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Materials Testing and Sustainability in Composites for Motorsport & Automotive Industries

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Nomenclature

L – length

CSA – cross-sectional area

F – force

σ – stress

ε – strain

E – young's modulus of elasticity

1. Introduction

Composites are a key material in the automotive and motorsport industry, due to their light weight and high strength. In recent years sustainability has become a consideration for manufacturers due to sustainable development goal 12 (responsible consumption and production), leading to the production and testing of biodegradable composites. These composites allow for a greener alternative to traditional composites, offering a bio-degradable alternative. This study will analyse stress and strain data for current and biodegradable composites comparing to baseline aluminium tests. As both aluminium and modern composites are currently used, they can be compared to the more environmentally friendly alternatives so that their behaviour under load can be analysed comparing to current materials. A range of materials, resins and fabric layering methods will be used to see the effects of these different approaches on the behaviour of the sample when testing.

1.1. Aims and Objectives

The main aim of this study is to evaluate the sustainable use of composites in the automotive and motorsport industry for use in vehicle components. This will allow for an understanding of the potential role bio-composites could play in modern engineering, and how further development may be required for sustainable alternative to replace current less sustainable options. This study will achieve this aim by:

- Conducting comprehensive material testing (on aluminium, current composites, and bio-composites)
- Conducting the correct calculations to require adequate data for analysis
- Completing a comparative analysis which examines the effects of different materials and layering methods in composites
- Using research to support findings and contribute information to the sustainability of the composites.
- Using all information to validate the sustainable use of each composite

2. Methodology

Here the methodology and the parameters of the testing will be discussed to allow for a clear view of the process. Potential issues with the testing will be highlighted as they may lead to error evident in the results. All calculations were completed in MATLAB, see appendix.

2.1. Testing Process

The tests were conducted with Denison Tensile/Compression test equipment, seen in figure 1. For this study only tensile testing was conducted to allow for comparable data. The dog bone test

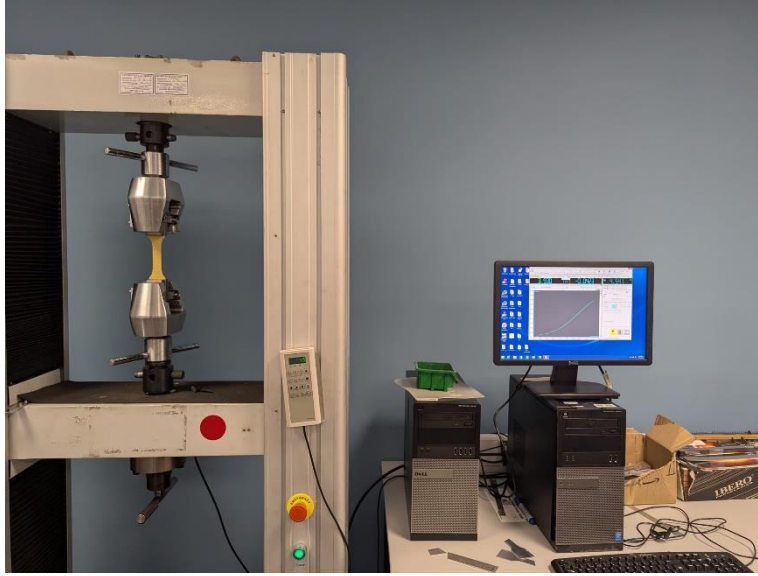


Figure 1: Denison Tensile/Compression test equipment (with woven Kevlar bio-epoxy sample installed)

samples were installed into the clamps, then to allow for accurate comparisons and fair testing each sample was pre-tensioned to 10 N. all data was recorded from this point with all values set to zero, this reduced error due to possible varying slackness in each sample. To limit errors a large testing pool was conducted with each material 14 tests were conducted. This enabled any anomalous tests to be discarded and still maintain accurate analysis of the materials. The load and displacement of the material were recorded for stress and strain calculations. A vernier calliper was used to measure the cross-sectional area of the samples and the length. Stress and strain were calculated using equations 1 & 2.

Equations 1 & 2: stress and strain calculations

$$\sigma = F/CSA, \quad \varepsilon = (L - L_0)/L_0$$

From the graphs the point where, elastic deformation transitioned to plastic deformation could be determined, and from this young's modulus of elasticity could be calculated using equation 3. This allows for an analysis of the behaviour of each material before permanent deformation occurs.

Equation 2: young's modulus of elasticity calculation

$$E = \sigma/\varepsilon$$

2.2. Thesis

Unwoven materials, due to the lack of structural reinforcement across the samples, will fail at the lowest loadings compared to other samples. For unwoven composites there is generally no consistent direction that the fibres follow, this results in weaker samples and less consistent behaviour of the composite. Woven samples are expected to withstand higher stresses and undergo lower strains in comparison to unwoven composites, this is due to the woven fibre creating a more equal distribution of tension across the sample. Natural fibres are expected to fail at lower stresses than carbon fibre and Kevlar, this is due to the weaker bond between the fibre and epoxy matrix due to the natural fibres being hydrophobic. This weaker bond allows the fibres to separate from the matrix under lower loading, resulting in higher stress concentrations leading to a failure at lower stresses. Strength of the matrix is dependent on curing time; however, the lowest possible tensile strength of the epoxy resin is higher than the maximum possible bio-epoxy tensile strength by 0.5 Mpa. Based on this it can be determined that the bio-epoxy will fail at lower stresses than the conventional epoxy based of tensile strength.

3. Literature Review

“From the previous results, it is clear that the value of total deformation in the case of using composite is lower than it in the case of aluminum.” Pg. 98 “From the previous results, it is obvious that the weight of the composite materials is less than it for aluminum which was considered as an advantage of the usage of composite materials in the manufacturing.” Pg.100 (Khames, M., Embaby, A. and Agha, A. (2019)). This study tests composites in place of an aluminium aeroplane wing frame using FEA, and analyses the resultant stress, strain and deformation. This study found that a lower mass of the composite was required for the frame lowering mass which is one of the main benefits of composites. Deformation in the composite cases are lower than the aluminium case which for certain components is desired, however across all cases strain is higher, and for two of the composite cases stress was higher. The composites experience less deformation however higher stresses, whether the composite is viable in applications would depend on its strength. “According to a number of studies, the Young’s modulus in the fiber direction of carbon-fiber composites changes under loading both in tension, and compression.” (Fallahi, H., Taheri-Behrooz, F. and Asadi, A. (2019)) this study notes that other studies have found that after a certain stress composites no longer operate under Hooke’s law but can still withstand increased loading. This is shown in figure 2 as after the elastic limit it can be seen that the gradient lowers then increases until the failure point. “... compression molding, extrusion, injection molding, resin transfer molding, and vacuum transfer

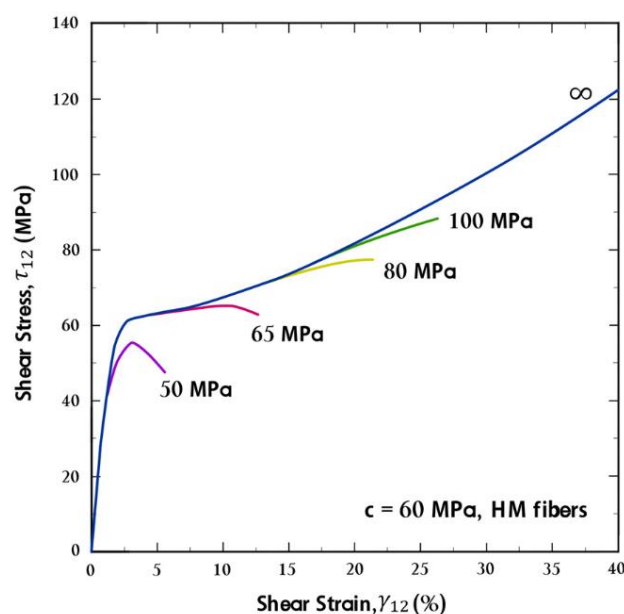


Figure 2: Composite stress, strain behaviour (Fallahi, H., Taheri-Behrooz, F. and Asadi, A. (2019))

molding.”” But for the fabrication of CF-based polymer composites pultrusion, molding, filament winding, and laminated composite beginning from prepregs are commonly used.” (Das, T.K., Ghosh, P. and Das, N.Ch. (2019)). This paper highlights the production methods of composites, and the prepreg processes for carbon fibre (CF). there are various methods to make composites, which allow it to be used for making intricate component designs, making composites ideal in the automotive industry. This study found that “There was four fold increase in strength when continuous fibre was used as compared to chopped, discontinuous fibre.” (Ojha, K.K., Gugliani, G. and Francis, V. (2022)).

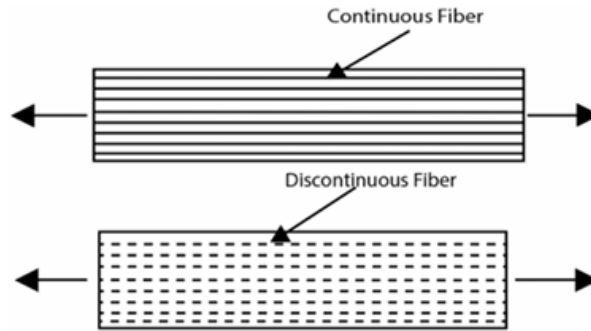


Figure 3: comparison of continuous and discontinuous fibre composites (Ojha, K.K., Gugliani, G. and Francis, V. (2022))

Figure 3 is a visual representation of continuous and discontinuous fibres in the composites, the study suggests that composites with fibres in the direction of load. furthermore, the effects of how the direction of the fibres effects the composites material properties such as young's modulus, tensile strength, flexural strength etc, is highlighted in the study. The following study describes the process of recycling carbon fibre "Firstly, composites are pulled apart and shredded to a 50–100 mm size, and further grinding or milling is applied to obtain recyclates with different sizes that range from fine powder to fibrous recyclates" (Zhang, J. et al. (2020)). This process of recycling carbon fibre composites produces short fibres that can only be used to make non-woven carbon fibre composites. This shows the limits to recycling non-biodegradable composites as they have limited uses after the recycling process due to the short fibre lengths, as non-woven carbon fibre composites have a lower tensile strength supported by previous studies. "The high cost of biopolymers compared to traditional plastics is not due to the rawmaterial costs for biopolymer synthe- sis; rather it is mainly attributed to the low volume of production" (Mohanty, A.K., Misra, M. and Drzal, L.T. (2002)) this study highlights current issues with bio-composites, due to their low production volume leading to high prices reducing its economic viability for manufacturing companies. This would increase vehicle prices and in motorsport applications require a large portion of the budget. This study also highlights that if demand increases production will follow which would eventually lower prices. "The most serious drawback of these natural fibres is their hydrophilic nature, which causes a fragile interfacial bonding between fibre and matrix in polymer composites." (Siakeng, R. et al. (2018)). This paper highlights a large issue with plant based fibres used in bio-composites, which is their hydrophobic

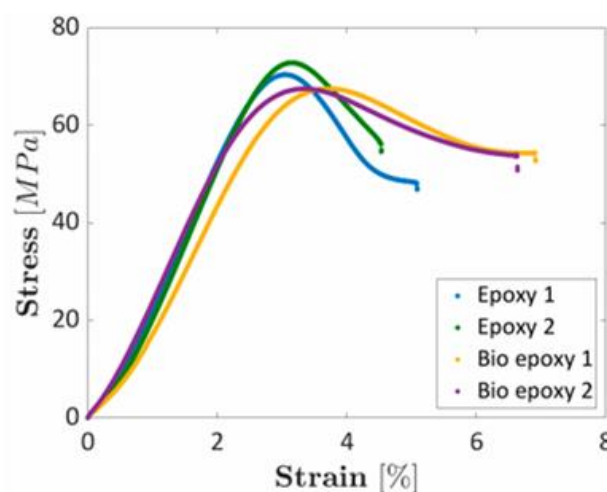


Figure 4: stress against strain graph for epoxy and bio-epoxy (Nietta, C.B. et al. (2023))

nature. This lowers the strength of the bond between the fibres and the matrix, this makes the fibres and matrix at increased risk of dissociation when under load which leads to component failure. Figure 4 (Niutta, C.B. et al. (2023)) this graph displays the relationship between stress and strain for epoxy and bio-epoxy composites, epoxy composites can withstand a higher stress before permanent deformation, however bio-epoxy composites undergo increased strains before failure highlighting that the bio-epoxy composites have a higher ductility. The working environment of a component would dictate whether epoxy or bio-epoxy would be more suited. “Low tensile modulus found at the D specimens also proved that the combination of the intimate weave of fibres and ductile Kevlar fibres have positive effect on its impact resistance” (Hashim, N. et al. (2017)). This study uses both carbon fibre and Kevlar weaved together, the study shows that in the direction of the carbon fibres high strength is shown, however with the addition of Kevlar impact resistance is increased. This displays the methods of using multiple fibre types to be able to achieve desired effects as this mixture achieves a high strength and an increased impact resistance as opposed to carbon fibre alone suggesting increased ductility due to the Kevlar addition. supported by (Egab, K. et al. (2019)) which states “The variation of modulus of elasticity in the lower material has a significant effect on the distributions of stresses and displacements in lower material as well as in the upper material.” This supports the previous study suggesting that if multiple fibres are used within a composite, then young’s modulus and shear stress are altered due to the mixture. Due to this, composite properties would be more easily adjusted than their metal counterparts which require alloying additions. This would allow engineers to reinforce bio-composites with stronger materials to increase shear stress, however depending on the material used this could potentially sacrifice some of the biodegradable benefits of the bio-composite depending on what reinforcement fibre is used. This would still have a greener effect than traditional composites such as carbon fibre which are difficult to recycle.

4. Stress Analysis

This section will analyse the test data and highlight key data points for all tests conducted. The base test of aluminium will be analysed first with the crucial composite tests following which will ignore anomalous results when taking averages of key values. Once the data is analysed a comparative analysis can be made between the composites based on; resin used, material selection, and fibre structure.

4.1. Aluminium

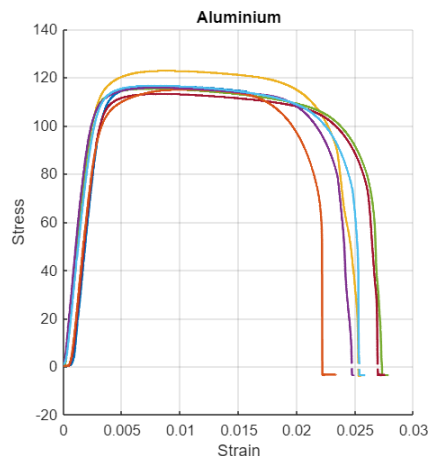


Figure 6: Aluminium stress against strain (all groups, test 1)

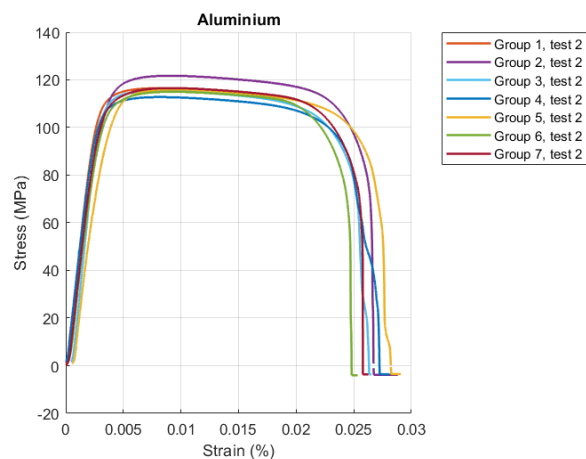


Figure 5: Aluminium stress against strain (all groups, test 2)

Figures 5 & 6 show the stress against strain graphs for the aluminium tests, after around 100 MPa the aluminium tests stop obeying Hooke's law and reach their elastic limit. This is where permanent deformation begins and maximum stress is reached, which is on average 116 Mpa, the graphs then have a small negative gradient as the samples deform. After 0.02 strain the magnitude of the negative gradient increases as the test samples reach failure which can be seen to take place at an average strain of 0.025. a linear fit was used on the elastic region for each test to determine young's modulus of the material, the mean of the values is 44.9 GPa.

4.2. Carbon Woven Epoxy

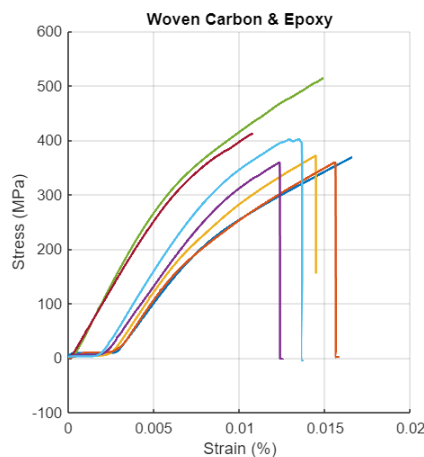


Figure 7: Woven Carbon & Epoxy stress against strain graph (tests 1)

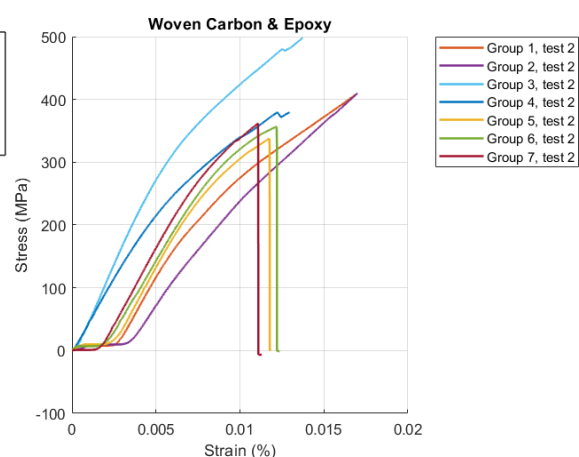


Figure 8: Woven Carbon & Epoxy stress against strain graph (tests 2)

Woven Carbon fibre and epoxy resin composite, seems to have a linear relationship between stress and strain shown in figures 7 & 8 at lower stress values then the gradient gradually changes. Before a strain of 0.005 a mean young's modulus is 45.8 GPa, which is close to aluminium during its elastic phase. Woven carbon fibre and epoxy experiences an average maximum stress of 366 MPa which is over three times higher than the maximum average stress that the aluminium sample experienced. This shows that woven carbon fibre and epoxy composites have an extremely high tensile strength compared to aluminium, however the woven carbon composite also experiences only half the maximum strain of aluminium at failure. This indicates that the carbon fibre and epoxy composite is brittle which allows cracks to propagated through components faster than ductile materials.

4.3. Carbon Woven Bio-resin

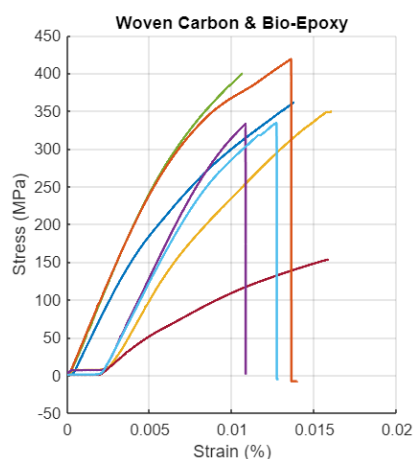


Figure 10: Woven Carbon & Bio-Epoxy stress against strain graph (tests 1)

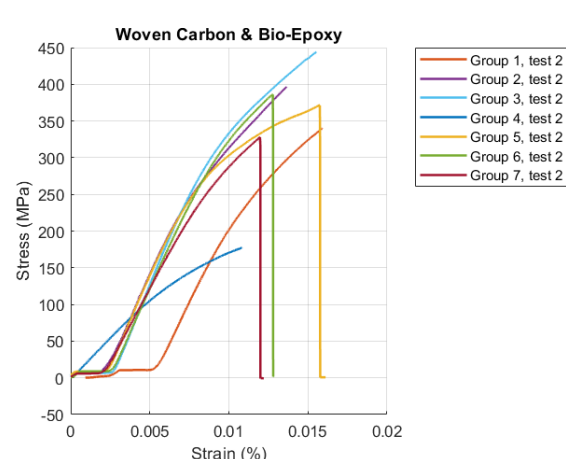


Figure 9: Woven Carbon & Bio-Epoxy stress against strain graph (tests 2)

Woven carbon fibre with bio-epoxy has a similar stress and strain behaviour, shown in figures 9 & 10, to woven carbon fibre with epoxy with a close to linear relationship early in the graph with the gradient gradually lowering until failure. The mean young's modulus for this material is 37.2 GPa which is roughly 7.7 GPa lower than aluminium. The woven carbon with bio resin experienced an

average maximum stress before failure of 356 MPa which is over three times that of aluminium, but experiences roughly half the strain, showing this carbon composite to be more brittle than aluminium.

4.4. Carbon Non-Woven Bio-resin

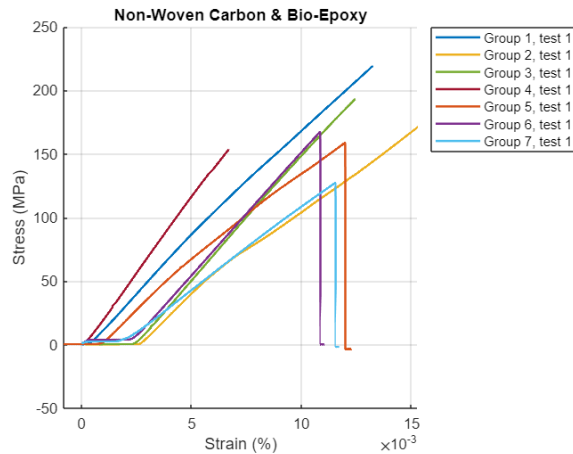


Figure 12: Non-Woven Carbon & Bio-Epoxy stress against strain graph (tests 1)

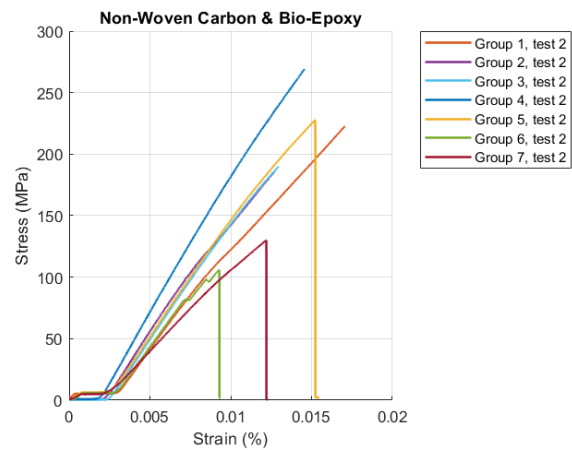


Figure 11: Non-Woven Carbon & Bio-Epoxy stress against strain graph (tests 2)

Figures 11 & 12 show the stress and strain behaviour of non-woven carbon and bio-epoxy composites, the relationship between stress and strain for these composites is linear as can be seen in the graphs. This materials behaviour can therefore be easily predicted when used in manufacturing as it seems to follow Hooke's law until failure, the mean young's modulus for these tests is 18.0 GPa which is significantly lower than that of aluminium. Due to the linear stress and strain relationship non-woven carbon and bio-epoxy experiences higher maximum stresses than aluminium, which average to 173 MPa. This composite only experiences less strain than aluminium indicating that the composite is brittle. This bio-epoxy and Kevlar composite fails at strains roughly 0.005 lower than aluminium. Overall, in comparison to aluminium it can withstand higher stresses, but lower strains before failure.

4.5. Kevlar Woven Bio-resin

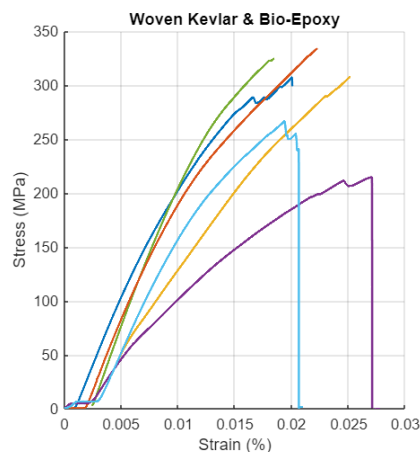


Figure 14: Woven Kevlar & Bio-Epoxy stress against strain graph (tests 1)

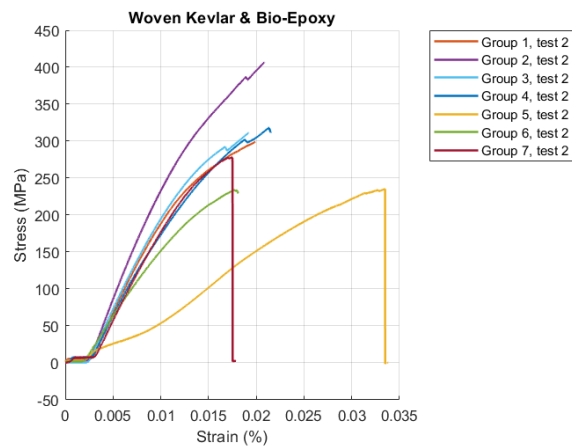


Figure 13: Woven Kevlar & Bio-Epoxy stress against strain graph (tests 2)

The stress and strain relationship shown in figures 14 & 13 for the Kevlar composite using bio-epoxy is not linear as can be seen by the curvature of the graphs, however a rough average young's modulus can be determined to be 23.9 GPa from the lower data. This is roughly half the modulus of the aluminium samples, however the Kevlar samples don't reach a clear elastic limit, so they experience higher stresses. On average the maximum stress experienced by the Kevlar composite samples is 308 MPa, which is over twice that of aluminium.

4.6. Flax Woven Bio-resin

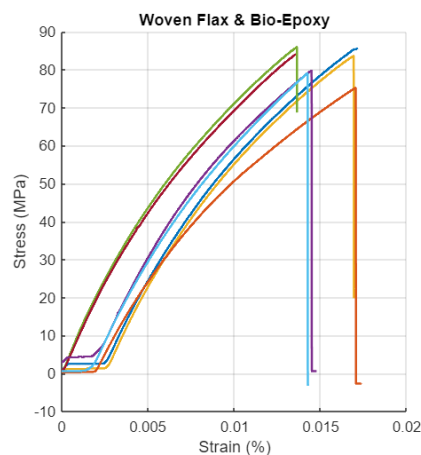


Figure 16: Woven Flax & Bio-Epoxy stress against strain graph (tests 1)

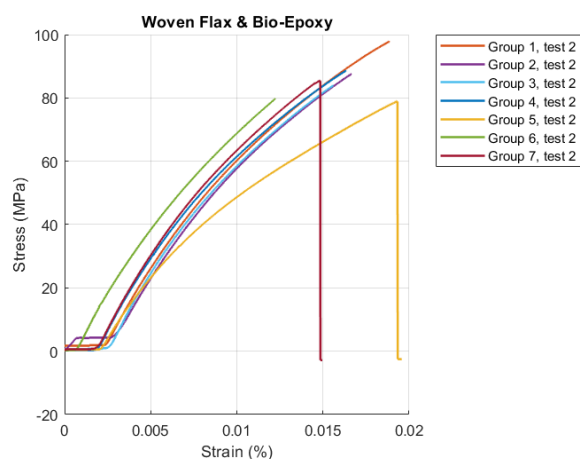


Figure 15: Woven Flax & Bio-Epoxy stress against strain graph (tests 2)

For woven flax and bio-epoxy, the stress and strain relationship shown in figures 16 & 15 is not linear and has a constantly lowering gradient until failure. And average young's modulus based of the lower stress and strain values is estimated to be 8.4 GPa, which is less than a fifth of the young's modulus of the aluminium samples. This composite fails at a stress of 85 MPa on average, and a strain of 0.015. both these values are noticeably lower than aluminium, showing that flax is likely brittle in comparison to aluminium and has a lower tensile strength.

4.7. Flax Non-Woven Bio-resin

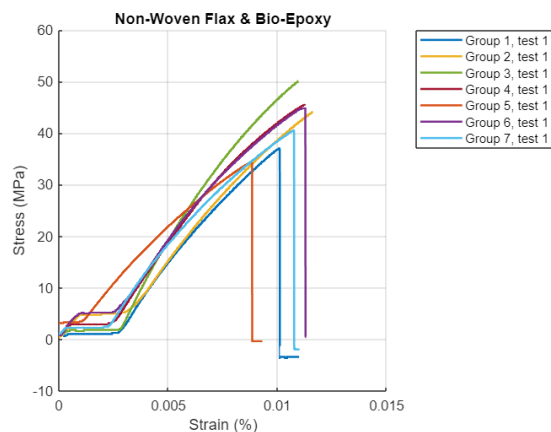


Figure 18: Non-Woven Flax & Bio-Epoxy stress against strain graph (tests 1)

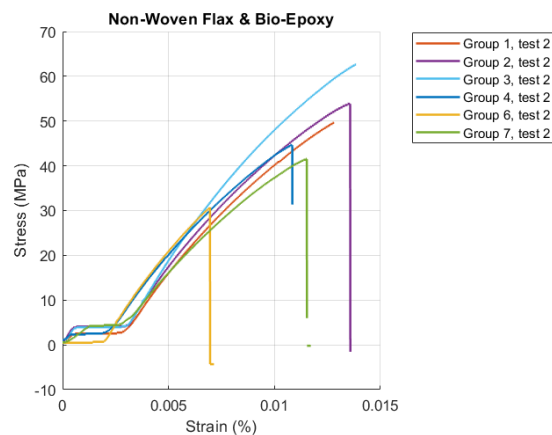


Figure 17: Non-Woven Flax & Bio-Epoxy stress against strain graph (tests 2)

The stress and strain relationship of non-woven flax with bio-epoxy can be seen in figures 17 & 18 to not have a linear relationship, however an average estimate of the young's modulus at lower values is 5.8 GPa which nearly nine times smaller than aluminium. This composite has a experiences a max stress before failure on average of 49 MPa which is less than half that of aluminium, and experiences lower strains at failure. In comparison to aluminium this composite has a lower tensile strength and is brittle.

4.8. Hemp Non-Woven Bio-resin

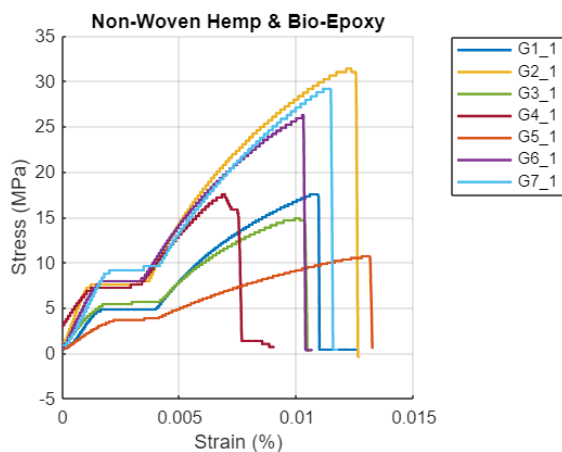


Figure 19: Non-Woven Hemp & Bio-Epoxy stress against strain graph (tests 1)

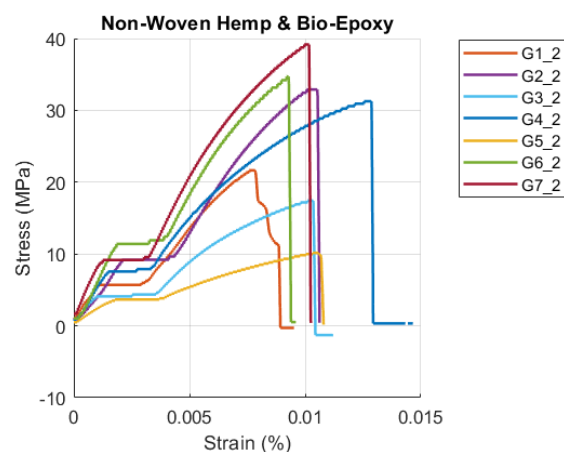


Figure 20: Non-Woven Hemp & Bio-Epoxy stress against strain graph (tests 2)

The hemp composites stress against strain behaviour, shown in figures 19 & 20, follows Hooke's law at lower values then experiences a high strain change then the young's modulus can be seemed to change similar to the result in the study by Fallahi, H., Taheri-Behrooz, F. and Asadi, A. (2019). The initial average young's modulus before the graphs change is 1.9 GPa which is extremely lower in comparison to aluminium and only lowers further during the changing young's modulus. An average maximum stress that the hemp sample experience is 23 MPa, which is a fifth of the maximum aluminium experienced. Hemp also experiences significantly lower strains, showing that it has a lower tensile strength and is brittle in comparison.

5. Sustainability Analysis

This section will compare singular differences so that the effects of individual features can be understood. This will allow for true evaluation of the bio-composites in comparison to currently used composites. All differences are relative to the materials in the comparison and percentage reductions are not based of aluminium.

5.1. Resin comparison

Bio-epoxy resulted in roughly a 19% reduction in young's modulus and a 2.73% reduction in tensile strength. This lowered young's modulus and similar failure stress indicates that compared to traditional epoxy, bio-epoxy has increased ductility which slows crack propagation and allows for a more reliable component.

5.2. Layering Methods

Non-woven composites experienced a reduction in young's modulus of 51.6% for traditional composites (carbon fibre), and 31.0% for the biodegradable composites (flax). A similar reduction in tensile strength can also be witnessed, 51.4% for traditional composites (carbon fibre), and 42.4% for the biodegradable composites (flax).

5.3. BIO- composites comparison (Non-woven)

Comparing flax and hemp a reduction in both tensile strength and young's modulus can be seen, with hemp having lower values. Hemp has a 67.2% lower young's modulus, and a 53.1% reduced young's modulus in comparison to flax. Both fail at similar strains so ductility/brittleness can be assumed to be similar.

5.4. Woven material comparison

This is a comparison between three woven materials that all use bio-epoxy, and carbon will be used as the base as it contains the highest values. Kevlar has a 35.8% lower young's modulus than carbon fibre, while flax has a 77.4% lower young's modulus than carbon fibre. Kevlar also has a 13.5% lower tensile strength than carbon fibre and flax has a 76.1% lower tensile strength than carbon fibre. As Kevlar has a large difference in young's modulus but a low difference in tensile strength this indicates that it is more ductile than carbon fibre, however still slightly weaker. Flax has a similar ductility to carbon fibre, however, has a lower young's modulus and a significantly lower tensile strength than both carbon fibre and Kevlar composites.

6. Conclusion

The data analysed in this study displayed the differences between bio-composites and traditional composites. It can be seen that biodegradable fibres have significantly lower young's modulus and tensile strength when compared to other materials like carbon fibre and Kevlar. Woven flax has a 26.7% lower tensile strength than aluminium, however, is brittle in comparison so it is potentially viable in lower stress and significantly lower strain applications. But unwoven flax and hemp would not be viable based on their low failure stress, as to see similar strength a larger volume of the composite would be required which would limit room around the component and could negate the lower mass benefit attributed to composites. Considering the studies researched, a combination of biodegradable and traditional fibres could be considered as it has been proven to increase the strength compared to the weaker fibres alone. The biodegradable epoxy has a slightly lower young's modulus compared to traditional epoxy and has a similar tensile strength. This results in an increased strain which indicates that it has a higher ductility than traditional epoxy which is desired as this reduces crack propagation reducing the chances that a component will fail due to fatigue. Overall, fully biodegradable composites currently have significant drawbacks that make them not viable for most scenarios/components, however bio-epoxy used with traditional composite fibres like carbon is viable and has potential benefits. Biodegradable fibres could be viable if combined with current/traditional fibres.

7. References

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Appendix

% data

```
F(1:size(G1_1,1),1) = G1_1(:,2);
F(1:size(G1_2,1),2) = G1_2(:,2);
F(1:size(G2_1,1),3) = G2_1(:,2);
F(1:size(G2_2,1),4) = G2_2(:,2);
F(1:size(G3_1,1),5) = G3_1(:,2);
F(1:size(G3_2,1),6) = G3_2(:,2);
F(1:size(G4_1,1),7) = G4_1(:,2);
F(1:size(G4_2,1),8) = G4_2(:,2);
F(1:size(G5_1,1),9) = G5_1(:,2);
F(1:size(G5_2,1),10) = G5_2(:,2);
F(1:size(G6_1,1),11) = G6_1(:,2);
F(1:size(G6_2,1),12) = G6_2(:,2);
F(1:size(G7_1,1),13) = G7_1(:,2);
F(1:size(G7_2,1),14) = G7_2(:,2);
```

```
L(1:size(G1_1,1),1) = G1_1(:,4);
L(1:size(G1_2,1),2) = G1_2(:,4);
L(1:size(G2_1,1),3) = G2_1(:,4);
L(1:size(G2_2,1),4) = G2_2(:,4);
L(1:size(G3_1,1),5) = G3_1(:,4);
L(1:size(G3_2,1),6) = G3_2(:,4);
L(1:size(G4_1,1),7) = G4_1(:,4);
L(1:size(G4_2,1),8) = G4_2(:,4);
L(1:size(G5_1,1),9) = G5_1(:,4);
L(1:size(G5_2,1),10) = G5_2(:,4);
L(1:size(G6_1,1),11) = G6_1(:,4);
L(1:size(G6_2,1),12) = G6_2(:,4);
L(1:size(G7_1,1),13) = G7_1(:,4);
L(1:size(G7_2,1),14) = G7_2(:,4);
```

% stress calculation

```
Force = F.*1000;
```

```
Area = CSA./(1000^2);
```

```
stress = zeros(4463, 14);
```

```
for i = 1:14;
```

```
stress(:,i) = Force(:,i)./Area(i);
```

```
end;
```

```
Stress = stress./1000000;
```

```
% strain calculation
Length_0 = 185; % m
Length = L(1:1:4463,:);
```

```
for i = 1:14
    strain(:,i) = (Length(:,i))./Length_0;
end
```

```
Stress(Stress == 0) = NaN;
```

```
labels = {'Group 1, test 1', 'Group 1, test 2', 'Group 2, test 1', 'Group 2, test 2', 'Group 3, test 1', 'Group 3, test 2', 'Group 4, test 1', 'Group 4, test 2', 'Group 5, test 1', 'Group 5, test 2', 'Group 6, test 1', 'Group 6, test 2', 'Group 7, test 1', 'Group 7, test 2'};
```

```
numCurves = 14; % Number of tests
colors = lines(numCurves); % Different color for each line
```

```
% Plot G#_1
figure
hold on
for i = 1:2:numCurves
    plot(strain(:,i), Stress(:,i), 'Color', colors(i,:), 'LineWidth', 1.5, 'DisplayName', labels{i});
end
hold off
legend show
legend('Location', 'bestoutside')
xlabel('Strain (%)');
ylabel('Stress (MPa)');
title('Woven Carbon & Bio-Epoxy');
grid on
```

```
% Plot G#_2
figure
hold on
for i = 2:2:numCurves
    plot(strain(:,i), Stress(:,i), 'Color', colors(i,:), 'LineWidth', 1.5, 'DisplayName', labels{i});
```

```

end
hold off
legend show
legend('Location', 'bestoutside')
xlabel('Strain (%)');
ylabel('Stress (MPa)');
title('Woven Carbon & Bio-Epoxy');
grid on

```

```

% -----
% === Parameter Thresholds ===
% -----
strain_min_real = 0.002;      % lower threshold for filtering real data
(strain)
stress_min_real = 20;         % lower threshold for filtering real data
(stress)
strain_max_real = 0.007;      % upper threshold for filtering real data
(strain)
stress_max_real = 120;        % upper threshold for filtering real data
(stress)
strain_limit_fit_min = 0.006; % lower limit for linear fit
strain_limit_fit = 0.007;     % upper limit for linear regression fit
num_tests = 14;               % number of columns/tests

% -----
% === Step 1: Determine max rows needed ===
% -----
max_rows = 0;

for i = 1:num_tests
    % Remove NaNs and ZEROs
    valid_idx = ~isnan(strain(:,i)) & ~isnan(Stress(:,i)) & ...
                strain(:,i) > 0 & Stress(:,i) > 0;

    current_strain = strain(valid_idx, i);
    current_stress = Stress(valid_idx, i);

    % Logical condition for early elastic region (with lower bounds added)
    selected_idx = (current_strain >= strain_min_real) & ...
                   (current_strain <= strain_max_real) & ...
                   (current_stress >= stress_min_real) & ...
                   (current_stress <= stress_max_real);

    max_rows = max(max_rows, sum(selected_idx));
end

```

```

% -----
% === Step 2: Extract valid data ===
% -----
strain_before = NaN(max_rows, num_tests);
stress_before = NaN(max_rows, num_tests);

for i = 1:num_tests
    valid_idx = ~isnan(strain(:,i)) & ~isnan(Stress(:,i)) & ...
                strain(:,i) > 0 & Stress(:,i) > 0;

    current_strain = strain(valid_idx, i);
    current_stress = Stress(valid_idx, i);

    % Apply threshold conditions (with lower bounds added)
    selected_idx = (current_strain >= strain_min_real) & ...
                  (current_strain <= strain_max_real) & ...
                  (current_stress >= stress_min_real) & ...
                  (current_stress <= stress_max_real);

    strain_values = current_strain(selected_idx);
    stress_values = current_stress(selected_idx);

    % Clean final values
    valid_final = (strain_values > 0) & (stress_values > 0) & ...
                  ~isnan(strain_values) & ~isnan(stress_values);

    strain_values = strain_values(valid_final);
    stress_values = stress_values(valid_final);

    % Fill matrices
    strain_before(1:length(strain_values), i) = strain_values;
    stress_before(1:length(stress_values), i) = stress_values;
end

disp(['Done. Matrices created with strain <= ', num2str(strain_max_real), ...
      ' and stress <= ', num2str(stress_max_real), ' MPa.']);

% Optional: display valid counts
valid_points = sum(~isnan(strain_before));
disp('Valid point counts per test (real data method):');
disp(valid_points);

% -----

```

```

% === Step 3: Pointwise Modulus ===
% -----
E = stress_before ./ strain_before;
E(~isfinite(E) | E <= 0) = NaN;

% -----
% === Step 4: Plot Modulus ===
% -----
figure;
plot(strain_before, E, 'LineWidth', 1.2);
xlabel('Strain');
ylabel('E (MPa)');
title('Pointwise Elastic Modulus (E =  $\sigma / \epsilon$ )');
grid on;

% -----
% === Step 5: Stats ===
% -----
Max_E = nanmax(E)
Min_E = nanmin(E)
Mean_E = nanmean(E)

% -----
% === Step 6: Linear Fit Method ===
% -----
E_linear_fit = NaN(1, num_tests);

for i = 1:num_tests
    valid_idx = ~isnan(strain(:,i)) & ~isnan(Stress(:,i)) & ...
        strain(:,i) > 0 & Stress(:,i) > 0;

    current_strain = strain(valid_idx, i);
    current_stress = Stress(valid_idx, i);

    % Apply lower and upper strain bounds for linear fit
    idx = (current_strain >= strain_limit_fit_min) & ...
        (current_strain <= strain_limit_fit);

    if sum(idx) >= 2
        p = polyfit(current_strain(idx), current_stress(idx), 1); % linear
fit
        E_linear_fit(i) = p(1); % slope = Young's modulus
    end
end
end

```

```
disp(['Young's modulus (linear fit, strain <= ', num2str(strain_limit_fit),  
' :)']);  
disp(E_linear_fit);
```