ASEN 2001 Lab 3: Composite Beam Bending

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This lab investigated the structural loading of a foam-balsa composite. Based on loading experiment results, a wing shape was derived to optimize structural integrity under typical aerodynamic forces. A foam-balsa planform was then created following the derived shape and tested under simulated aerodynamic forces. A "Wiffle Tree" test was conducted to achieve these loading conditions. The planform withstood 116.25 N of force and failed in shear at the narrowest section as predicted.

I. Nomenclature

FOS	=	Factor Of Safety
p_0	=	Total pressure
$q(x)$	=	Pressure Distribution
V	=	Shear Force
M	=	Bending Moment
σ_{fail}	=	Failure Stress
M_{fail}	=	Failure Bending Moment
c	=	Chord Length of Plan Form
I_b	=	Moment of Inertia of Balsa Wood
I_f	=	Moment of Inertia of Foam
E_b	=	Young's Modulus of Balsa Wood
E_f	=	Young's Modulus of Foam
τ_{fail}	=	Failure Shear Stress
V_{fail}	=	Failure Shear Force
A_f	=	Cross-Sectional Area of Foam

II. Introduction

Composites are used in numerous applications across the aerospace industry. One example is a foam-balsa composite comprised of a foam core covered by thin sheets of balsa wood. This type of composite along with other similar composite materials is commonly used in the construction of wings for small unmanned aircraft. These wings undergo aerodynamic forces resulting in shear stress and bending moment that must be understood and accounted for in order to develop a safe and effective design. In this lab, data from testing a foam-balsa composite beam consisting of a 3/4" foam core between two 1/32" sheets of balsa wood was provided. This data reflected the strength of the composite and was used to optimize a planform of the composite beam. A width function describing the ideal planform shape was derived using the relationships between the following formulas: pressure distribution described by

$$q(x) = p_0\sqrt{1-(2x/L)^2}w(x) \tag{1}$$

where w(x) is the width function of the planform, along with the relationships

$$\frac{dV}{dx} = q(x) \tag{2}$$

[redacted]

$$\frac{dM}{dx} = V(x) \tag{3}$$

where V is the shear force and M is the bending moment, the Flexure formula

$$\sigma_{fail} = -\frac{M_{fail}c}{(I_b + (E_f/E_b)I_f)} \tag{4}$$

where σ_{fail} is the failure stress of the beam, M_{fail} is the failure bending moment, c is the distance from the neutral axis to the outside edge of balsa. I_b and I_f are the moments of inertia of the balsa and the foam respectively, and E_f and E_b are the Young's Moduli of the foam and balsa respectively and the shear formula

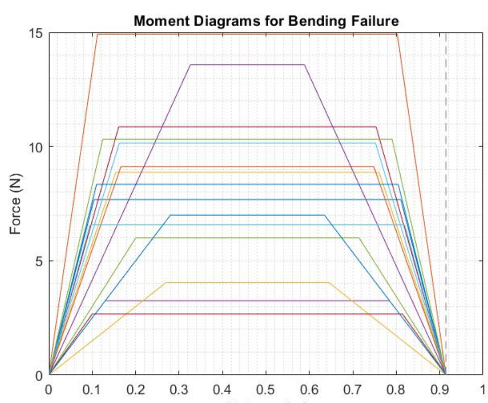
$$\tau_{fail} = \frac{3}{2}\frac{V_{fail}}{A_f} \tag{5}$$

where τ_{fail} is the failure shear stress of the beam, V_{fail} is the failure shear force, and A_f is the cross-sectional area of the foam.

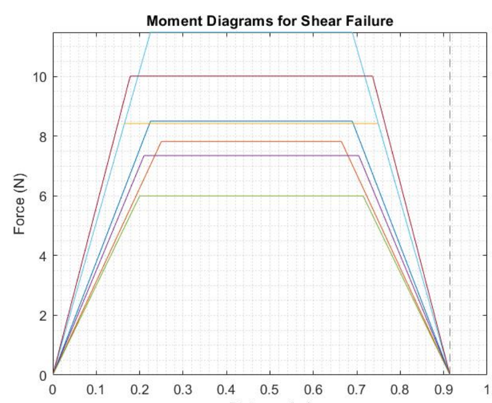
Additional details regarding the analysis of the composite beam and the derivation of the width function are included in the following sections

III. Strength Analysis

The sample being tested was a composite beam of foam and balsa. The first and third layers were 1/32" strips of balsa and the middle layer was 3/4" of foam. This was a 4" by 36" beam. The group used data from similar experiments to determine the strength of the specimen. In this scenario, the bars were loaded with one support on each end, and two straps used to hang weight (Fig. 3). Weight was added until the beam snapped. The force at which the specimen failed was then recorded along with whether the beam snapped in shear or bending. We used the formulas for Flexure and shear based on the moment and shear failures in the data. Figures 1 and 2 show the moment and shear diagrams for the data given. The calculated value for failure from shear was $4.19 * 10^4$ (Pascals) and was $9.70 * 10^6$ (Pascals) for the normal stress. Dividing these by the factor of safety gave us our maximum allowable shear stress and bending moment (τ_{fail} and M_{fail}). From the test data, we were able to determine that the sample was more likely to break under shear. We derived a w(x) function for width. The foam-balsa composite beam was then cut using the w(x) function for testing. Using wiffle tree loading, we were able to simulate aerodynamic forces on the wings.

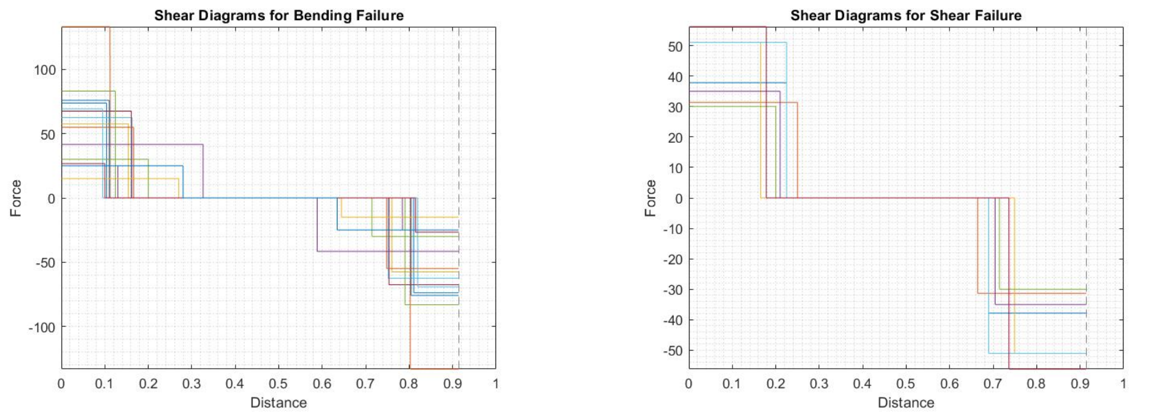


(a) Moment Diagram for Bending Failure



(b) Moment Diagram for Shear Failure

Fig. 1 Moment Diagrams



(a) Shear Diagram for Bending Failure **(b) Shear Diagram for Shear Failure**

Fig. 2 Shear Diagrams

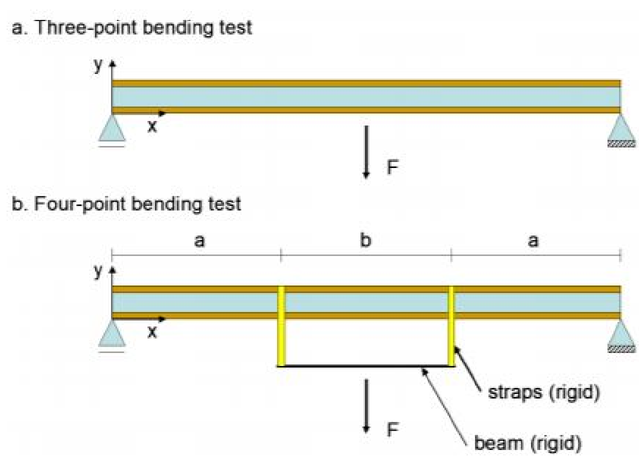


Fig. 3 Preliminary Strength Test Setup

IV. Wing Design

Once there was enough information to approximate the composite material strength, a design and load simulation was then considered. Initially, after excluding all outliers, a safety factor was cho a safety factor was chosen between 1.3 to 1.5, which is the typical range for aerospace applications. For this lab, 1.3 was chosen as the safety factor.

FOS	σ_{fail}	τ_{fail}	$\sigma_{allowed}$	$\tau_{allowed}$
1.3	9.70e+06	4.19e+04	7.46e+06	3.22e+04

Table 1 Normal and Shear Stresses and Safety Factor. Allowed values are after considering the safety factor. All values are in Pascals.

Table 1 displays the values for safety factor along with normal and shear stresses before and after considering the safety factor. Once a safety factor was decided upon, values for maximum allowed shear and normal stresses were determined. From there, given that the aerodynamic loading was given by equation (1) and knowing the relationship between the applied load, shear, and moment distribution, given by the relationships in equations (2) and (3), the loading function was integrated using MATLAB built in symbolic integration function to derive the shear diagram. Once the shear diagram was obtained, the same process of integration was repeated to derive the moment diagram.

It is important to note that it was assumed that the width in the load function is 4 inches. This was done just to obtain the value of the term p_0, and once the value of p_0 was obtained, given the chosen maximum allowed shear and normal stresses, the Flexure formula and shear formula (equations 4 and 5 respectively) were both rearranged to arrive at a width function across the whole length of the beam; one with respect to moment, and one with respect to shear. Afterwards, the maximum absolute values for width with respect to both shear and moment width functions were chosen and a final width function for the plan form was created. The moment and shear diagrams for the beam are shown in Figure 4.

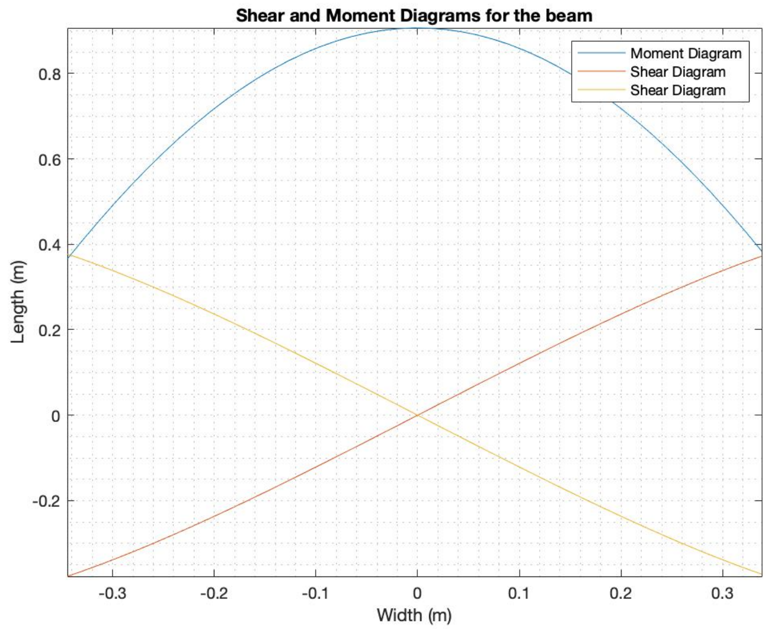


Fig. 4 Shear and Moment Diagrams for the Beam

To simulate typical aerodynamic loading, the "Wiffle Tree" approach was used. Simply, the centroid under each $\frac{1}{8}$th of the aerodynamic load function (equation 1) was determined, and this served as each location of a strap. These centroid locations were determined for half the wing and then symmetry was applied for the whole wing. Once that was known equation 6 was applied to find the location of the next part of the wiffle tree. This method is also shown in figure 5. It was determined that the force at each strap would be equal to $\frac{1}{8}$th of the integral of equation 1 for that section as well as the portion of the wiffle tree test setup that that section would have to withhold (Fig. 5).

$$l_1 = \frac{F_2 l}{F_1 + F_2} \tag{6}$$

Once the locations of all parts of the wiffle tree were found by the method in figure 5, the wiffle tree was constructed on the wing. Figure 8 shows the final setup. From there, the wing was loaded by adding loads in increments of 1.5 pounds to the bucket (Fig. 8) until failure.

V. Discussion

It was hypothesized that the beam is more likely to fail in shear than bending as the shear stress failure values were lower. As predicted, the plan form appeared to fail in shear. Figure 6 shows the break clearly happening in shear, with the balsa failing first.

Furthermore, the wing was able to support a greater force than predicted. The theoretical predictions and actual results are discussed more extensively in the conclusion. It is suspected that this difference is due to the fact that the expected force the plan form was expected to handle came based on initial strength test, which was based on the 4-point configuration test. The data from these tests was analyzed and the minimum bending and shear failure values were used to find the width function. In practice the material used was stronger than the weakest material from the test data as material properties vary significantly.

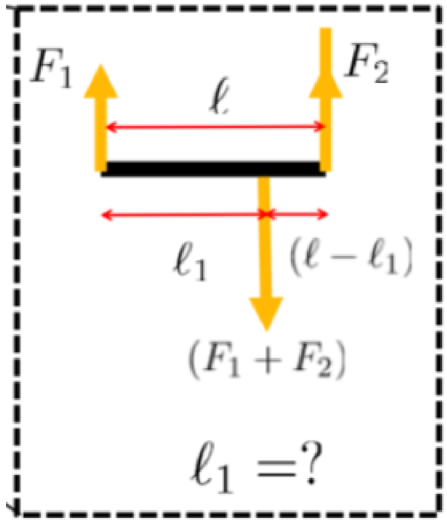


Fig. 5 Finding the location of the straps

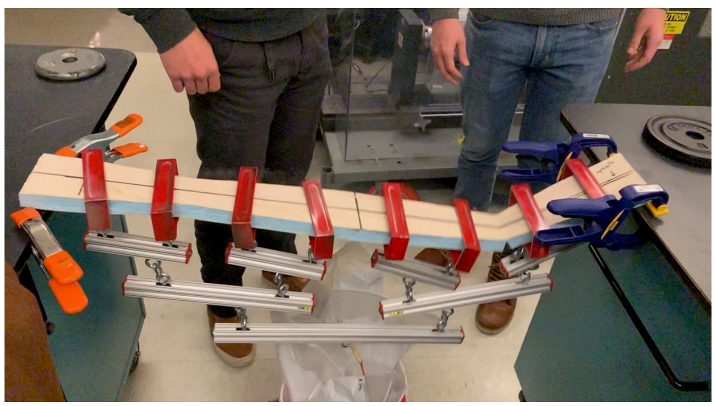


Fig. 6 Planform Fail

Additional failure modes that would require consideration in realistic applications are fatigue, thermal variations, and corrosion. Fatigue failure can be prevented by cyclic testing prior to implementation of a wing design, and thermal variations can be accounted for analytically by finding atmospheric variations due to altitude and re-calculating the aerodynamic forces given these variations. Failure due to corrosion can largely be written off for the wings themselves, as they are mostly made of non-corrosive composites, but bolts and screws on the wing are still susceptible to this mode of failure. This happened in 1979, when an engine pylon broke due to lack of proper maintenance and caused the deadliest aviation accident to occur in the US

Fig. 7 Shear of Planform

Fig. 8 Wiffle Loading Setup

VI. Conclusions

The results of the experiment and the lab followed what was expected. Based off of the given test data the wing plan form was predicted to hold 6.90 kilograms, but in practice the wing held 11.85 Kg. The wing was designed with a FOS of 1.3 in mind which means that the max force that the beam would experience in normal use would be 9.12 Kg. This follows the reasoning presented in the discussion on the strength of the material. The fact that the wing held more weight than was predicted also strongly suggests that the wing design followed proper practices and the equations used to derive the wing width were indeed applicable. The wing ended up failing at the right side thinnest point, when viewing as in Figure 6. This may be due to the fact that the stress was concentrated at the sharp corner as shown in the width function which would have meant the material at that point could have been experiencing more stress than it should have. Another reason that the thinnest point failed first could also be due to manufacturing errors where the area was thinner than it was intended to be.

References

[1] Statics and Structures, ASEN 2001, "Composite Beam Bending ASEN 2001 Lab 3, Session 3, Fall 2018," Lab 3 Session 2 2018.pptx.

[2] Statics and Structures, ASEN 2001, "Composite Beam Bending ASEN 2001 Lab 3, Session 3, Fall 2018," Lab 3 Session 3 2018.pptx.

[3] Hibbeler, R. C., and Yap, K. B., Statics and mechanics of materials, Harlow, United Kingdom: Pearson Education, Inc., 2017.

[4] Statics and Structures, ASEN 2001, "ASEN 2001 Lab 3 Fall 2018.pdf," ASEN 2001: Statics and Structures, Fall 18.

Appendix A: MATLAB Code

```
% info:

%{

This codes is part of CU's ASEN 2001: Statics and Structures

 This lab is concerned with the analysis and design of composite beams.
Beams are frequently used componentsin aerospace structures, such as wings,
booms, etc. To reduce their weight and to tailor their stiffness and strength
toparticular loading conditions, beams are often made of several materials.
Such beams are called composite beams. Incomparison with truss structures,
the structural response of beams can be rather complex and various forms of
failureneed to be carefully considered in the design process.

This code will take Test data for the the strength of the beam and get the
faliure normal and shear stresses and then plot optimal width function for
that beam, for more info read The files in AssignmentInfo .

Done by:

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%}

%% Housekeeping

clear;
clc;
close all;

%% read and extract file

E_Foam = 0.035483*10^9 ; %Pa
E_Bals = 3.2953*10^9 ; %Pa

% Wiffle Tree Weights:

Sleeve = 0.49 ; %N sleeve
six_in_bar = 1.77 ; %N 6 inch bar
twelve_in_bar = 2.94 ; %N 12 inch bar
eighteen_in_bar = 3.92 ; %N 18 inch bar

LengthCS = 0.0206375; %in meter.
%% read test data:

% read file
[ TestData Comments ] = xlsread('TestData.xlsx');

%get the comments as strings to see how it failed.
FailType = cellstr(Comments(2:length(Comments),6));

% Check if you failing bending or shear

% the contains is case-sensitive;
BendFail = contains(FailType,{'Bending','bending'});
ShearFail = contains(FailType,{'Shear','shear','perpendicular','both'});


%% excludeds :
```

```
% test 7 is excluded, no breakage
% test 11 : no comment

%%
% get the exact data related to bend and ehar

BendData = TestData(BendFail,:);
ShearData = TestData(ShearFail,:);

%% add data manually:

%{
if some if borken on both shear and moment or might be shear but is
reported as moment, it should be added manually.

%}


%% get the length of the middle bar b:

Barlength = 36*0.0254 ; % in m
bBend = (Barlength) - 2*BendData(:,3); % in meter
bShear = (Barlength) - 2*ShearData(:,3); % in meter

FoamLength = 3/4 * 0.0254 ; % in m
BalsaLength = 1/32 * 0.0254 ; % in m
WidthCS = 4 * 0.0254; %in m CS = Cross-section
WidthCSBendData = BendData(:,4);
WidthCSShearData = ShearData(:,4);





%% Shear/moment daiagram : TEST DATA


% the purpose of this is just to plot.


% do the shear/moment daiagrams for shear fail

ShearDiagram_ShearFail = {};

%place holders

ShearStress_ShearFail = zeros(1,length(bShear));
ShearStress_BendFail = zeros(1,length(bBend));
RootFunction_ShearFail = {};

%place holders for maximas
Max_Shear_ShearFail = zeros(1,length(bShear));
Max_Shear_BendFail = zeros(1,length(bBend));
Max_Moment_ShearFail = zeros(1,length(bShear));
Max_Moment_BendFail = zeros(1,length(bBend));


for i =1:length(bShear)
syms x
ShearDiagram_ShearFail{i} = piecewise ( 0<x<ShearData(i,3) , ShearData(i,2)/2 , ...
    ShearData(i,3)<x<bShear(i)+ShearData(i,3) , 0 , bShear(i)+ShearData(i,3)<x<Barlength , ...
    -ShearData(i,2)/2 );
Max_Shear_ShearFail(i) = ...
    double(max(abs(subs(cell2sym(ShearDiagram_ShearFail(i)),[0:0.01:Barlength]))));
MomentDiagram_ShearFail(i) = piecewise ( 0<x<ShearData(i,3) , ShearData(i,2)/2 * x, ...
    ShearData(i,3)<x<bShear(i)+ShearData(i,3) , ShearData(i,3) * ShearData(i,2)/2 , ...
    bShear(i)+ShearData(i,3)<x<Barlength , (-ShearData(i,2)/2 * (x-Barlength)));
```

```
%ShearStress_ShearFail(i) = ((3/2) * (Max_Shear_ShearFail(i)) )/ (WidthCS*FoamLength) ;


end

% bending fail

ShearDiagram_BendFail = {};

for i =1:length(bBend)
syms x
ShearDiagram_BendFail{i} = piecewise ( 0<x<BendData(i,3) , BendData(i,2)/2 , ...
    BendData(i,3)<x<bBend(i)+ BendData(i,3) , 0 , bBend(i)+BendData(i,3)<x<Barlength , ...
    -BendData(i,2)/2 );
Max_Shear_BendFail(i) = ...
    double(max(abs(subs(cell2sym(ShearDiagram_BendFail(i)),[0:0.01:Barlength])))) ;
MomentDiagram_BendFail(i) = piecewise ( 0<x<BendData(i,3) , BendData(i,2)/2 * x, ...
    BendData(i,3)<x<bBend(i)+ BendData(i,3) ,  BendData(i,3) * BendData(i,2)/2 , ...
    bBend(i)+BendData(i,3)<x<Barlength , (-BendData(i,2)/2 * (x-Barlength)));
%ShearStress_BendFail(i) = ((3/2) * (Max_Shear_BendFail(i)) )/ (WidthCS*FoamLength) ;

end

%moment diagrams =

%not needed:
%{
%loop to get max
% remove ABS if you do not need the absloute value of max-min!
for i =1:length(bShear)

Max_Moment_ShearFail(i) = ...
    double(max(abs(subs(MomentDiagram_ShearFail(i),[0:0.01:Barlength])))) ;

end

for i =1:length(bBend)

Max_Moment_BendFail(i) = ...
    double(max(abs(subs(MomentDiagram_BendFail(i),[0:0.01:Barlength])))) ;

end
%}
%% PLOT HERE
figure(1)
fplot(MomentDiagram_BendFail, [0, 1])
title('Moment Diagrams for Bending Failure')
xlabel('Distance (m)')
ylabel('Force (N)')
grid minor

figure(2)
fplot(ShearDiagram_BendFail, [0, 1])
title('Shear Diagrams for Bending Failure')
xlabel('Distance (m)')
ylabel('Force (N)')
grid minor

figure(3)
fplot(MomentDiagram_ShearFail, [0, 1])
title('Moment Diagrams for Shear Failure')
xlabel('Distance (m)')
ylabel('Force (N)')
grid minor

figure(4)
fplot(ShearDiagram_ShearFail, [0, 1])
title('Shear Diagrams for Shear Failure')
```

```
xlabel('Distance (m)')
ylabel('Force (N)')
grid minor



%% Find Maximum moment: the moment at the location of faliure

for i =1:length(bBend)

Max_Moment_BendFail(i) = double(abs(subs(MomentDiagram_BendFail(i),x,BendData(i,5)))) ;

end

for i =1:length(bShear)

Max_Moment_ShearFail(i) = double(abs(subs(MomentDiagram_ShearFail(i),ShearData(i,5)))) ;

end



%}

%Largest moment
[ r c ] = size(BendData) ;
for i=1:r

    if 0 ≤ BendData(i,5) < BendData(i,3)

        Mfail(i) = (BendData(i,2)/2)*BendData(i,5);

    elseif BendData(i,3) ≤ BendData(i,5) && BendData(i,5) < BendData(i,3)+bBend(i)

       Mfail(i) = (BendData(i,2)/2)*BendData(i,3);

    else

        Mfail(i) = (BendData(i,2)/2)*BendData(i,5);

    end


end

%Largest shear
[ r c ] = size(ShearData) ;
for i=1:r

    if 0 ≤ ShearData(i,5) < ShearData(i,3)

        Vfail(i) = ShearData(i,2)/2;

    elseif ShearData(i,3) ≤ ShearData(i,5) && ShearData(i,5) < ShearData(i,3)+ShearData(i)

       Vfail(i) = ShearData(i,2)/2; % It should be 0 but they didn't account
       %for the strap in the test, so we will just use the value before it.
       %Because there's no way it'll break @ 0 shear.

    else

        Vfail(i) = -ShearData(i,2)/2;

    end


end
```

```
%% Moment of Inertia: from centroidal axis.

% the neutral axis is the z axis, thus moment about z axis for foam will be
% just at the axis itself,

CentroidShape = ((FoamLength+(2*BalsaLength))/2) ;
CnetroidTopBalsa = ( (FoamLength + BalsaLength) + BalsaLength/2 );

IFoam_Bend = (1/12).*( WidthCSBendData ).*(FoamLength)^3 ;
IBalsa_Bend = 2*((1/12).*(WidthCSBendData).*(BalsaLength)^3 + ( CentroidShape - ...
    CnetroidTopBalsa ) ^2 ).*(WidthCSBendData.*BalsaLength) ;

IFoam_Shear = (1/12).*( WidthCSShearData ).*(FoamLength)^3 ;
IBalsa_Shear = 2*((1/12).*(WidthCSShearData).*(BalsaLength)^3 + ( CentroidShape - ...
    CnetroidTopBalsa ) ^2 ).*(WidthCSShearData.*BalsaLength) ;

%% safety factor

FOS = 1.3;

%% Max Normal Stress: Flexural Formula

MaxNormalStress_BendFail = -(Mfail' .* (BalsaLength+(FoamLength/2)))./ ( IBalsa_Bend + ...
    (E_Foam/E_Bals).*IFoam_Bend) ;
%remove outlayers

MaxNormalStress_BendFail(5) = [];

% they're both the same, it's sample 10;

%max alloweable normal stress
MaxAllowNormal = mean(MaxNormalStress_BendFail)./ FOS ;

%% Max Shear Stress: Shear Formula

% the ShearStress_BendFail takes the whole area instead of half, double
% check.

%we checked, it's the full area.

for i=1:length(Vfail)
MaxShearStress_ShearFail = (3/2) * (abs(Vfail)'./((FoamLength).*ShearData(i,4))) ;
end

%remove outlayers

%get picket values

%all of them are 0 here but this needs to be checked later.

PickedAllow = min(MaxShearStress_ShearFail);

%{
% determine which width of the beam you have picked:

if isnumeric(find(MaxShearStress_ShearFail == PickedAllow))==1

    PickedWidth = find(MaxShearStress_ShearFail == PickedAllow);

else

    PickedWidth = find(MaxShearStress_BendFail == PickedAllow);

end

%}
```

```
MaxAllowShear = ( PickedAllow /1.3);

%%


%% get p(0), V, and M : DESIGN

syms p0 x
qx = (4*0.0254)*p0 * sqrt ( 1 - ((2*x)/Barlength)^2) ;

%Get F:
F = int(qx,x,(-Barlength/2),(Barlength/2));
%get V

Vx = -F/2 + int(qx,x,(-Barlength/2),x);

Mx = int(Vx,x,(-Barlength/2),x);

%solve for M as function of p0, then solve for p0;


% here If and Ib will use the width of the cross section, 4 inches or
% what's stored as WidthCS;

If = (1/12).*( WidthCS ).*(FoamLength)^3 ;

%we had to mulyiply by 2 to make it work, check why:
Ib = 2*((1/12).*(WidthCS).*(BalsaLength)^3 + ( CentroidShape - 2*CnetroidTopBalsa ) ^2 ...
    ).*(WidthCS.*BalsaLength) ;



MP0 = subs(Mx,x,0); %sub 0 for x in Mx;

Equation = MaxAllowNormal == (MP0 .* (BalsaLength+(FoamLength/2)))/ ( Ib + ...
    (E_Foam/E_Bals)* If ) ;
p0Value = solve(Equation,p0);

%SUB back P0 in the moment function

Mx_WithP0 = subs(Mx,p0,p0Value);
Vx_WithP0 = subs(Vx,p0,p0Value);
% C = distance from neutral axis
Cvalue = (BalsaLength+(FoamLength/2));


%moment of inertia of foam and balasa for bending data, width now isn't
%constant width is function will be solved for o

If = (1/12)*(FoamLength)^3 ;
Ib = 2*((1/12)*(BalsaLength)^3 + ( CentroidShape - CnetroidTopBalsa ) ^2 *BalsaLength);


Width_Moment_Function = Mx_WithP0 * (BalsaLength+(FoamLength/2))/((Ib + ...
    (E_Foam/E_Bals).*If)*MaxAllowNormal);
Width_Shear_Function = (((MaxAllowShear*(3/2))/(Vx_WithP0))^-1)/(FoamLength);

%loop over the two plots to get width function
j = 1; %index of storing
for i=(-Barlength/2):0.01:(Barlength/2)
    %width is maximum of both graphs of shear and moment
    WidthFunction(j) = max(abs(subs(Width_Moment_Function,i)), ...
        abs(subs(Width_Shear_Function,i)));
    iValues(j) = i; %store x values
    j = j+1;
end

WidthFunction = WidthFunction/2;
```

```
%Just to half the width because it gives us width for full span of 4 inches
% and we're doing half top and half bottom.

ForCut = double([ iValues' WidthFunction' ]);
% this just for us to cut the wing in practice.

ForCut = ForCut * 100 ; %convert
%% plotting

figure(5)
fplot(Width_Moment_Function)
hold on
fplot(Width_Shear_Function)
hold on
fplot(-Width_Shear_Function)
legend('Moment Diagram', 'Shear Diagram','Shear Diagram');
title('Shear and Moment Diagrams for the beam')
xlabel('Width (m)')
ylabel('Length (m)')
grid minor
hold off


figure(6);
plot(iValues,WidthFunction)
hold on
plot(iValues,-WidthFunction)
title('Width function');
xlabel('Length')
ylabel('Width')
hold on
grid minor

%% Determine the testing


% Loading function

syms x
Px = p0Value  * sqrt(1-(2*x/Barlength)^2);
ItegralBounds = 0:(Barlength/8):(Barlength/2);
% Integrate the weighted x values as well as the function
for i = 1:length(ItegralBounds)-1
    wint(i) = int(Px*x,x,ItegralBounds(i),ItegralBounds(i+1));
    nwint(i) = int(Px,x,ItegralBounds(i),ItegralBounds(i+1));
    centroid(i) = wint(i)/nwint(i);
end

%location of straps
l1 = centroid(2)-centroid(1);
l2 = ...
    ((nwint(1)+Sleeve+(.5*six_in_bar))*l1)/((nwint(1)+Sleeve+(.5*six_in_bar))+(nwint(2)+Sleeve+(.5*six_in_bar
l3 = centroid(4)-centroid(3);
l4 = ...
    ((nwint(3)+Sleeve+(.5*six_in_bar))*l3)/((nwint(3)+Sleeve+(.5*six_in_bar))+(nwint(4)+Sleeve+(.5*six_in_bar

l5 = (centroid(4)-l4)-(centroid(2)-l2);

l6 = ...
    (((nwint(1)+Sleeve+(.5*six_in_bar))+(nwint(2)+Sleeve+(.5*six_in_bar))+(.5*twelve_in_bar))*l5)/((nwint(1)+

%% Theoretical:

% how much force we excpect the wing to handle.

MaxNormalForce = MaxAllowNormal * LengthCS * WidthCS;

MaxShearForce = MaxAllowShear * LengthCS * WidthCS;
```