Natural Frequency and Ultimate Load of Composite spars

Cal Poly Mechanical Engineering

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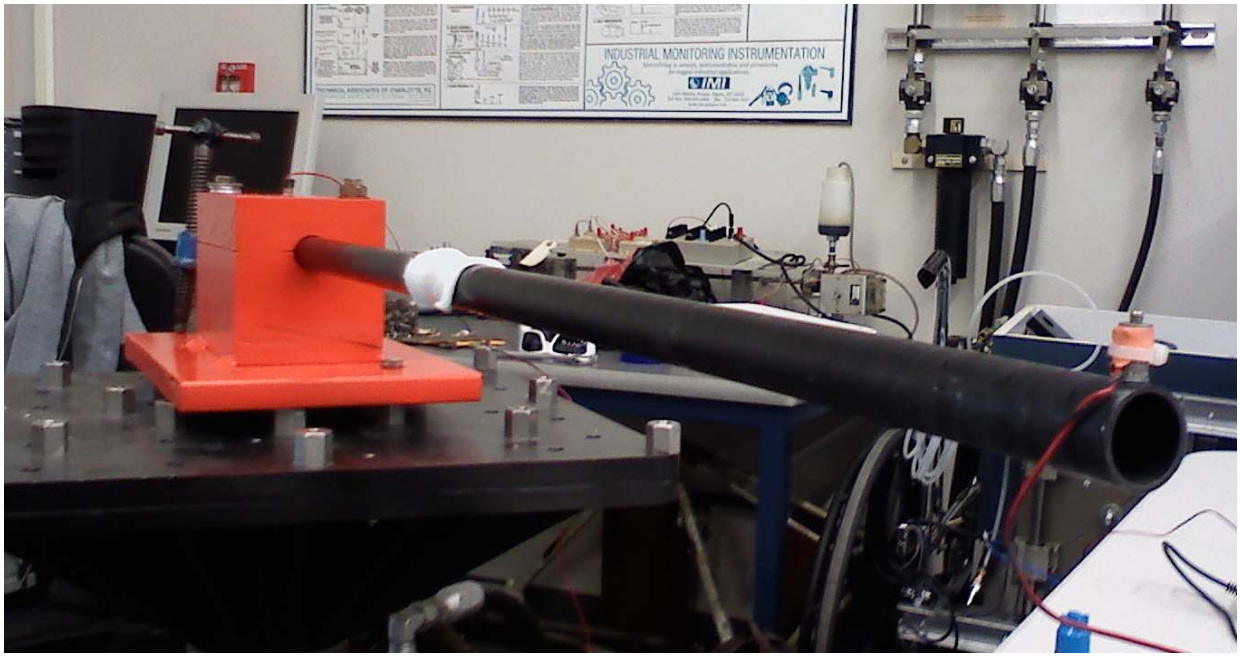

1. Abstract

The natural frequency and ultimate bending load was found for two of three carbon fiber tubes of varying ply orientation. The tubes measured .75” ID X 30” with .065” wall thickness. The all unidirectional (uni) tube buildup had a fundamental frequency of 61 Hz and experienced matrix failure at a load of 245 lbs. Both the -/+ 15° and -/+ 45° tube buildup experienced fiber failure at loads of 389 lbs and 422 lbs, respectively. Whereas the natural frequency of the -/+ 15° tube was not determined, the -/+ 45° tube had a fundamental frequency of 39 Hz.

An axial vibrations table along with an RTS Pro/Dactron data acquisition system was used with two Endevco 258M2 accelerometers. One accelerometer was mounted on the fixture and one was mounted on the tip of the test specimen. The Dactron collected data and displayed (in real-time) the amplitude ratio of the two accelerometers.

An Instron 1331/8500 Plus load frame used to apply load for the bending test. National Instruments LabVIEW 6.2 was used to collect data measured by the Vishay CEA-125-350 strain gages bonded to the test specimens.

Theoretical calculations were performed using MATLAB software. The experimental results proved to differ greatly from the expected results due to shear stresses not accounted for during the testing process.

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3. Introduction

The intention of this project was to analyze the internal strain, deflection, and vibrational response of carbon tube spars for use in airfoils. This analysis accompanied research performed by the Human Powered Helicopter Team here at Cal Poly, San Luis Obispo. Carbon spars are necessary to construct airfoils used in scale model testing of airframes for various rotor arrangements. Over the lifetime of the project, multiple spar sizes were used in airfoil construction in order to mitigate the coning experienced at higher RPMs. Coning (seen in Figure 1 below) causes a nonlinear reduction in lift generated by each rotor.

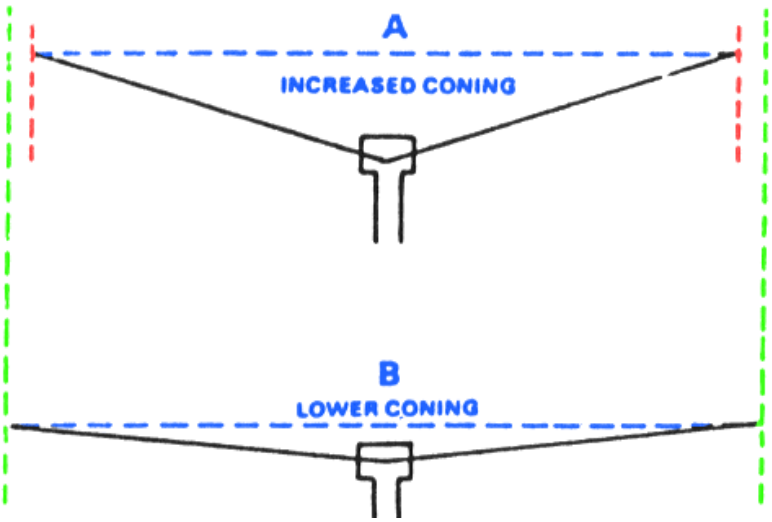

Figure 1: The effect of coning on rotors can be seen in this figure. Less coning is preferred, the reduction in disk area also reduces lift.

When using multiple rotors, uneven lift distribution across each rotor will cause the rotorcraft to become unbalanced and create detrimental vibrations across the platform. Unbalances like this can cause structural failure and negatively influence any data collected during testing. A larger and stronger carbon spar, such as those seen in Figure 2 below, was designed for use within the HPH airfoils. These spars were expensive to purchase however were affordable if manufactured in house for the application. Due to the importance of the spars as an integral part of the scaled rotorcraft, it was useful to perform further tests to determine their mechanical properties.

Figure 2: Larger, Cal Poly manufactured carbon spar in airfoil. Data from our test will support design changes to the spars being used in the configuration above.

Analyzing deflection allowed us to optimize the carbon ply arrangement in order to yield the stiffest spars possible while maintaining the lightweight construct crucial to flight. By empirically measuring strain as a function of load, we were able to compare our MATLAB analysis to the actual results and draw conclusions failure prediction. The information gathered added general knowledge about carbon fiber tubes, supporting hand calculations and formulas based on others' research.

Determining the modal frequencies of the spars allowed us to better understand the stability of the rotating airfoil. While the scaled rotors do not see a very demanding vibration environment, it was important to verify the spars would not be subject to their fundamental frequency while at operating speed. The use of the shake table allowed for frequency isolation otherwise not possible to produce during dynamic testing of the HPH prototype.

4. Background

While carbon fiber with resin has been used for years, each application differs based on the methods and materials used in the lay-up process. As a result, it is difficult to predict failure modes and finished material properties. As the orientation of the fiber plies varies, the composite tube can either experience a failure along the fibers (fiber failure) or from within the epoxy resin (matrix failure). A matrix failure within the tube indicates a lack of fibers resisting the load. In a matrix failure, epoxy binding the fiber together is being loaded more than the fibers themselves causing premature failure. A fiber failure under testing is much more desirable, as it indicates the carbon fibers were supporting the load. When using carbon as a structural member, testing is almost always necessary to determine effective properties that will vary among lay-ups.

Testing bending strength as a function of fiber orientation was necessary to optimize strength while minimizing weight for the HPH rotors. Unidirectional pre-impregnated carbon fiber was known to have excellent strength in tension; however there was typically matrix failure when it was subject to torsion, shear, or compression. Building a tube with unidirectional fibers oriented lengthwise created a tube that had excellent resistance to bending but was subject to ovaling under compression. In order to mitigate this, certain plies were wrapped around the mandrel at varying angles to the previous layer. As a result, some fibers were able to carry transverse loads, thus reducing ovaling and ultimately matrix failure. Figure 3 illustrates the effect of adding non-parallel plies to the tube.

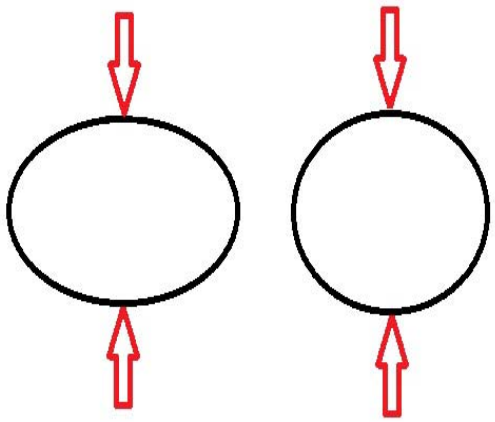

Figure 3: This figure illustrates the effect a compressive load has on carbon tubes. From this cross-section, you can see the tube on the left (all unidirectional) deflects more than the tube on the right

(unidirectional with bias ply). Less deflection is desireable for the spars being used in the HPH airfoils.

Spar construction included pre-impregnated composite fiber (T700/LS-930) wrapped in varying ply orientation around a .75” diameter mandrel. The composite assembly was cured at a soak temperature of 250° for 2.5 hours. Although not in a journal, the McIntyre article “A Manual for Making CFRP Tubes” was the process we followed. The journal publication, "The Effect of Fiber Alignment on Composite Strength: II. The Strength of Angle Ply Laminates." delves into great detail about the mechanics of various ply composite tubes. ASTM Standard E2534 – 10 “Standard Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts” was referenced when performing sine sweep vibration analysis on the cantilevered spar. Beam deflection can be performed using the appropriate strategies described in the eighth edition of Shigley’s Mechanical Engineering Design.

5. Theoretical Results/Calculations

Theoretical values for stress, strain, failure load, and natural frequency were calculated in order to predict test results. Partnering with the HPH team, a composite tube failure MATLAB program was developed and utilized to help predict failure modes and characteristics. Data provided by the pre-impregnated carbon manufacturer (seen in Appendix C) was input into the program. The expected results are seen in tables 1, 2, and 3 below.

Table 1: Predicted values of failure for carbon tubes in pure bending

Ply Angle [deg]	Failure Load [lb]	Failure Mode	Location of Failure
0	703.85	Fiber	N/A
15 (-/+)	444.79	Matrix	Inner Ply
45 (-/+)	354.14	Fiber	Outer Ply

Table 2: Predicted stress and strain for carbon tubes under failure conditions. Values correspond to outer ply only

Ply Angle [deg]	Max Axial Stress [psi]	Max Transverse Stress [psi]	Max Axial Strain	Max Transverse Strain
0	1.90E+05	4.55E-13	1.12E-02	-3.47E-03
15 (-/+)	-8.84E-03	-4.96E+03	9.52E-03	-7.98E-03
45 (-/+)	1.89E+05	-5.29E+03	1.12E-02	-8.84E-03

Table 3: Predicted natural frequencies of carbon tubes

Ply Angle [deg]	Natural Frequency [Hz]
0	51.86
15 (-/+)	49.16
45 (-/+)	40.93

The load calculations were based on a five ply carbon tube 20” long subjected to pure bending in a simply supported fashion. The program assumed no temperature change, a weight per unit length of 0.0094 lbs/in, and loading only in the vertical direction. The code was written to display layer specific properties in matrix form, with entries corresponding to both sides of the layer. Therefore, for a lay-up of 5 plies, the stress and strain matrices computed under specified conditions consist of 10 values per column. The above data corresponds to the outside face of the outermost layer, as this is where the strain gages were bonded. The total code and sample readouts for maximum loading criterion can be seen in Appendix A. For the modal analysis, the tube was analyzed at a length of 30”.

The theoretical calculations do make logical sense. Under pure, simply supported bending conditions, it seems plausible the all unidirectional tube would hold the most load before failure. In that case, all five plies would support the bending force provided other, out of plane forces were not present. As the angle of off axis plies increases, less unidirectional fiber is aligned along the length of tube and therefore less material is present to resist bending. This trend can be seen in Table 1 above, where the failure load applied decreased as the degree of off axis plies increased. It was important to remember the presence of out of plane forces. Out of plane forces distort readings by introducing shear or transverse loads. Only spars with off-axis ply would be resist the additional shear stresses. In this case, the unidirectional tube may not carry the most load of the three tubes.

In order to better understand the natural frequency, it was useful to compare the theoretical results of carbon to that of a more common material such as aluminum. A fundamental frequency comparison is included in Appendix A. For a 6061-T6 aluminum rod of the same dimensions (30” X 0.75” ID X 0.065” thick), the aluminum yielded a fundamental frequency of 5.18 Hz. Aluminum of this size and shape implies a weight of approximately half a pound. When compared to the theoretical natural frequency of carbon (51.86 Hz for all-unidirectional) at roughly a third of a pound, the beneficial properties of carbon were impressive. Even the least stiff carbon tube yielded a much higher predicted natural frequency than the aluminum.

6. Spar Construction

Using T700/LS-930 unidirectional carbon fiber sheeting, strips were cut and wrapped around an aluminum mandrel. The mandrel measured .75” diameter by 48” long. Prior to wrapping the first layer of carbon, the mandrel was sprayed with a chemical release agent to prevent the carbon from adhering to the mandrel when curing. The first ply was cut 2.356” wide by 36” long. The strip was then wrapped around the mandrel. When the strip was completely wrapped around the mandrel, each side met along the mandrel eliminating any seam. See Figure 4 for lay-up clarification. Each additional ply width was calculated by measuring the outer diameter of the tube and multiplying it by Pi. For the plies that were laid at -/+15° and -/+45° angles, the width of the plies were calculated by measuring the outer diameter of the previous layer and multiplying it by Pi*cos(ø), where ø= angle of ply.

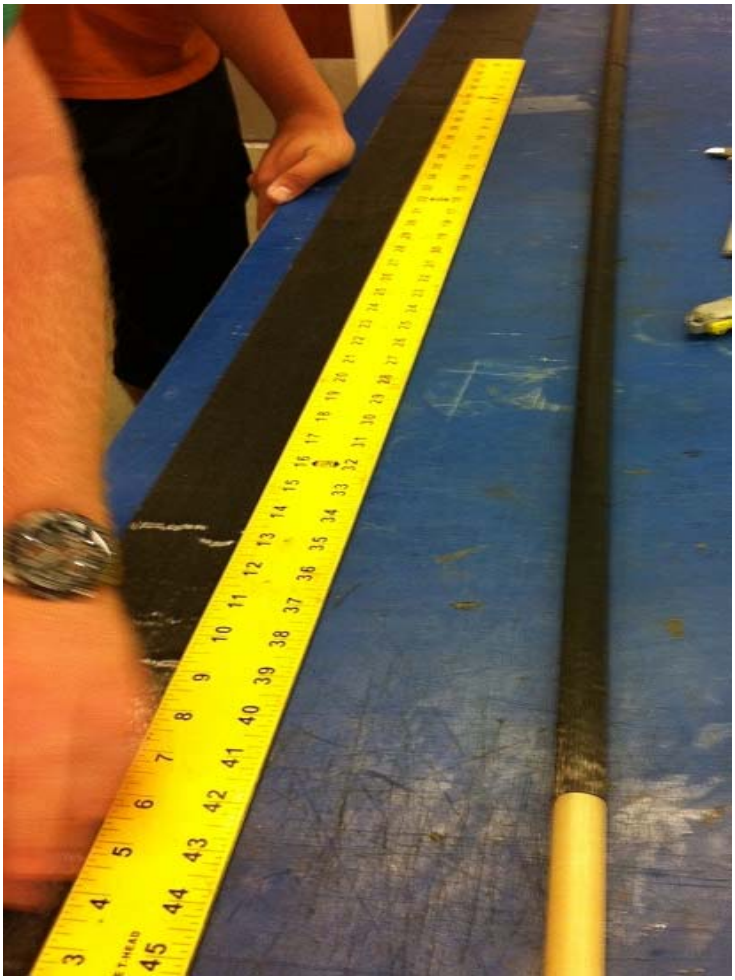

Figure 4: Strips of unidirectional carbon pre-preg are cut in 36” length and wrapped around the mandrel. This figure shows the approximate width necessary to fully wrap the mandrel with one layer of uni.

The three tubes created were laid up in the following configuration (starting from inside to outside):

Tube A- Uni, Uni, Uni, Uni, Uni. Each seam rotated 90° from the previous layer
Tube B- Uni, Uni, +15°, -15°, Uni
Tube C- Uni, Uni, +45°, -45°, Uni

Once the mandrels were wrapped with carbon, 1" wide shrink tape was tightly wrapped around the mandrel (as seen in Figure 5). As the shrink tape was wrapped, we maintained a tape overlap of 1/2" to ensure consistent pressure and surface finish. Finally the tubes were baked in the autoclave per recipe for T700/LS-930. The recipe consisted of a 45 minute ramp up in temperature (from room temperature to 250°F), then held at 250°F for two hours before the temperature was ramped back down to room temperature. The spars were then cut to length using a high speed band saw.

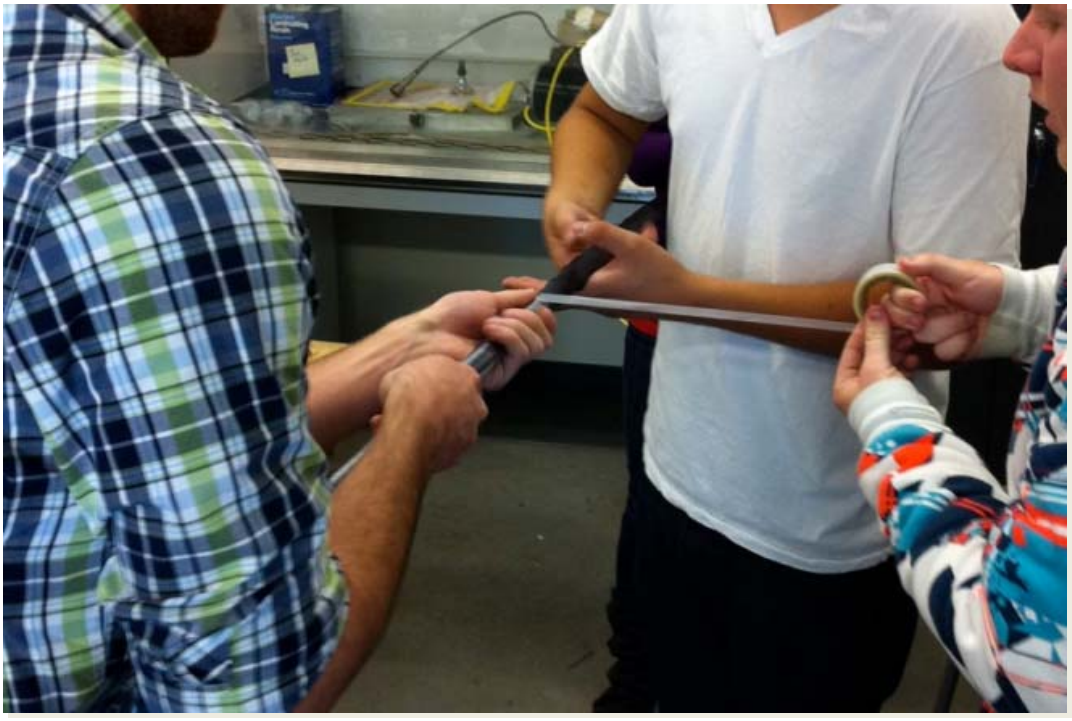

Figure 5: Wrapping uncured carbon spar with shrink tape illustrated above was a method used to induce pressure on the carbon without baking the spars in a vacuum chamber. When the shrink tape was heated it contracted, thus adding additional pressure to the mandrel/carbon layup.

7. Instrumentation

Each spar was outfitted with two Vishay CEA125-350 strain gages and one Endevco 258M2 accelerometer. We followed Vishay's strain gage preparation recipe located on their website (see Appendix C). Strain gages were placed in the middle of each spar as seen in Figure 6 below. One gage was oriented along the direction of the outer unidirectional ply, while the other was wrapped around the tube radially. They were then wired in a half bridge to account for strain in two directions.

Figure 6: Finished gage assembly bonded to spar. Each Vishay CEA125-350 gage was prepped according to the Vishay surface prep guide seen in Appendix C.

The accelerometers were place on the furthermost end of the spar and fixed to it using cyanoacrylate glue. When the accelerometers were secured, we verified they were perpendicular to the surface of each spar using a protractor. This ensured we were measuring acceleration in the vertical direction only.

8. Fixtures

The fixture seen below in Figure 7 (and again in Appendix B) was designed to fulfill our vibes testing need. Due to the harsh environment experienced during a sine sweep test, the fixture utilized four 3/8” bolts to mount to the shake table. A top clamp using (4) 5/16” bolts was utilized to secure the spars in the fixture. To keep the spars from failing due to the compression of the clamp, a portion of the aluminum mandrel used in the curing process was inserted into the clamped portion of the spar.

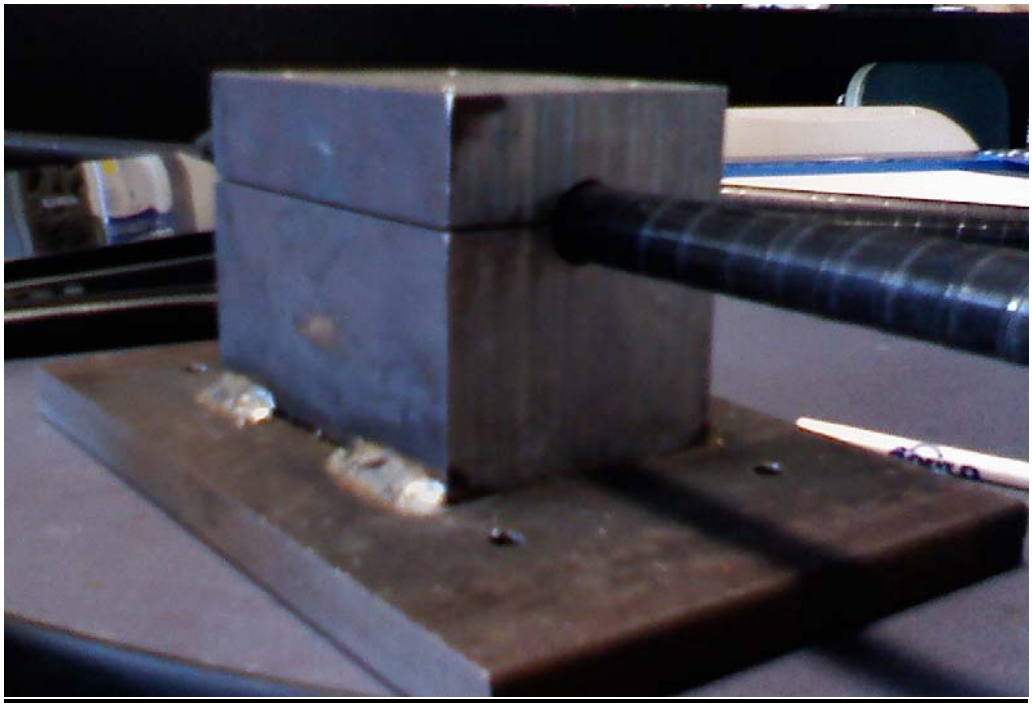

Figure 7: This shows the assembled fixture used in vibrations testing. Four bolts are used to secure the baseplate to the shake table while four additional bolts are used to secure the upper portion (clamp) to the base. The spar was sandwiched between the two halves with a tube inserted in the spar to mitigate crushing of the matrix.

Figure 8 shows the fixture utilized for the ultimate load test. The fixture measured 20” between pivot points and allowed us to perform a three point bending test with the Instron load frame. The load was applied using a 2” wide disk with a foam pad on the surface (this prevented point loading during the test). The ends holding the spar were padded and allowed to rotate freely.

Figure 8: Three point bending fixture used in ultimate load test for each carbon spar. The ends were free to pivot while the load was applied to the center of the spar.

9. Testing

9.1 Vibration

In order to find the first two natural frequencies, we performed a sine sweep test on each spar. The vibes fixture was mounted to a vertical axis shake table and secured using four bolts. Each spar was fully clamped into the fixture with 30” of spar cantilevered out one side of the fixture. An aluminum rod was inserted in the clamped portion of the spar to keep from crushing. The ‘output’ accelerometer was oriented vertically in order to measure accelerations in the direction of the shake table movement. An accelerometer was also secured to the center of the text fixture clamp in order to measure the 'input' acceleration. Later the 'output'/'input' was analyzed to find natural frequencies.

An RTS Pro/Dactron was used to create the signal for the shake table. A sine sweep was performed over the course of 15 seconds from 1 to 1000 Hz. The shake table signal was also plotted as a function of time to illustrate the frequency it was shaking the table.

An amplifier was used on each accelerometer output prior to entering the RTS Pro/Dactron analyzer. The Dactron then plotted the ratio of accelerometer 'output'/'input' vs. frequency. This plot was used to determine which frequencies yielded the highest ratio, thus correlating to the natural frequencies of the spars.

An oscilloscope was also used to visually verify the signal being generated for the shake table, and to verify natural frequencies from the outputs. While the oscilloscope was not necessary to perform the test, it added an additional source of data to verify the Dactron.

9.2 Ultimate Load

An Instron 1331/8500 Plus load frame was used to load each spar until failure. A LabVIEW program was used to capture data from the strain gages and to plot other information from the load frame. Each spar was cut to 21” in length in order to fit between the load frame uprights.

The three point bending fixture was loaded into the load frame and was leveled using a 6” magnetic bubble level. Once the fixture was secured in the Instron, the spars were centered

on the simple supports. The gages were located directly below the pressure disk facing downward. Wires from the gages were connected to the computer via the National Instruments interface. Using a pre-programmed LabVIEW file for the Instron, the strain gage signal was amplified and calibrated to measure strain. Position and load data was also collected from the Instron and plotted using the LabVIEW file.

With the spar in place, the upper carriage was brought down in contact with the spar. The carriage was then set to travel .001”/sec until the spar failed to support increased loading. As the carriage deflected the spar, the load was displayed on one of the on screen plots. Each of the data channels was saved to a file and then plotted using Microsoft Excel.

10. Results

Table 4 shows the results from the vibration testing we performed. We were unable to measure the fundamental frequency of the -/+15° spar due to complication with the data acquisition equipment and time constraints in the lab. However, we were able to compare the experimental results to the theoretical calculations for the other two spars. We verified our estimate that the all unidirectional carbon spar was the stiffest.

Table 4: Comparative vibration results between theoretical and experimental procedures

Ply Angle [deg]	Theoretical Natural Frequency [Hz]	Experimental Natural Frequency [Hz]
0	51.86	61
15 (-/+)	49.16	*
45 (-/+)	40.93	39

Data for the vibration test was difficult to obtain due to RTS Pro interface difficulties with the users. We were unable to plot a histogram of the frequency response as the shake table moved through the sine sweep. In order to obtain data, we manually input a sine wave at a given frequency and watched the output. As we increased the frequency we noticed an increase of the 'output'/'input' voltages from the accelerometers. Once the fundamental frequency was passed, the 'output'/'input' voltage would decrease, thus showing we had passed the fundamental frequency.

Though we are unable to include any raw data or histograms of the sine sweep test, we are confident our experimental values are accurate within -/+1Hz. By using the oscilloscope in conjunction with the on screen data from RTS Pro, we were able to dial in the natural frequency and notice a sizable difference when shaking the table at .5Hz increments.

Figure 9 below shows strain vs. load for each of the spars. The all unidirectional spar failed at a load of 245 lbs, the failure was in the matrix. The -/+15° spar had a fiber failure at a load of 389 lbs. The -/+45° spar had a fiber failure at 422 lbs. The -/+15° and -/+45° lines each have a spot where strain decreases for a moment as load continues to increase. This can be attributed to a transfer of load from one ply to the next. We expected a failure in one of the

inner fibers first, and the results from the testing show that was most likely the case. Along with empirical data, there was also an auditory indication that an inner fiber failed while the spar continued to take more loading.

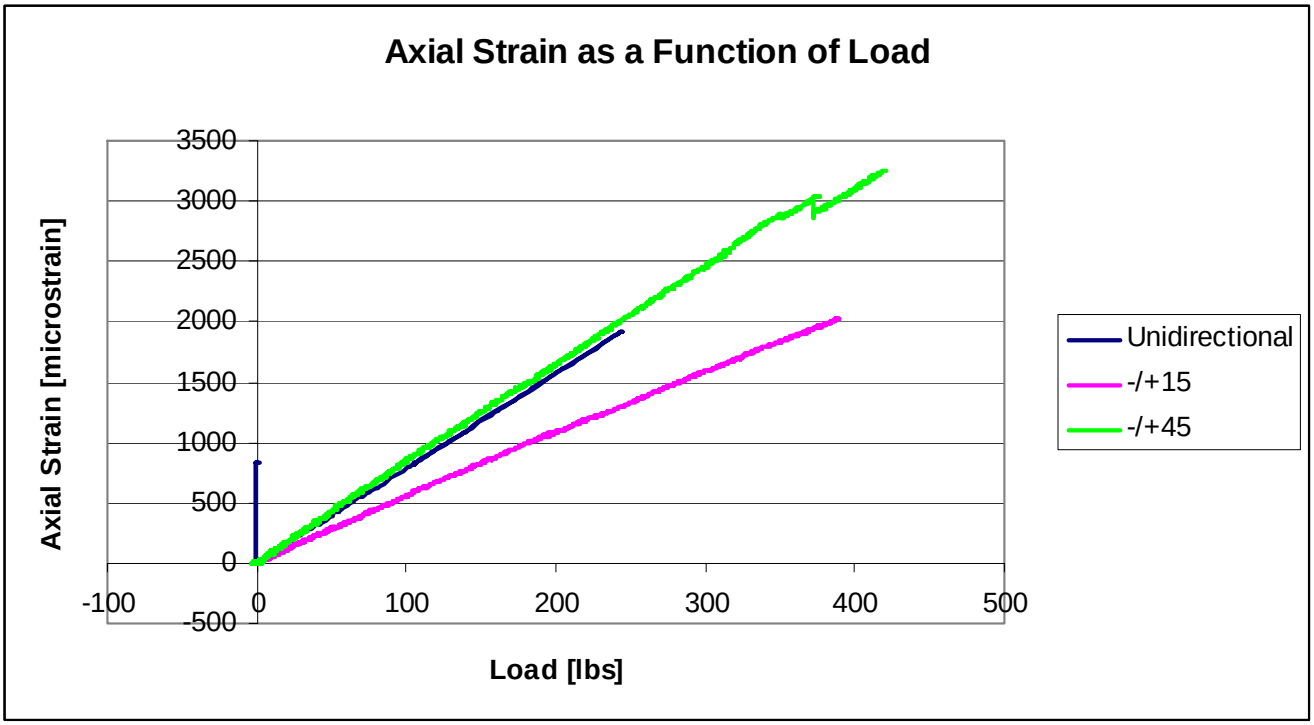

Figure 9: Axial strain as a function of load. The -/+45° spar withstood the most loading prior to failure with a maximum strain of 3257 micro strain at 422 lbs.

These results were highly unexpected. We expected the strongest spar to be the unidirectional spar and the weakest to be -/+45°. The difference can be attributed to the shear stress being applied to the beam during the three point bend test. Had we utilized a four point bend test, we could have changed the location and magnitude of the shear stress. As a result, the point of maximum stress due to bending would be different from the point of maximum shear stress, allowing the beam to take more loading until failure.

Figure 10 shows the deflection as a function of load for the all unidirectional spar. Due to data acquisition difficulties, we were only able to measure this relation for the all unidirectional spar. The data could be used to find an empirical value for the stiffness of the beam. Unfortunately due to the measures taken to reduce point loading, this deflection vs. load plot also includes deflection of the fixture and any additional deflections in the system.

We recommend using an optical device to measure deflection of just the beam in order to find accurate deflection as a function of force.

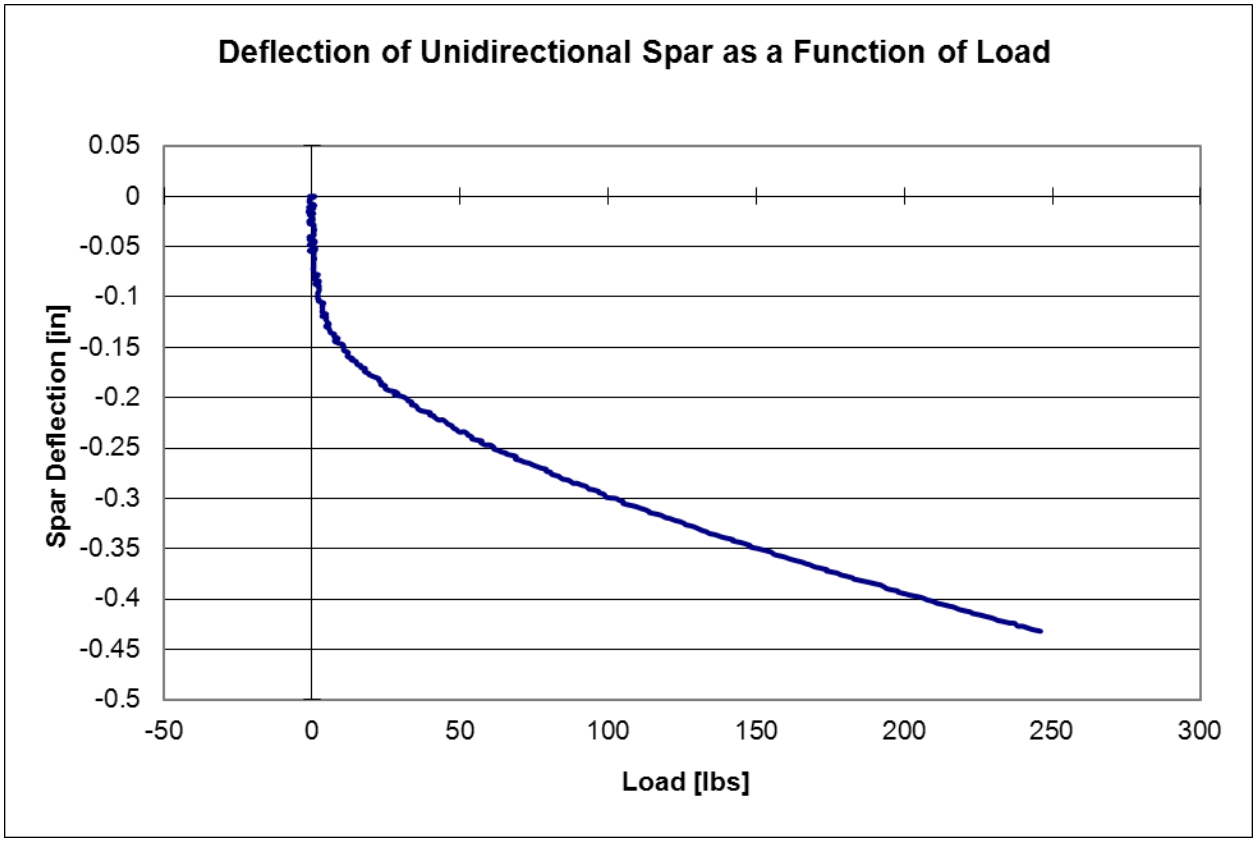

Figure 10: This plot shows the deflection at the center of the beam as a function of load. The deflection however includes that of the fixture as well. The plot is useful to show the deflection vs. load relationship, but nominal values should not be used for calculations.

11. Conclusion

Carbon spars of varying ply buildup were tested for their natural frequencies and resistance to bending loads. An Instron 1331/8500 Plus and shake table were used to conduct these tests. LabVIEW was used to analyze data from the load test while RTS Pro was used to analyze data from the vibration test. From experimentation, the all unidirectional carbon spar was the stiffest and the -/+45° ply buildup was the strongest in bending. Hand calculations estimated the first natural frequency of the all unidirectional spar to be 52 Hz while the experimental testing yielded a natural frequency of 61 Hz. The amount of load each spar carried varied greatly from what we expected. Shear loading turned out to be a major factor in the three point bending test we performed. For better results, we recommend performing the same test using a four point bending test. This would reduce the amount of shear seen in the center of the spar during the load test. We also recommend using a filter when conducting a vibration test. Filtering would reduce the amount of noise seen and therefore the natural frequency would be easier to observe.

12. Works Cited

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13. Appendix A – Calculations

MATLAB Code: Special thanks to Eric Behne, ME student and HPH member

```
%Classical Lamination Theory design code modified for use with
%tubing
%Note: this thing has plots and pauses hit return play with scaling factors

clear all
close all

%set up a diary file
diary CLT.dat


%units are US customary (lb, in, E in psi)

% total laminate definition in matrix below
% [ply angles, thicknesses, matl. #]

%Set up for two materials

% Data in there now is
%1-carbon
%2-Eglass

%Laminate is defined in this matrix l (sorry it looks like a one)
% [ angle  thick  matl #]
l=[   0   1*0.014      1
      +45   1*0.014      1
      -45   1*0.014      1
      0   1*0.014      1
      0   1*0.014      1];

% this is the total laminate
% cut, paste, edit above to study your laminate of choice

%delta temp
disp('Temperature Change [Degrees F]')
DT = 0.0

% size command to get number of plies
n = size(l,1);

%      Lamina Properties
%      matrix for engineering constants
      %E1     E2    v12  G12   a11     a22
 E = [17e6 0.98e6  .31  .42e6   -.5e-6  15e-6; %T700 PrePreg
      5.84e6 .9e6  .2  .3e6    0.0e-6  0.0e-6]; %E-Glass/Epoxy
 % a's are CTE's
```

```
%intiialize the ply distance and ABD matrices
NT = zeros(3,1);
MT = zeros(3,1);

h = zeros(n+1,1);
A = zeros(3);
B = zeros(3);
D = zeros(3);
% Form R matrix which relates engineering to tensor strain
R = [1  0  0;
     0  1  0;
     0  0  2];

%find the total thickness
disp('Total Laminate Thickness [inches]')
total = sum(l,1);
thick = total(1,2)

% locate the bottom of the first ply
h(1) = -thick/2.;
imax = n + 1;
%loop for rest of the ply distances from midsurf
for i = 2 : imax
   h(i) = h(i-1) + l(i-1,2);
end

%loop over each ply to integrate the ABD matrices
for i = 1:n

   %ply material ID
   mi=l(i,3);
   v21 = E(mi,2)*E(mi,3)/E(mi,1);
   d = 1 - E(mi,3)*v21;

   %Q12 matrix
   Q = [E(mi,1)/d          v21*E(mi,1)/d      0;
        E(mi,3)*E(mi,2)/d   E(mi,2)/d          0;
        0                 0               E(mi,4)];


   %ply angle in radians
   a1=l(i,1)*pi/180;

    %Form transformation matrices T1 for ply
    T1 = [(cos(a1))^2       (sin(a1))^2              2*sin(a1)*cos(a1);
          (sin(a1))^2       (cos(a1))^2             -2*sin(a1)*cos(a1);
         -sin(a1)*cos(a1)    sin(a1)*cos(a1)   (cos(a1))^2-(sin(a1))^2 ];


   %Form Qxy
   Qxy = inv(T1)*Q*R*T1*inv(R);
```

```
% build up the laminate stiffness matrices
   A = A + Qxy*(h(i+1)-h(i));
   B = B + Qxy*(h(i+1)^2 - h(i)^2);
   D = D + Qxy*(h(i+1)^3 - h(i)^3);

   %load alphs into and array
   a=[E(mi,5); E(mi,6); 0.0];

   %transform cte's mult by DT to get thermal strain exy
   exy = (R*inv(T1)*inv(R)*a)*DT;
   %build up thermal load as well now
   NT = NT +  Qxy*exy*(h(i+1)-h(i));
   MT = MT + .5*(Qxy*exy*(h(i+1)^2 - h(i)^2));

%end of stiffness loop
end

%change the display format for compliance matrix
format short e

disp('Laminate Matrices A,B & D')
A = 1.0*A
B = .5*B
D = (1/3)*D

%Stiffness Matrix
disp('Laminate Stiffness Matrix, K')
K = [A, B;
     B, D]

%Compliance Matrix
disp('Laminate Compliance Matrix, C (Inverse of K)')
C = inv(K)

 %Input Tube Data Here
 %Length of the span in inches
 disp('Length of Tube Span [inches]')
 L=20

 %Tube weight per unit length [lbs/in]
 disp('')
 W=.0094

 %Force to deflect the tube
 disp('Force on Tube [lb]')
 F=200

%Bending Moment
 disp('Max Bending Moment [in-lbs]')
 Mb=F*(L/2)

 %Innerdiameter of the tube
 tm=0.75;

 %Distance from the center line to the wall => y=Midradius of the tube!!!
 Rad=(tm+thick)/2;
```

```
%Resulting Force in x-Direction
 disp('X-direction Line Load on Tube [lb/in]')
 Nx=Mb/(Rad^2*pi)

 %Resulting Shear Force
 disp('Shear Line Load on Tube [lb/in]')
 Nxy=F/(pi*Rad)

 %Effective EI
 disp('Effective EI of the Tube')
 EI=pi*Rad^3/(C(1,1))

 %Deflection of the tube Simply Supported
 disp('Max Deflection of the Tube [Inches]')
 defl=(F*L^3)/(48*EI)

%put in mechanical loads here
%mech loads
  Nx=Nx
  Ny=0.0
  Ns=Nxy
  Mx=0.0
  My=0.0
  Ms=0.0
%
% superimpose mech and thermal loads
load = [ NT(1) + Nx;
         NT(2) + Ny;
         NT(3) + Ns;
         MT(1) + Mx;
         MT(2) + My;
         MT(3) + Ms];

%compute the strains = compliance times load
disp('Overall Laminate Stains [in/in]')
e = C*load

%compute the natural frequency in Hz:
disp('Natural frequency of tube [Hz]')
fn = (pi/2)*((32.2*EI)/(W*L^4))^.5

% calc radii of curvature
Rx = 1/e(4);
Ry = 1/e(5);
Rxy= 1/e(6);


%_____________________________________________________________
% This stuff below is simply to plot the deformed shape
% attempt to plot the deformed element
%
%
% plot scaling, magnification factor
A=2.0;
```

```
% define half of unit element
u=.5;
%
ux = [-u;
       u;
       u;
      -u;
      -u];
%
uy = [-u;
      -u;
       u;
       u;
      -u];
%
dx = [-e(1)*u*A;
       e(1)*u*A;
       e(1)*u*A;
      -e(1)*u*A;
      -e(1)*u*A];
%
%
dy = [-e(2)*u*A;
      -e(2)*u*A;
       e(2)*u*A;
       e(2)*u*A;
      -e(2)*u*A];
%
dxy= [-e(3)*u*A;
      -e(3)*u*A;
       e(3)*u*A;
       e(3)*u*A;
      -e(3)*u*A];
%
x1= ux+dx+dxy;
y1= uy+dy;
%
hold on
plot(ux,uy, '--b')
plot(x1,y1, '-r')
axis([-1  1  -1  1])
hold off
%
pause
%_____________________________________________________________________
%_____________________________________________________________________
% Given constant curvatures
% plot for ME412
%

Kx  = e(4);
Ky  = e(5);
Kxy = e(6);

%plate W
L=6;
```

```
%Constants of integration
C2 = (L/2)*Kx;
C3 = (L/2)*Ky;

% create X and Y over the domain of the function
[X,Y] = meshgrid(0:L,0:L);

for i = 1:L+1;
    for j = 1:L+1;
   w(i,j) = -.5*(Kx*X(i,j)^2+Ky*Y(i,j)^2+.5*Kxy*X(i,j)*Y(i,j))...
       + C2*X(i,j) + C3*Y(i,j);
    end
end

w;
%w(1,L)

mesh(w)
%
%_____________________________________________________________________
% Now calc stress and strain and failure index using Max strain
%
% reduction factor for ultimate (pseudo A-basis use .80)
RF=.80;
%
%
% allowable strains reduced to account for ultimate strength after impact
% row1 is carbon
% row2 is E-glass
% transverse prperties assumed same
% load allowable strains into array
%     ELU        ELUP       ETU      ETUP     ELTU
ea = [RF*.014   RF*.012   RF*.007   RF*.031  RF*.0296;
      RF*.02    RF*.018   RF*.0067  RF*.031  RF*.0296];
%
%
%zero out results array
ERES = zeros(2*n,6);
SRES = zeros(2*n,6);

% loop over each ply and calculate strain
for i=1 : n;
   %loop over top and bottom of each ply
   for j=1 : 2;
   % one is bottom two is top for loc
   ply = i;
   loc = j;

   z = h(i-1+j);

   %ply strain from midplane strain
   el= [ e(1)+z*e(4);  e(2)+z*e(5);  e(3)+z*e(6)];

   %ply material ID
   mi=l(i,3);
   v21 = E(mi,2)*E(mi,3)/E(mi,1);
   d = 1 - E(mi,3)*v21;
```

```
   %Q12 matrix
   Q = [E(mi,1)/d          v21*E(mi,1)/d      0;
        E(mi,3)*E(mi,2)/d   E(mi,2)/d          0;
        0                 0               E(mi,4)];

   %
   %ply angle in radians
   a1=l(i,1)*pi/180;

    %Form transformation matrices T1 for ply
    T1 = [(cos(a1))^2       (sin(a1))^2              2*sin(a1)*cos(a1);
        (sin(a1))^2        (cos(a1))^2             -2*sin(a1)*cos(a1);
        -sin(a1)*cos(a1)    sin(a1)*cos(a1)  (cos(a1))^2-(sin(a1))^2 ];

   % load alpha for the ply
   a=[E(mi,5); E(mi,6); 0.0];

   % tranform to 1,2
   % subtract off alpha delta T to get mech strain that causes stress
   ep = R*T1*inv(R)*el - a*DT;

   %calculate stress in 1,2 coords
   sp = Q*ep;

%failure index now looks at two different materials

   if ep(1) > 0.0;
      FI = ep(1)/ea(mi,1);
      FIF=FI;
     elseif ep(1) < 0.0;
        FI = abs( ep(1) )/ea(mi,2);
        FIF=FI;
   end

   if ep(2) > 0.0;
     F1 = ep(2)/ea(mi,3);
   elseif ep(2) < 0.0;
     F1 = abs( ep(2) )/ea(mi,4);
   end
%

  if F1 > FI;
   FI = F1;
  end
%
%
   F1 = abs( ep(3) )/ea(mi,5);
  if F1 > FI ;
   FIe = F1;
  elseif F1 < FI;
   FIe = FI;
  end
```

```
%load the results array
   % note top and botom of every ply!

%strain results, FI based on Max Strain
   %angle,eps1,eps2,gamma12,FI, FIfiber
    ERES(2*i+j-2,1)=l(i);
    ERES(2*i+j-2,2)=ep(1);
    ERES(2*i+j-2,3)=ep(2);
    ERES(2*i+j-2,4)=ep(3);
    ERES(2*i+j-2,5)=FIe;
    ERES(2*i+j-2,6)=FIF;

   %stress results, FI based on max strain
   %angle,Sigma1,Sigma2,Tau12, FI, FIfiber
    SRES(2*i+j-2,1)=l(i);
    SRES(2*i+j-2,2)=sp(1);
    SRES(2*i+j-2,3)=sp(2);
    SRES(2*i+j-2,4)=sp(3);
    SRES(2*i+j-2,5)=FIe;
    SRES(2*i+j-2,6)=FIF;


end
%
end

disp('Strains at top and bottom of each ply in the laminate')
disp('Ply Angle,Strain Longitudinal,Strain Transverse,Shear Strain, Failure Index,
Failure Index Fiber')
ERES=ERES*1
disp('Stresses at top and bottom of each ply in the laminate')
disp('Ply Angle,Stress Longitudinal,Stress Transverse,Shear Stress, Failure Index,
Failure Index Fiber')
SRES=SRES*1

diary off
%

%
```

Sample MATLAB Calculation: -/+45 tube, under failure loading

Temperature Change [Degrees F]

DT = 0

Total Laminate Thickness [inches]

thick = 7.0000e-002

Laminate Matrices A,B & D

A =

8.6058e+005 1.3191e+005 0

1.3191e+005 1.8399e+005 0

0 0 1.3992e+005

B =

2.3524e+003 -7.7367e+002 -7.8935e+002

-7.7367e+002 -8.0504e+002 -7.8935e+002

-7.8935e+002 -7.8935e+002 -7.7367e+002

D =

4.5020e+002 2.1369e+001 1.1051e+001

2.1369e+001 4.1317e+001 1.1051e+001

1.1051e+001 1.1051e+001 2.4642e+001

Laminate Stiffness Matrix, K

K =

8.6058e+005 1.3191e+005 0 2.3524e+003 -7.7367e+002 -7.8935e+002

1.3191e+005 1.8399e+005 0 -7.7367e+002 -8.0504e+002 -7.8935e+002

0 0 1.3992e+005 -7.8935e+002 -7.8935e+002 -7.7367e+002

2.3524e+003 -7.7367e+002 -7.8935e+002 4.5020e+002 2.1369e+001 1.1051e+001

-7.7367e+002 -8.0504e+002 -7.8935e+002 2.1369e+001 4.1317e+001 1.1051e+001

-7.8935e+002 -7.8935e+002 -7.7367e+002 1.1051e+001 1.1051e+001 2.4642e+001

Laminate Compliance Matrix, C (Inverse of K)

C =

1.3485e-006 -8.8624e-007 1.0178e-007 -9.2998e-006 1.0007e-005 1.7686e-005

-8.8624e-007 7.4975e-006 1.8416e-006 1.0582e-005 1.0040e-004 2.1983e-004

1.0178e-007 1.8416e-006 9.6157e-006 5.5658e-006 1.3850e-004 2.9955e-004

-9.2998e-006 1.0582e-005 5.5658e-006 2.3538e-003 -9.7080e-004 -4.0438e-004

1.0007e-005 1.0040e-004 1.3850e-004 -9.7080e-004 3.0986e-002 -5.5759e-003

1.7686e-005 2.1983e-004 2.9955e-004 -4.0438e-004 -5.5759e-003 6.0277e-002

Length of Tube Span [inches]

L = 20

Weight per unit length [lb/in]

W = 9.4000e-003

Force on Tube [lb]

F = 3.5414e+002

Max Bending Moment [in-lbs]

Mb = 3.5414e+003

X-direction Line Load on Tube [lb/in]

Nx = 6.7059e+003

Shear Line Load on Tube [lb/in]

Nxy = 2.7494e+002

Effective EI of the Tube

EI = 1.6057e+005

Max Deflection of the Tube [Inches]

defl = 3.6760e-001

Nx = 6.7059e+003

Ny = 0

Ns = 2.7494e+002

Mx = 0

My = 0

Ms = 0

Overall Laminate Stains [in/in]

e =

9.0708e-003

-5.4367e-003

3.3263e-003

-6.0833e-002

1.0518e-001

2.0096e-001

Natural frequency of tube [Hz]

fn = 9.2098e+001

Strains at top and bottom of each ply in the laminate

Ply Angle,Strain Longitudinal,Strain Transverse,Shear Strain, Failure Index, Failure Index Fiber

ERES =

0	1.1200e-002	-9.1181e-003	-3.7073e-003	1.0000e+000	1.0000e+000
0	1.0348e-002	-7.6455e-003	-8.9386e-004	9.2396e-001	9.2396e-001
4.5000e+001	9.0446e-004	1.7983e-003	-1.7994e-002	7.5988e-001	8.0755e-002
4.5000e+001	2.6216e-003	7.0206e-004	-1.5670e-002	6.6172e-001	2.3407e-001
-4.5000e+001	7.0206e-004	2.6216e-003	1.5670e-002	6.6172e-001	6.2684e-002
-4.5000e+001	-3.9419e-004	4.3388e-003	1.3345e-002	7.7478e-001	4.1061e-002
0	8.6450e-003	-4.7004e-003	4.7330e-003	7.7188e-001	7.7188e-001
0	7.7933e-003	-3.2278e-003	7.5464e-003	6.9583e-001	6.9583e-001
0	7.7933e-003	-3.2278e-003	7.5464e-003	6.9583e-001	6.9583e-001
0	6.9417e-003	-1.7553e-003	1.0360e-002	6.1979e-001	6.1979e-001

Stresses at top and bottom of each ply in the laminate

Ply Angle,Stress Longitudinal,Stress Transverse,Shear Stress, Failure Index, Failure Index Fiber

SRES =

0	1.8867e+005	-5.5640e+003	-1.5571e+003	1.0000e+000	1.0000e+000
0	1.7457e+005	-4.3730e+003	-3.7542e+002	9.2396e-001	9.2396e-001
4.5000e+001	1.6011e+004	2.0485e+003	-7.5574e+003	7.5988e-001	8.0755e-002
4.5000e+001	4.5030e+004	1.4927e+003	-6.5813e+003	6.6172e-001	2.3407e-001
-4.5000e+001	1.2802e+004	2.7980e+003	6.5813e+003	6.6172e-001	6.2684e-002
-4.5000e+001	-5.4131e+003	4.1553e+003	5.6051e+003	7.7478e-001	4.1061e-002
0	1.4635e+005	-1.9911e+003	1.9878e+003	7.7188e-001	7.7188e-001
0	1.3224e+005	-8.0010e+002	3.1695e+003	6.9583e-001	6.9583e-001
0	1.3224e+005	-8.0010e+002	3.1695e+003	6.9583e-001	6.9583e-001
0	1.1813e+005	3.9088e+002	4.3511e+003	6.1979e-001	6.1979e-001

14. Appendix B – Additional Figures

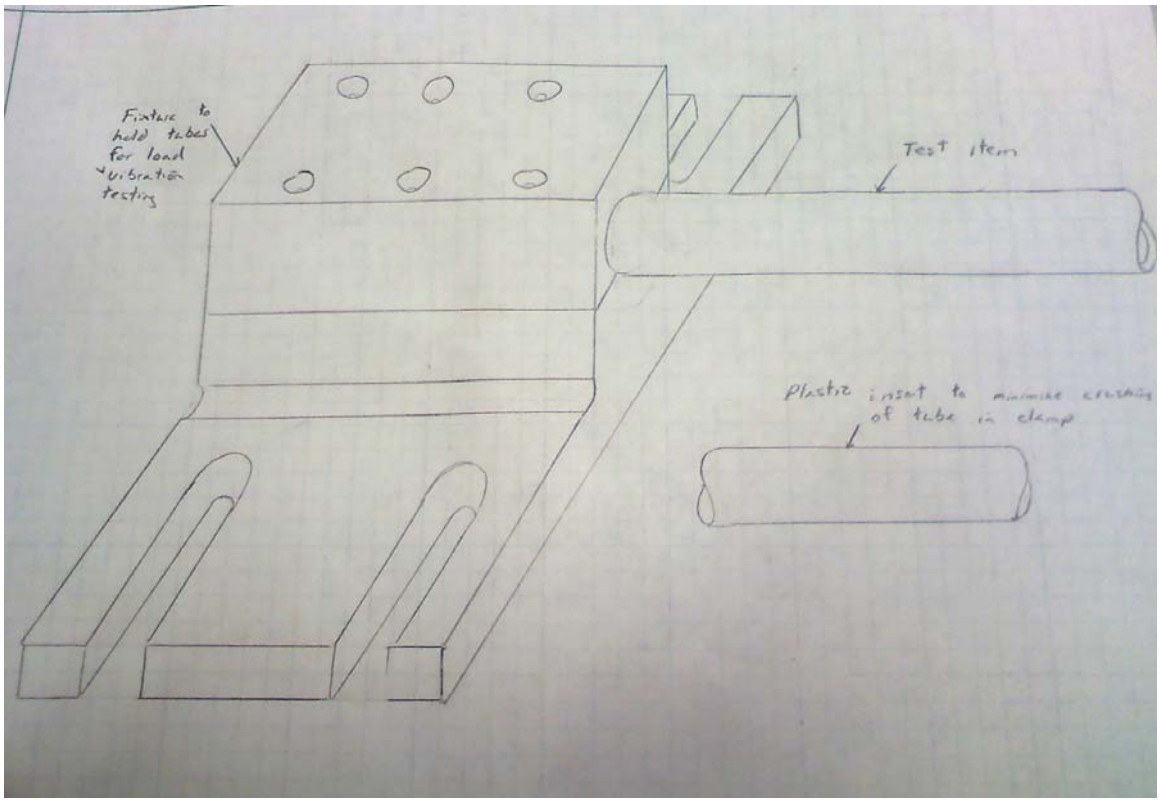


Figure 11: Initial test fixture design. Changes were made to reduce machining time and save material costs.

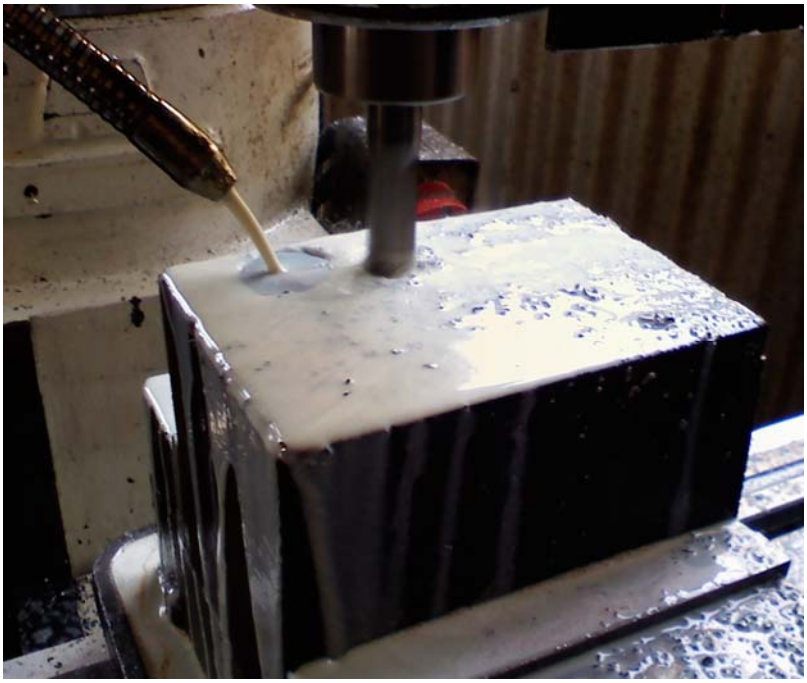


Figure 12: Squaring the steel block to be used for the vibrations fixture. This ensures parallel surfaces so the spar is level during testing

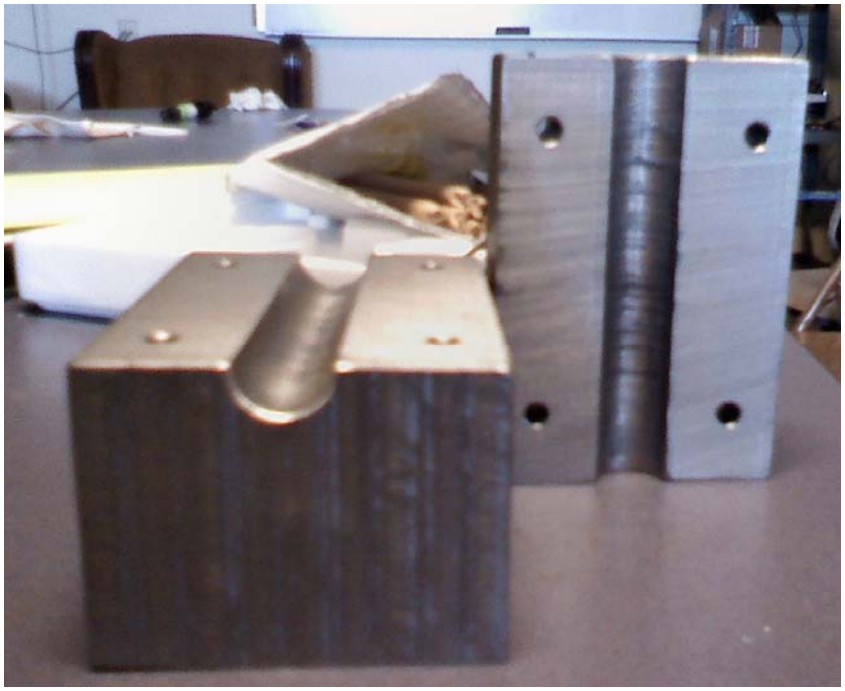


Figure 13: Sectioned view of both halves of the fixture. Note the channel for the spar and 4 bolt holes. This was later welded to a steel base.

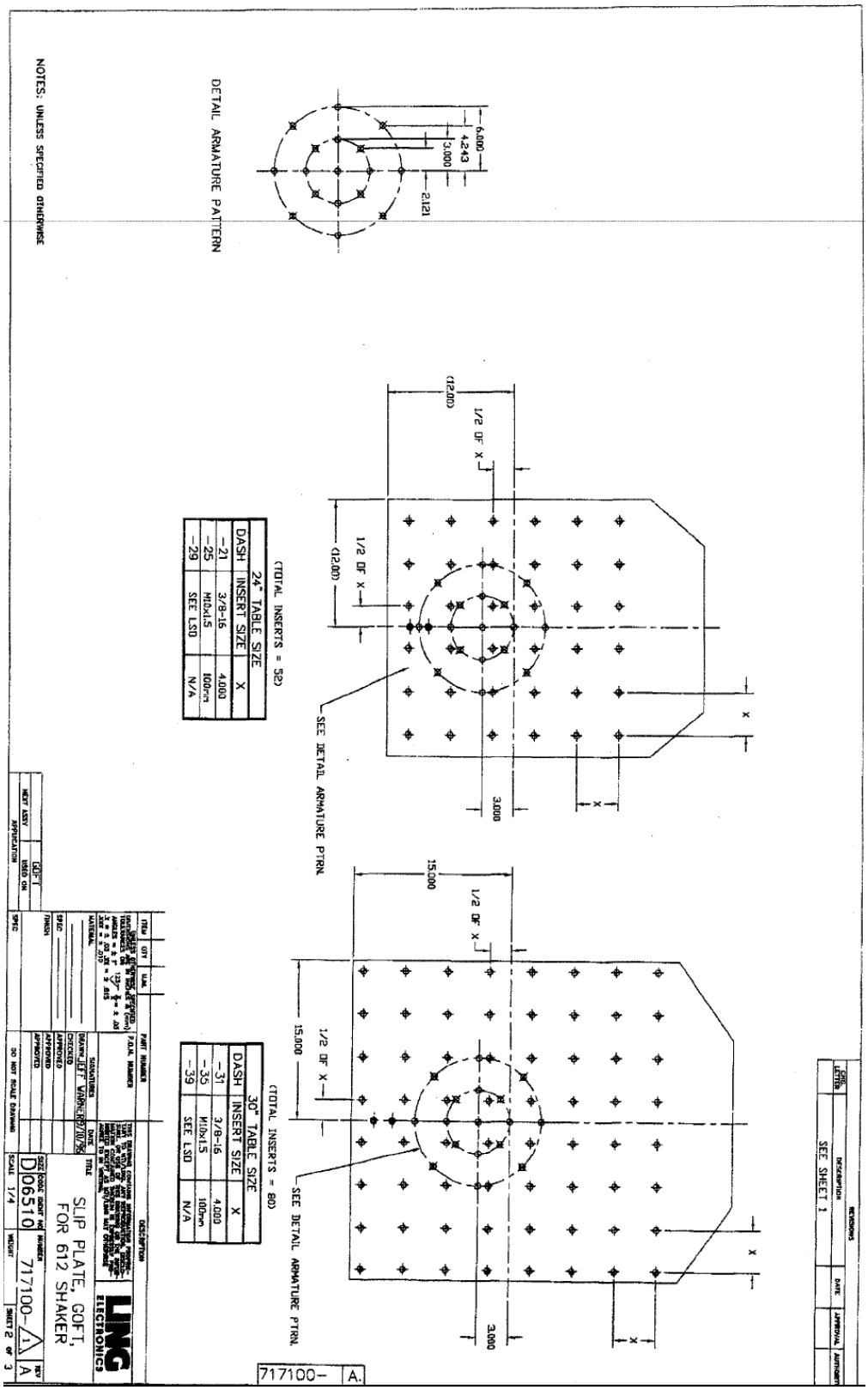


Figure 14: Bolt pattern of the top surface of the vibrations shake table. This was followed in drilling mounting holes on the base of the vibrations fixture

15. Appendix C – Data Sheets

Endevco

Model 258A
Isotron® accelerometer

Features

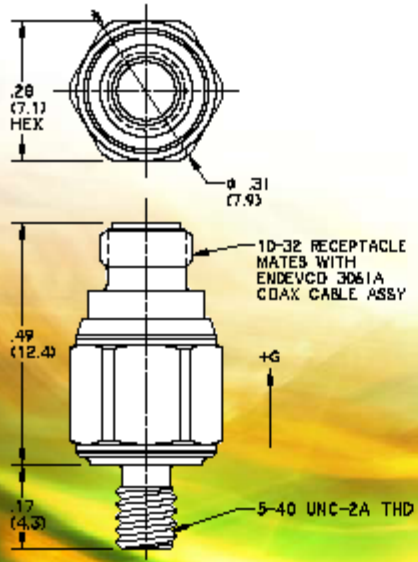
- Low Cost, High Performance
- Standard 10-32 Connector
- Light Weight (1.9 gm)
- Hermetically Sealed
- Milli-g's Resolution
- Flat to 15 kHz
- Titanium Housing

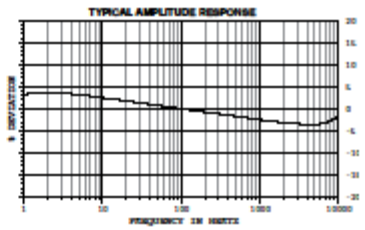
Description

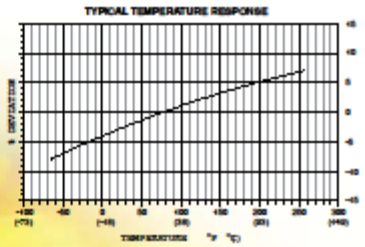
Endevco® model 258A is a very small piezoelectric accelerometer with integral electronics, designed specifically for making structural and vibration measurements. The transducer is designed for stud mounting, utilizing a 5-40 integral stud. The hermetically sealed top connector and welded housing provide long-term reliability even in harsh environments. Its light weight (1.9 gm) effectively minimizes mass loading effects.

Model 258A features Endevco's unique Piezite® Type P-8 crystal element, operating in annular shear mode, exhibits excellent thermal transient stability. This accelerometer uses a built-in low noise microelectronic amplifier which transmits its low impedance voltage output through the same two-wire cable that supplies the required constant current power. Model 258A has an output sensitivity of 10 mV/g or 100 mV/g.

Endevco Signal Conditioner Models 44148, 133, 27928, 2793, 27788 or Oasis 2000 Computer-Controlled System are recommended for use with this accelerometer.







MEGGITT
smart engineering for extreme environments

Figure 15: Manufacturer data sheet for accelerometers used.

T700/LS-930 Epoxy Material for Project Three

Material Form	Unidirectional Tape
Width (in)	12
Ply Thickness (in)	0.0056

Property	Value	where from?
E1 (msi)	17	student measurements
E2 (msi)	0.98	micromechanics
G12 (msi)	0.42	micromechanics
nu12	0.31	micromechanics
F1t (ksi)	250-280	student measurements

Figure 16: Manufacturer information for T700 pre-impregnated carbon fiber

Surface Preparation for Strain Gage Bonding

1.0 Introduction

Strain gages can be satisfactorily bonded to almost any solid material if the material surface is *properly* prepared. While a properly prepared surface can be achieved in more than one way, the specific procedures and techniques described here offer a number of advantages. To begin with, they constitute a carefully developed and thoroughly proven system; and, when the instructions are followed precisely (along with those for gage and adhesive handling), the consistent result will be strong stable bonds. The procedures are simple to learn, easy to perform, and readily reproducible. Furthermore, the surface preparation materials used in these procedures are, unless otherwise noted, generally low in toxicity, and do not require special ventilation systems or other stringent safety measures. Of course, as with any materials containing solvents or producing vapors, adequate ventilation is necessary.

The importance of attention to detail, and precise adherence to instructions, cannot be overstressed in surface preparation for strain gage bonding. Less thorough, or even casual, approaches to surface preparation may sometimes yield satisfactory gage installations; but for *consistent* success in achieving high-quality bonds, the methods given here can be recommended without qualification. Fundamental to the Micro-Measurements system of surface preparation is an understanding of *cleanliness* and *contamination*. All open surfaces not thoroughly and freshly cleaned must be considered contaminated, and require cleaning immediately prior to gage bonding. Similarly, it is imperative that the materials used in the surface preparation be fresh, clean, and uncontaminated. It is worth noting that strain gages as received from Micro-Measurements are chemically clean, and specially treated on the underside to promote adhesion. Simply touching the gages with the fingers (which are always contaminated) can be detrimental to bond quality.

The Micro-Measurements system of surface preparation includes five basic operations. These are, in the usual order of execution:

1. *Solvent degreasing*
2. *Abrading (dry and wet)*
3. *Application of gage layout lines*
4. *Conditioning*
5. *Neutralizing*

These five operations are varied and modified for compatibility with different test material properties, and exceptions are introduced as appropriate for certain special materials and situations.

The surface preparation operations are described individually in ***Section 2.0***, following a summary of the general principles applicable to the entire process. ***Section 3.0*** discusses special precautions and considerations which should be borne in mind when working with unusual materials and/or surface conditions.

The various surface preparation and installation accessories referred to throughout this Application Note are Micro-Measurements Accessories, listed in Strain Gage Accessories Data Book and available directly from Micro-Measurements.

As a convenience to the gage installer in quickly determining the specific surface preparation steps applicable to any particular test material, ***Section 4.0*** includes a chart listing approximately 75 common (and uncommon) materials and the corresponding surface preparation treatments.

2.0 Basic Surface Preparation Operations and Techniques

2.1 General Principles of Surface Preparation for Strain Gage Bonding

The purpose of surface preparation is to develop a chemically clean surface having a roughness appropriate to the gage installation requirements, a surface alkalinity corresponding to a pH of 7 or so, and visible gage layout lines for locating and orienting the strain gage. It is toward this purpose that the operations described here are directed.

As noted earlier, cleanliness is vital throughout the surface preparation process. It is also important to guard against recontamination of a once-cleaned surface. Following are several examples of surface recontamination to be avoided:

a. Touching the cleaned surface with the fingers.
b. Wiping back and forth with a gauze sponge, or reusing a once-used surface of the sponge (or of a cotton swab).
c. Dragging contaminants into the cleaned area from the uncleaned boundary of that area.
d. Allowing a cleaning solution to evaporate on the surface.
e. Allowing a cleaned surface to sit for more than a few minutes before gage installation, or allowing a partially prepared surface to sit between steps in the cleaning procedure.

Beyond the above, it is good practice to approach the surface preparation task with freshly washed hands, and to wash hands as needed during the procedure.

2.2 Solvent Degreasing

Degreasing is performed to remove oils, greases, organic contaminants, and soluable chemical residues. Degreasing should always be the first operation. This is to avoid having subsequent abrading operations drive surface contaminants into the surface material. Porous materials such as titanium,

cast iron, and cast aluminum may require heating to drive off absorbed hydrocarbons or other liquids.
Degreasing can be accomplished using a hot vapor degreaser, an ultrasonically agitated liquid bath, aerosol type spray cans of CSM-2 Degreaser, or wiping with GC-6 Isopropyl Alcohol. One-way applicators, such as the aerosol type, of cleaning solvents are always preferable because dissolved contaminants cannot be carried back into the parent solvent. Whenever possible, the entire test piece should be degreased. In the case of large bulky objects which cannot be completely degreased, an area covering 4 to 6 in [100 to 150mm] on all sides of the gage area should be cleaned. This will minimize the chance of contamination in subsequent operations, and will provide an area adequately large for applying protective coatings in the final stage of gage installation.

2.3 Surface Abrading

General — In preparation for gage installation, the surface is abraded to remove any loosely bonded adherents (scale, rust, paint, galvanized coatings, oxides, etc.), and to develop a surface texture suitable for bonding. The abrading operation can be performed in a variety of ways, depending upon the initial condition of the surface and the desired finish for gage installation. For rough or coarse surfaces, it may be necessary to start with a grinder, disc sander, or file. (***Note:*** *Before performing any abrading operations, see* ***Section 3.1*** *for safety precautions*.) Finish abrading is done with silicon-carbide paper of the appropriate grit, and recommended grit sizes for specific materials are given in ***Section 4.0***.
If grit blasting is used instead of abrading, either clean alumina or silica (100 to 400 grit) is satisfactory. In any case, the air supply should be well filtered to remove oil and other contaminant vapors coming from the air compressor.
The grit used in blasting should not be recycled or used again in surface preparation for bonding strain gages.
The optimum surface finish for gage bonding depends somewhat upon the nature and purpose of the installation. For general stress analysis applications, a relatively smooth surface (in the order of 100µin [2.5µm] rms) is suitable, and has the advantage over rougher surfaces that it can be cleaned more easily and thoroughly. Smoother surfaces, compatible with the thin "gluelines" required for minimum creep, are used for transducer installations. In contrast, when very high elongations must be measured, a rougher (and preferably cross-hatched) surface should be prepared. The recommended surface finishes for several classes of gage installations are summarized in Table I, below.

TABLE I

CLASS OF INSTALLATION	SURFACE FINISH, rms	
	min	mm
General stress analysis	63-125	1.6-3.2
High elongation	>250	>6.4
	cross-hatched	
Transducers	16-63	0.4-1.6

Wet Abrading — Whenever *M-Prep* Conditioner A is compatible with the test material (see ***Section 4.0***), the abrading should be done while keeping the surface wet with this solution, if physically practicable. Conditioner A is a mildly acidic solution which generally accelerates the cleaning process and, on some materials, acts as a gentle etchant. It is not recommended for use on magnesium, synthetic rubber, or wood.

2.4 Gage-Location Layout Lines

The normal method of accurately locating and orienting a strain gage on the test surface is to first mark the surface with a pair of crossed reference lines at the point where the strain measurement is to be made. The lines are made perpendicular to one another, with one line oriented in the direction of strain measurement. The gage is then installed so that the triangular index marks defining the longitudinal and transverse axes of the grid are aligned with the reference lines on the test surface.
The reference, or layout, lines should be made with a tool that *burnishes*, rather than scores or scribes, the surface. A scribed line may raise a burr or create a stress concentration. In either case, such a line can be detrimental to strain gage performance and to the fatigue life of the test part. On aluminum and most other nonferrous alloys, a 4H drafting pencil is a satisfactory and convenient burnishing tool. However, graphite pencils should never be used on high temperature alloys, where the operating temperature might cause a carbon embrittlement problem. On these and other hard alloys, burnished alignment marks can be made with a ballpoint pen or a round-pointed brass rod. Layout lines are ordinarily applied following the abrading operation and before final cleaning. All residue from the burnishing operation should be removed by scrubbing with Conditioner A as described in the following section.

2.5 Surface Conditioning

After the layout lines are marked, Conditioner A should be applied repeatedly, and the surface scrubbed with cotton tipped applicators until a clean tip is no longer discolored by the scrubbing. During this process the surface should be kept constantly wet with Conditioner A until the cleaning is completed. *Cleaning solutions should never be allowed to dry on the surface*. When clean, the surface should be dried by wiping through the cleaned area with a single slow stroke of a gauze sponge. The stroke should begin inside

the cleaned area to avoid dragging contaminants in from the boundary of the area. Then, with a fresh sponge, a single slow stroke is made in the opposite direction. The sponge should never be wiped back and forth, since this may redeposit the contaminants on the cleaned surface.

2.6 Neutralizing

The final step in surface preparation is to bring the surface condition back to an optimum alkalinity of 7.0 to 7.5pH, which is suitable for all Micro-Measurements strain gage adhesive systems. This should be done by liberally applying *M-Prep* Neutralizer 5A to the cleaned surface, and scrubbing the surface with a clean cotton-tipped applicator. The cleaned surface should be kept completely wet with Neutralizer 5A throughout this operation. When neutralized, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a clean gauze sponge. With a fresh sponge, a *single* stroke should then be made in the opposite direction, beginning with the cleaned area to avoid recontamination from the uncleaned boundary.
If the foregoing instructions are followed precisely, the surface is now properly prepared for gage bonding, and the gage or gages should be installed as soon as possible.

3.0 Special Precautions and Considerations

3.1 Safety Precautions

As in any technical activity, safety should always be a prime consideration in surface preparation for strain gage bonding. For example, when grinding, disc sanding, or filing, the operator should wear safety glasses and take such other safety precautions as specified by his organization or by the Occupational Safety and Health Administration (OSHA).
When dealing with toxic materials such as beryllium, lead, uranium, plutonium, etc., all procedures and safety measures should be approved by the safety officer of the establishment before commencing surface preparation.

3.2 Surfaces Requiring Special Treatment

Concrete — Concrete surfaces are usually uneven, rough, and porous. In order to develop a proper substrate for gage bonding, it is necessary to apply a leveling and sealing precoat of epoxy adhesive to the concrete. Before applying the precoat, the concrete surface must be prepared by a procedure which accounts for the porosity of this material. Contamination from oils, greases, plant growth, and other soils should be removed by vigorous scrubbing with a stiff-bristled brush and a mild detergent solution. The surface is then rinsed with clean water. Surface irregularities can be removed by wire brushing, disc sanding, or grit blasting, after which all loose dust should be blown or brushed from the surface.
The next step is to apply Conditioner A generously to the surface in and around the gaging area, and scrub the area with a stiff-bristled brush. Contaminated Conditioner A should be blotted with gauze sponges, and then the surface should be rinsed thoroughly with clean water. Following the water rinse, the surface acidity must be reduced by scrubbing with Neutralizer 5A, blotting with gauze sponges, and rinsing with water. A final thorough rinse with distilled water is useful to remove the residual traces of water-soluble cleaning solutions. Before precoating, the cleaned surface must be thoroughly dried. Warming the surface gently with a propane torch or electric heat gun will hasten evaporation.
Micro-Measurements M-Bond AE-10 room-temperature-curing epoxy adhesive is an ideal material for precoating the concrete. For those cases in which the test temperature may exceed the specified maximum operating temperature of AE-10 (+200°F [+95°C]), it will be necessary to fill the surface with a higher temperature resin system such as M-Bond GA-61.
In applying the coating to the porous material, the adhesive should be worked into any voids, and leveled to form a smooth surface. When the adhesive is completely cured, it should be abraded until the base material begins to be exposed again. Following this, the epoxy surface is cleaned and prepared conventionally, according to the procedure specified in ***Section 4.0*** for bonding gages to epoxies.
Plated Surfaces — In general, plated surfaces are detrimental to strain gage stability, and it is preferable to remove the plating at the gage location, if this is permissible. Cadmium and nickel plating are particularly subject to creep, and even harder platings may creep because of the imperfect bond between the plating and the base metal. When it is not permissible to remove the plating, the surface should be prepared according to the procedure given in ***Section 4.0*** for the specific plating involved. Note that it may be necessary to adjust testing procedures to minimize the effects of creep.
Use of Solvents on Plastics — Plastics vary widely in their reactivity to solvents such as those employed in the surface preparation procedures described here. Before applying a solvent to any plastic, ***Section 4.0***, which includes most common plastics, should be referred to for the recommended compatible solvent. For plastics not listed in ***Section 4.0***, the manufacturer of the material should be consulted, or tests should be performed to verify nonreactivity between the solvent and the plastic.
Dimensional or Mechanical Changes Due to Surface Preparation— For most materials, strain measurement results are usually not significantly changed by the surface preparation procedures described in this Application Note. Even with appreciable material removal, effects on the static mechanical properties of the test part are generally negligible compared to other error sources in the experiment. It

should be understood, however, that removal of a plated or hardened surface layer, or of a surface layer with significant residual stresses, may noticeably affect the fatigue life or the wear characteristics of the part when operated under dynamic service conditions.

Silicone Contamination —The properties of silicones which make them excellent lubricants and mold-release agents also make them the enemies of adhesion, and therefore potentially the most serious of contaminants to be encountered in the practice of bonding strain gages. The problem is compounded by the high natural affinity of the silicones for most materials, and by their tendency to migrate. Furthermore, since silicones are relatively inert chemically, and unaffected by most solvents, they are among the most difficult surface contaminants to remove. The best practice is to keep the gage-bonding area free of silicones. This may not be as easy as it sounds, since the widely used silicones can be introduced from a variety of sources. For instance, many hand creams and cosmetics contain silicones, and these should not be used by persons involved in gage installation. Some of the machining lubricants also contain silicones, and such lubricants should be avoided when machining parts that are to have strain gages installed. Similarly, silicone-saturated cleaning tissues for eyeglasses should not be used in the gage-bonding area or by gage-installation personnel.

Regardless of efforts to avoid silicones, contamination may still occur. Light contamination can sometimes be removed by cleaning with Conditioner A, preferably heated to +200°F [+95°C]. More severe cases may require special cleaning solutions and procedures, recommendations for which should be obtained from the manufacturer of the silicone compound involved in the contamination.

4.0 Index of Test Materials and Surface Preparation Procedures

In this section, the specific step-by-step surface preparation procedures are given for approximately 75 different materials. For compactness, and convenient, quick access to the procedure for any particular material, the information is presented in chart form in Table II. The test materials are listed alphabetically, from ABS Plastics to Zirconium; and the complete procedure for each material is defined by one or more digits in each of the applicable operations columns of the table. Each digit identifies the required operation and specifies the step number for that operation in the complete procedure.

For example, assume that the necessity arises for bonding one or more strain gages to a brass test specimen. Reading down the *Specimen Material* column of Table II to Brass, and following that row across the table to the right, the first step in surface preparation consists of degreasing the specimen with CSM-2 Degreaser. The symbol (1) in the *Isopropyl Alcohol* column indicates that this is a suitable substitute degreasing operation. Continuing across the row, the second operation calls for abrading the specimen surface with 320-grit silicon-carbide paper. In the third operation the specimen is reabraded with 400-grit silicon-carbide paper, wet lapping with Conditioner A if feasible. The fourth and fifth operations consist of applying layout lines for locating the gages, and scrubbing the surface clean with Conditioner A. Cleaning with isopropyl alcohol is the final operation in the procedure.

In the *Remarks* column, it is recommended that the gages be installed within 20 minutes after completing the surface preparation, because the freshly bared brass surface tends to oxidize rapidly. In addition, in the *Grit Blast* column, the gage installer is specifically advised not to substitute grit blasting for other surface abrading methods, in order to avoid significantly altering the surface condition of this relatively soft material. Surface preparation procedures for other materials are defined similarly in the table, and, in many cases, accompanied by special warnings or recommendations in the *Remarks* column. When an operation not included in the first ten column headings is required, it is indexed in the *Other* column, with an arrow pointing to the *Remarks* column where the operation is specified.

Additional References

For additional information, refer to Instruction Bulletins listed below:

B-127, "Strain Gage Installations with M-Bond 200 Adhesive".

B-130, "Strain Gage Installations with M-Bond 43-B, 600, and 610 Adhesives".

B-137, "Strain Gage Applications with M-Bond AE-10, AE-15, and GA-2 Adhesive Systems".

Important Notice

The procedures, operations, and chemical agents recommended in this Application Note are, to the best knowledge of Micro-Measurements, reliable and fit for the purposes for which recommended. This information on surface preparation for strain gage bonding is presented in good faith as an aid to the strain gage installer; but no warranty, expressed or implied, is given, nor shall Micro-Measurements be liable for any injury, loss, or damage, direct or consequential, connected with the use of the information. Before applying the procedures to any material, the user is urged to carefully review the application with respect to human health and safety, and to environmental quality

TABLE II

Index of Test Materials and Surface Preparation Procedures (Sheet 1 of 3)

See Section:	2.2		2.3					2.4	2.5	2.6	
SPECIMEN MATERIAL	CSM-2 DEGREASER	GC-6 ISOPROPYL ALCOHOL	GRIT-BLAST†	220-GRIT ABRASIVE PAPER	320-GRIT ABRASIVE PAPER	400-GRIT ABRASIVE PAPER††	GAGE LOCATION LAYOUT	CONDITIONER A (SCRUB)	NEUTRALIZER 5A	OTHER	REMARKS
ABS PLASTICS		1	No			2	3	4	5		ABS plastics may be affected by ketones, esters, aromatics, and chlorinated hydrocarbons.
ACRYLICS		1				2	3	4	5		Acrylics may be affected by ketones, esters, aromatics, and chlorinated hydrocarbons.
ALUMINUM, ALCLAD	1					2	3	4	5		Alclad coating must be removed prior to gage installation by abrading with 180-grit or 220-grit silicon-carbide paper. Test for completeness of Alclad removal: (a) swab area with 10% sodium hydroxide solution - area will darken within 60 sec if cladding is completely removed; (b) neutralize surface with Conditioner A; (c) flush area with distilled water. Proceed with surface preparation as specified at left.
ALUMINUM, ANODIZED	1					2	3	4	5		Black or colored anodizing must be removed prior to gage installation. Use nonchlorinated household cleaner to strip sealer. Clear anodized surface acceptable for elastic strain level only.
ALUMINUM, CASTINGS	1		(2)	(2)	2	3	4	5	6		Gages should be bonded within 30 min after final surface preparation.
ALUMINUM, WROUGHT	1		(2)		2	3	4	5	6		Gages should be bonded within 30 min after final surface preparation.
ANTIMONY		1	No			2	3	4	5		
ASPHALT		1	No				3		4	2	Often necessary to grind, disc sand, or file surface.
BERYLLIUM	1		No				3	4	5	2	Obtain safety department approval for surface removal. Abraded particles must be kept wet to prevent becoming airborne, and must be properly disposed of. Some individuals may develop allergic reaction. Gloves should be worn.
BERYLLIUM COPPER	1*	(1)*				3	4	5	6	2	Obtain safety department approval for surface removal. Abraded particles must be kept wet to prevent becoming airborne, and must be properly disposed of. Some individuals may develop allergic reaction.
BISMUTH		1	No			2	3	4	5		
BONE		(3)								1,2,3	Clean with ether under proper ventilation, then scrape surface, and redry with ether.
BORON-EPOXY COMPOSITES		1,5*	No			2	3	4	(5*)	(2)	Scrub with a slurry of pumice powder and Conditioner A.
BRASS	1	(1)	No		2	3	4	5**			Install gages within 20 min of final surface preparation.
BRICK		1,3*							4*	2	Wire-brush or disc-sand, and remove dust with dry paint brush. Fill and seal surface with epoxy adhesive, such as Micro-Measurements AE-10, and sand smooth after adhesive is cured.
BRONZE	1	(1)			2	3	4	5**			Install gages within 20 min of final surface preparation.
CADMIUM PLATE	1	(1)	No		2	3	4	5	6		Cadmium plating has a tendency to creep, and the plating should be removed if permissible.
CARBON (see GRAPHITE)											
CERAMICS		1*			2		3	4	5*		
CHROMIUM PLATE	1	(1)			2		3	4	5		Chromium plating should be removed at gage installation site if permissible.
CONCRETE										1	See Concrete Section 3.2 in text.
COPPER AND COPPER-BASED ALLOYS	1	(1)	No		2	3	4	5**	No		Install gages within 20 min after final surface preparation.

SPECIAL NOTES
* Heating specimen will help drive out oils, moisture, and solvent.
** Rinse with distilled water, and wipe dry.
† Use clean (filtered), dry air. Do not recycle alumina or silica grits.
†† Wet lap with Conditioner A when compatibility is indicated by "Conditioner A (Scrub)" column.
( ) Parentheses indicate alternate step(s).

Index of Test Materials and Surface Preparation Procedures (Sheet 2 of 3)

See Section:	2.2			2.3				2.4	2.5	2.6	
SPECIMEN MATERIAL	CSM-2 DEGREASER	GC-6 ISOPROPYL ALCOHOL	GRIT-BLAST†	220-GRIT ABRASIVE PAPER	320-GRIT ABRASIVE PAPER	400-GRIT ABRASIVE PAPER††	GAGE LOCATION LAYOUT	CONDITIONER A (SCRUB)	NEUTRALIZER 5A	OTHER	REMARKS
ENAMEL PAINTS						2	3		4	1	Paint is normally removed for gage installation. Baked enamels may be left on surface if essential to test.
EPOXIES	1	(1)			2		3	(3)	4		Surface may require several initial cleanings with Conditioner A if silicones are present.
FIBERGLASS LAMINATES		1				2	3	4	5*		Coarser abrasive may be necessary in Step 2 to remove all surface gloss.
GRAPHITE AND GRAPHITE COMPOSITES		1, 3, 5*				2	4		(5*)		
GLASS	1	(1)	No					2	3		Abrasion not usually necessary. Engineering approval for abrading is generally required.
GOLD	1	(1)					2		3		
INCONEL	1		2	(2a)	(2b)		3	4	5		Repeat Steps 4 and 5 if gages cannot be installed within 45 min.
INDIUM	1						2		3		
INVAR	1		2	(2a)	(2b)		3	4	5		Repeat Steps 4 and 5 if gages cannot be installed within 45 min.
IRON, CAST, OR WROUGHT	1*		2	(2a)	(2b)		3	4	5		Repeat Steps 2 through 5 if gages cannot be installed within 30 min.
ISOELASTIC	1		No		2		3	4	5		Repeat Steps 4 and 5 if gages cannot be installed within 45 min.
KAPTON	1	(1)	(2)			2	3		4		
LEAD		1	No		2		3	4	5		
MAGNESIUM	1	(1)					3	No	4	2	Do not abrade magnesium (i.e., avoid producing fine particles). Scrape gage site with deburring knife or file. Do not use Conditioner A on magnesium.
MANGANIN	1	(1),5				2	3	4			
MASONRY		1,4*					3	5	6	2	Wire-brush or disc-sand, and remove dust with dry paint brush. Fill and seal surface with epoxy adhesive, such as AE-10, and sand smooth after adhesive is cured.
MODELTECH® (aluminum-filled cast epoxy)		1				2	3	4	5		
MOLYBDENUM	1	(1)			2		3	4	5		
MONEL	1	(1)			2		3	4	5		
MYLAR		1	(2)			2	3		4		
NICHROME	1	(1)	(2)		2		3	4	5		
NICKEL AND NICKEL PLATE	1	(1)			2		3	4	5		If permissible, nickel plating should be removed at gage installation site.
NI-SPAN C	1	(1)	(2)		2		3	4	5		
NYLON		1	(2)			2	3		4		
PHENOLIC COMPOSITES		1,5*				2	3	4	(5*)		Step 2 may require coarser abrasive to remove all surface gloss.
PHOSPHOR BRONZE	1	(6**)			2	3	4	5**			
PLATINUM							2	3	4		

SPECIAL NOTES

* Heating specimen will help drive out oils, moisture, and solvent.
** Rinse with distilled water, and wipe dry.
† Use clean (filtered), dry air. Do not recycle alumina or silica grits.
†† Wet lap with Conditioner A when compatibility is indicated by "Conditioner A (Scrub)" column.
( ) Parentheses indicate alternate step(s).

Index of Test Materials and Surface Preparation Procedures (Sheet 3 of 3)

See Section:	2.2			2.3				2.4	2.5	2.6	
SPECIMEN MATERIAL	CSM-2 DEGREASER	GC-6 ISOPROPYL ALCOHOL	GRIT-BLAST†	220-GRIT ABRASIVE PAPER	320-GRIT ABRASIVE PAPER	400-GRIT ABRASIVE PAPER††	GAGE LOCATION LAYOUT	CONDITIONER A (SCRUB)	NEUTRALIZER 5A	OTHER	REMARKS
PLUTONIUM		1					3	4	5	2	Should be electroplated with nickel before gage installation. Contact Vishay Micro-Measurements Applications Engineering Department for specific instructions.
POLYCARBONATES		1	No			2	3	4	5		
POLYETHYLENE		1				(2)	3	No	4	2	Scour with household cleanser and rinse with water, or flame-burnish surface.
POLYURETHANE		1				2	3		4		
POLYVINYL CHLORIDE		1				(2)	3		4	2	Scour with household cleanser and rinse with water.
PORCELAIN	1							2	3		
QUARTZ	1							2	3		
RENE 41	1		(2)		2		3	4	5		
RUBBER, NATURAL OR SYNTHETIC		1			2		3		4	(2)	Scour with household cleanser and rinse with water.
SILVER	1						3		4	2	Scrub with slurry of pumice powder and isopropyl alcohol.
SINTERED METALS	1				2	3	4	5*	6*	(1)	Hot-vapor degrease.
STEEL (Carbon and Stainless)	1		2	(2a)	(2b)		3	4	5		Repeat Steps 4 and 5 if gages cannot be bonded within 45 min of final surface preparation.
STEEL, 4000 SERIES	1		(2)	2			3	No	4		Conditioner A tends to produce black residue on surface.
STEEL, SURFACE HARDENED	1						2	3,4	5		Removal of surface material may alter residual stress conditions and/or fatigue life and wear resistance.
STONE		2*						3	4	1	Wire-brush, grind, or disc-sand, and dust surface with dry paint brush. Fill and seal surface with epoxy adhesive, such as AE-10, and sand smooth after adhesive is cured.
TANTALUM	1	(1)				2	3	4	5		
TEFLON	1	(1)					3		4	2	Etch surface with Tetra-Etch, rinse with isopropyl alcohol, then with water.
TIN	1	(1)				2	3	4	5		
TITANIUM		1	2		(2)		3	4	5		It may be necessary to heat-cycle the specimen two or three times to +350°F [+175°C] as initial step in surface preparation. Halogens should never be used for degreasing if the specimen is to be tested at temperatures above +700°F [+370°C]. Install gages within 10 min of final surface preparation.
TITANIUM SILICATE	1	(1)		2			3	4	5		
TUNGSTEN CARBIDE	1	(1)		2			3	4	5		
URANIUM		1	No				3	4	5	2	Should be electroplated with nickel before gage installation. Contact Vishay Micro-Measurements Applications Engineering Department for specific instructions.
WOOD			No	(2)	2		3			1	It may be necessary to kiln-dry wood of more than 20% moisture content. After abrasion, dust surface with dry paint brush.
ZINC		1	No		2		3	4	5		
ZIRCONIUM	1	(1)			2		3	4	5		It may be necessary to repeat Step 5 until proper surface pH is achieved.

SPECIAL NOTES

* Heating specimen will help drive out oils, moisture, and solvent.
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† Use clean (filtered), dry air. Do not recycle alumina or silica grits.
†† Wet lap with Conditioner A when compatibility is indicated by "Conditioner A (Scrub)" column.
( ) Parentheses indicate alternate step(s).