acl_data.("Strain___")/100; % convert % to fraction
stress_acl = acl_data.("Stress_MPa_");

strain_pcl_plga = pcl_plga_data.("Strain___")/100;
stress_pcl_plga = pcl_plga_data.("Stress_MPa_");
```

```
% Let's plot Stress-Strain curves
figure;
plot(strain_acl, stress_acl, 'r', 'LineWidth', 2);
hold on;
plot(strain_pcl_plga,stress_pcl_plga, 'b','LineWidth', 2);
xlabel('Strain (Fraction)');
ylabel('Stress (MPa');
legend('Native ACL', 'PCL/PLGA (3:1)');
title('Stress-Strain Comparison of ACL vs. PCL/PLGA');
grid on;
```



Let'set up Finite ELement Analysis

```
% Let's create a Stl Model
% Create Structural Model for Solid Mechanics (3D FEA)
model = createpde('structural', 'static-solid');

% Define 3D rectangular block (ACL graft dimensions)
W = 10e-3; % Width in meters (10mm)
H = 3e-3;  % Height in meters (3mm)
L = 30e-3; % Length in meters (30mm)

% Create 3D box geometry (ACL graft)
g = multicuboid(W, H, L);

% Assign geometry to the structural model
model.Geometry = g;

% Plot the 3D geometry to verify
figure;
pdegplot(model, 'FaceLabels', 'on', 'EdgeLabels', 'on');
title('3D ACL Graft Geometry');
axis equal;
```

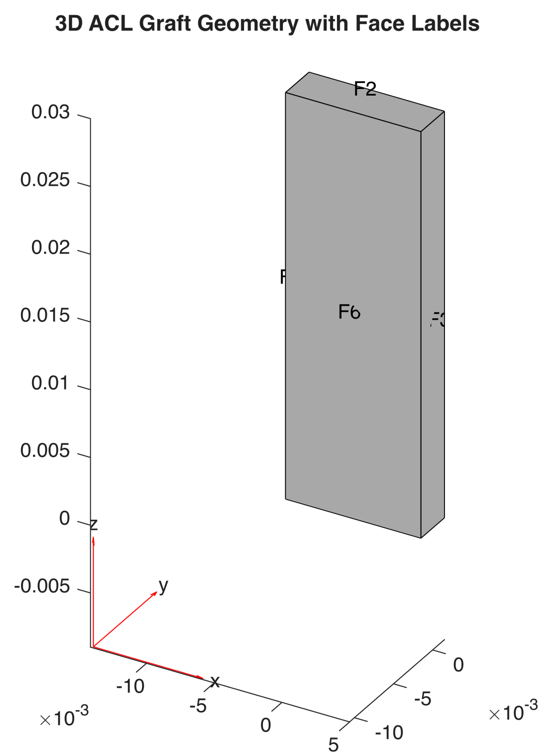


Asign Material Properties

```
% Asign Native ACL properties
E_acl = 150e6; % Convert MPa to Pascals
nu_acl = 0.45;

% Assign Synthetic PCL/PLGA properties
E_pcl_plga = 35e6; % Convert MPa to Pascals
nu_pcl_plga = 0.40;

% Choose which material to simulate
use_acl = true; % Change to false for PCL/PLGA

if use_acl
    structuralProperties(model, 'YoungsModulus', E_acl, 'PoissonsRatio',
nu_acl, 'MassDensity', 1000);
else
    structuralProperties(model, 'YoungsModulus', E_pcl_plga,
'PoissonsRatio', nu_pcl_plga, 'MassDensity', 1000);
end
```

```
% Let's Define Boundary Conditions & Load
% Fix one edge (to simulate graft fixation)
structuralBC(model, "Face", 1,"Constraint","fixed");
```

```
% Apply a tensile load on the opposite edge (ACL under stress)
applied_force = 100; % Newtons
structuralBoundaryLoad(model,"Face",2,"SurfaceTraction", [applied_force; 0;
0]);

% Let's check Face Indexes Using pdeegplot
figure;
pdegplot(model, 'FaceLabels', 'on');
title('3D ACL Graft Geometry with Face Labels');
axis equal;
```



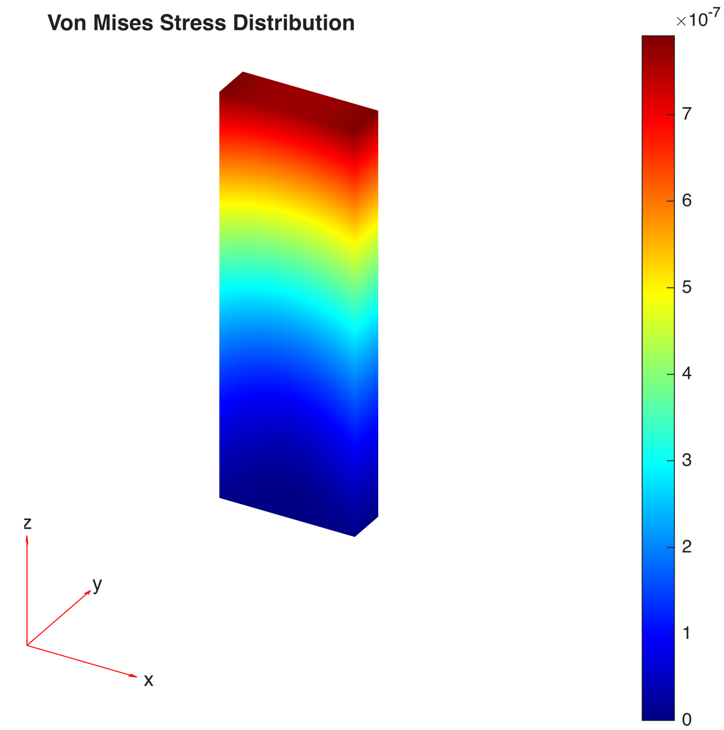
Let's Generate the Mesh and Solve

```
% Generate the finite element mesh
generateMesh(model,"Hmax", 0.0005);

% Solve the FEA model
result = solve(model);
```

Let's Visualize the Simulation

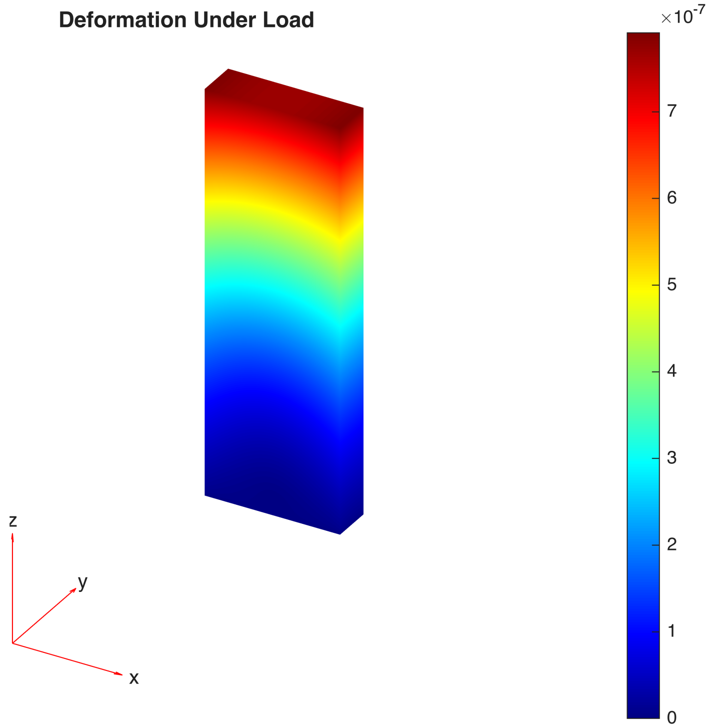
```
% Plot stress distribution and deformation
figure;
pdeplot3D(model, 'ColorMapData', result.Displacement.Magnitude);
```

```
title('Von Mises Stress Distribution');
colorbar;
```



Show Deformation

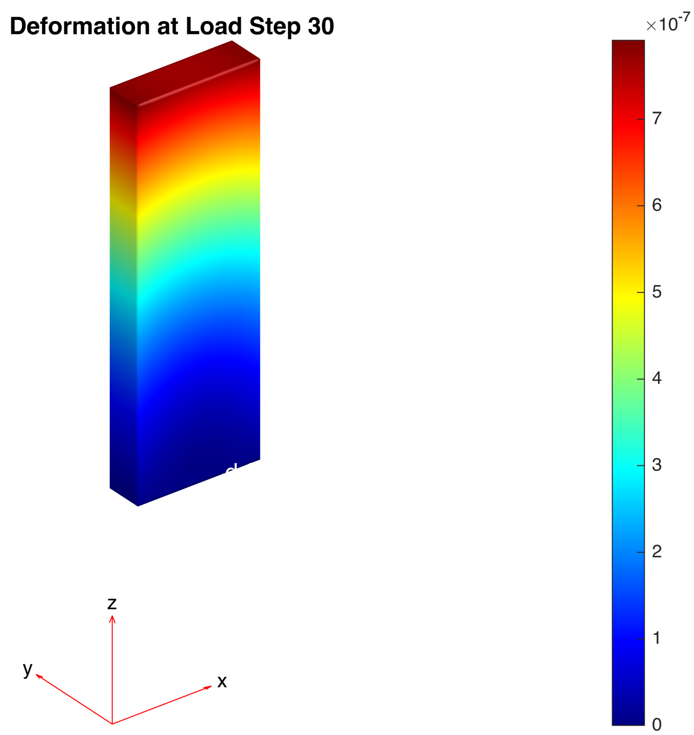
```
% Plot deformation (displacement magnitude) in 3D
figure;
pdeplot3D(model,"ColorMapData", result.Displacement.Magnitude);
title("Deformation Under Load")
colorbar;
```



Simulation of Deformation

```
% Create a video writer object
video = VideoWriter('Deformation_simulation_enhanced.mp4', 'MPEG-4');
open(video);

% Define the number of steps for progressive loading
num_steps = 30;  % Reduced number of steps for faster results
load_increment = 100 / num_steps;  % Increase in force at each step

% Solve the model once for the base load
base_force = 100;  % Apply the maximum force
structuralBoundaryLoad(model, "Face", 2, "SurfaceTraction", [base_force; 0;
0]);
result = solve(model);  % Solve for the maximum load

% Set up the figure for the animation
figure;

% Apply a progressive load and generate deformation plots
for step = 1:num_steps
    % Scale displacement for the current step
    applied_force = load_increment * step;  % Progressive force application
    scaled_displacement = result.Displacement.Magnitude * (applied_force /
base_force);  % Scale displacement
```

```
    % Plot deformation (displacement magnitude) for the current load step
    pdeplot3D(model, 'ColorMapData', scaled_displacement);
    title(['Deformation at Load Step ' num2str(step)], 'FontSize', 12);
    colorbar;
    axis equal;

    % Optionally, rotate the view for dynamic effect
    view(3); % 3D view
    camlight; lighting gouraud; % Add lighting for better visualization

    % Add labels or time indicators
    text(0, 0, max(scaled_displacement)/2, ...
        ['Load Step: ' num2str(step) '/' num2str(num_steps)], ...
        'FontSize', 12, 'Color', 'white');

    % Clear the figure for the next frame to avoid memory overload
    drawnow;  % Make sure the plot updates before capture

    % Capture the current plot as a frame for the video (every nth frame)
    if mod(step, 2) == 0  % Skip frames to reduce processing (every 2nd
frame)
        frame = getframe(gcf);  % Capture the frame
        writeVideo(video, frame);  % Write the frame to the video file
    end
end
```



```
% Close the video file
close(video);

% Notify that the video is saved
disp('Enhanced animation saved as deformation_simulation_enhanced.mp4');
```

```
Enhanced animation saved as deformation_simulation_enhanced.mp4
```