ASEN 2001 Lab 3: Composite Beam Bending – Fall 2016

1. Summary

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

This lab is motivated by the increased interest in small, unmanned airplanes. The wings of these aircraft are often made of a foam core covered either by balsa wood or glass/carbon fiber reinforced epoxy layer. Despite the seemingly simple architecture of these wings, predicting the failure and properly designing such wings is not trivial (as previous senior design teams have experienced).

This lab will provide a first exposure to the analysis and design of composite beams. You will be provided with information on the strength of a balsa wood – foam-core test specimen. Based on these strength predictions you will design, optimize and fabricate a foam-core wing for aerodynamic loading conditions. The performance of the optimized wing will be experimentally tested simulating the aerodynamic wing loading via a so-called wiffle-tree.

2. Logistics

Group assignments are available on D2L. Schedules for use of the composite fabrication lab and the experimental test hardware will also be provided. When your group is not fabricating the wing, you should develop analysis and design tools.

Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
October 31 Lab 3 starts; lab description and data analysis	November 1 Lecture	November 2	November 3 Unit Exam 3	November 4
November 7 Fabrication of wing composite structure	November 8 Lecture	November 9	November 10 Lecture	November 11
November 14 Wing design and fabrication	November 15 Lecture	November 16	November 17 Lecture	November 18
November 21 **Thanksgiving break**	November 22 **Thanksgiving break**	November 23 **Thanksgiving break**	November 24 **Thanksgiving break**	November 25 **Thanksgiving break**
November 28 Wing testing	November 29 Lecture	November 30	December 1 Lecture	December 2
December 5 Finalize	December 6 Lecture	December 7	December 8 Lecture	December 9 **Lab 3 report due at 7:00 am**

Due to limitations in fabrication facilities and experimental hardware it is important that your group closely follows this schedule.

Before testing the wing, you will have to present a test plan to an instructor or a TA. The test plan should include a detailed analysis of the structural response during test and in particular a prediction when failure is expected. While the presentation of the test plan is informal, a clear and concise presentation of the analysis is required.

This combined experimental and design lab assignment will involve a number of analytical and testing tasks which should be evenly distributed amongst the team members. Clear communication within the group as to individual responsibilities throughout the lab will be critical to a successful team effort.

The deliverable of this lab is a group report, which is due December 9, 7:00 am. An electronic copy needs to be uploaded to D2L (No hardcopies will be accepted).

3. Composite Beam

In this lab we will consider a rather simple layout of a composite beam which is representative for more complex architectures. As shown in Figure 1a, the layout studied in this lab consists of a ¾" thick foam core sandwiched between two layers of 1/32" balsa wood sheets. The balsa sheets are glued to the foam core using *Gorilla Glue*®. The foam is "blue" Extruded Polystyrene (EP) with a minimum density of 1.30 pounds per cubic foot.

To experimentally determine the strength of this layout a number of simple 36" x 2" test specimens (see Figure 1b) were fabricated and tested. These data are provided to you in a spreadsheet posted on D2L. Based on the strength test results you will design, fabricate, and test a wing-type structure. You will optimize the plan form of the wing which can be cut from 36" x 4" composite plate (see Figure 1c).

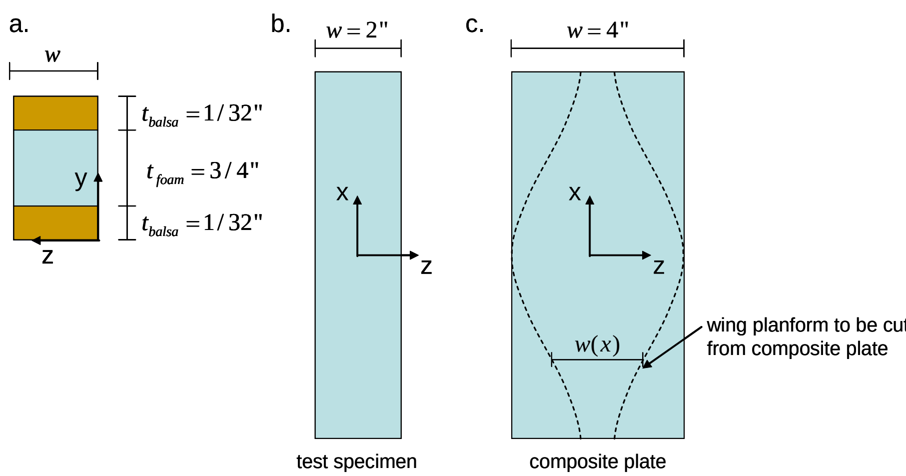

Figure 1: Composite beam configurations

Note: At the beginning of this lab, you will first fabricate the 36" x 4" composite plate in the Composite Fabrication Lab. The final planform shape of the wing will be cut from this 36" x 4" composite plate.

4. Strength Test of Specimen

The combination of balsa wood and PE foam provides surprisingly high strength at low material and fabrication costs. However, the material properties of both may significantly vary. While tabulated data may be useful to get a rough idea when failure may occur, experimental testing is needed to establish reliable strength data. This testing has already been completed for you, and results are provided.

Composite beams are typically tested in either a 3-point or 4-point loading-support configuration shown in Figure 3. For this lab, testing was done using only the 4-point configuration. During the test, the load *F* was slowly increased until the specimen failed. Using proper analysis and assuming a linear elastic response of the material up to failure, the strength of the composite beam can be extracted from the experimental results.

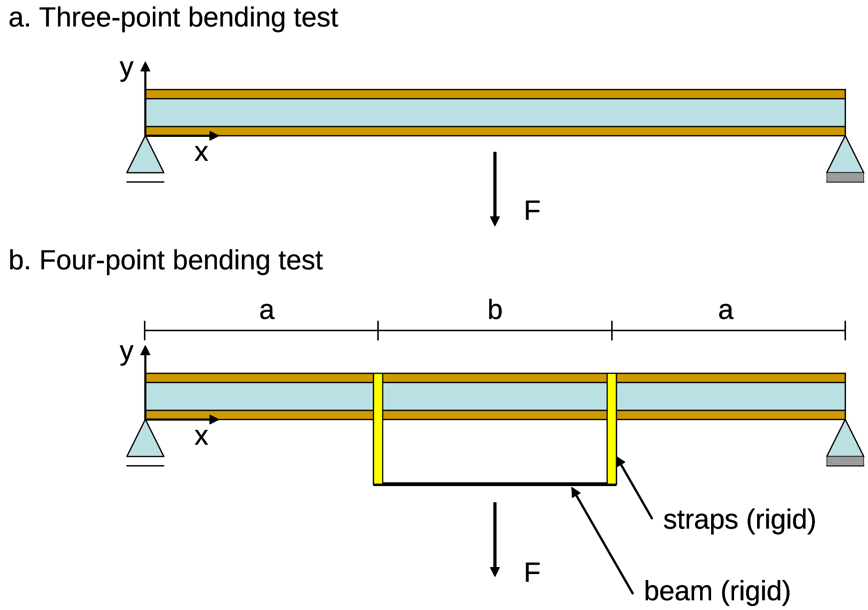

Figure 2: Bending test scenarios

4.1. Specimen Construction

Materials for Construction:

Balsa Wood (2) 4 x 36”, 1/32” thickness
Foam (1) 4 x 36”, 3/4” thickness

Gorilla Glue® and wet paper towels
Wax paper
White Plastic Putty Knife

Construction Procedure:

1) Remove the plastic films attached to both sides of the foam.
2) Damp one side of one of the 4” x 36” balsa pieces with a wet paper towel.
3) Apply Gorilla Glue® evenly around all edges of the piece.
4) Use the spatula to spread the glue to a consistent thickness. *NOTE: Do not apply glue too liberally: Only a thin layer across the entire wing is necessary*.
5) Press the adhesive side of the balsa piece to the foam with corresponding dimensions.
6) Repeat steps (1-4) to attach the other piece of balsa to the opposite side of the foam, creating the “sandwiched” composite wing shown in Figure 3.

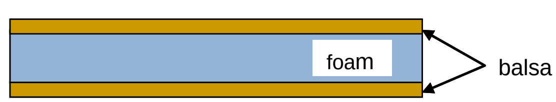

Figure 3: Test specimen

7) Secure the wing by using the provided weights to keep the composites fastened together. Wrap wax paper around the wing to prevent the glue from making a mess.
   NOTE: The composite beam must be clamped under an even pressure distribution to ensure a better quality result.
8) Allow wing to cure under clamped pressure for at least 1-2 hours.

4.2. Design of test

The test setup used to generate the provided data is depicted in Figures 4a and 4b. When analyzing the data, consider how the beam failed (in shear or bending). Using estimates for the strength of the foam and balsa wood (search the web) you can approximately predict at which load *F* the beam should fail in dependence of the strap location "a".

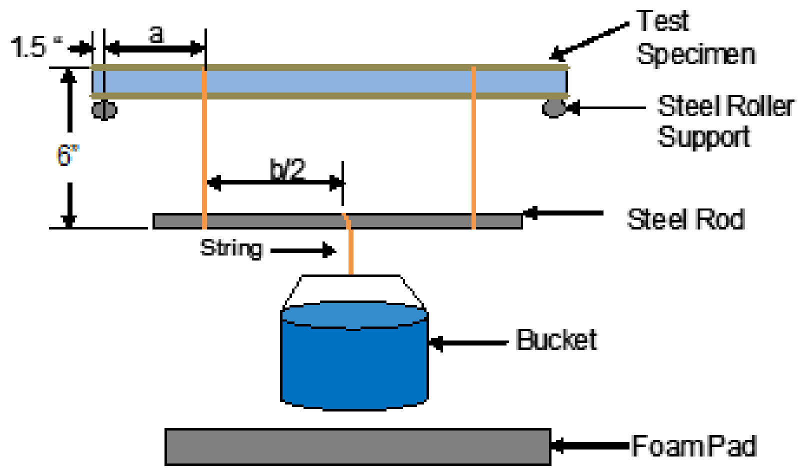

Figure 4a: Front view of test setup

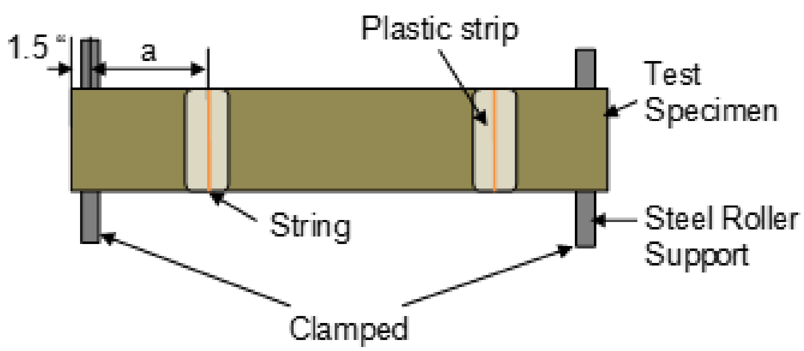

Figure 4b: Top view of test setup

4.3. Testing procedure

<u>Materials for Testing:</u>

(1) *Bucket*
(2) *Steel Roller Supports*
(1) *Steel Rod*
(1) *Foam Pad*
(4) *Clamps*
(2) *Pieces of Plastic/Metal*
(2) *Lab Carts*
Catfish Line

Testing Procedure:

1) The weight of all components that apply a force to the beam - bucket, pulley, rods, etc. - were determined and recorded.
2) 2 lab carts with 1 steel roller support clamped to each lab cart were obtained.
3) A test specimen was placed on the steel roller supports that act as pinned supports. (See Figures 4a and 4b). These were 1.5” from the middle of the support to the end of the test specimen on each side.
4) With two plastic/metal pieces protecting the balsa wood, two catfish line loops were placed on the specimen. These were placed at a distance “a” from the middle of each support. The long metal rod was hung from these loops, taking care to evenly distribute its weight across each loop.
5) Using Figure 4a as a guide, the bucket was attached to the middle of the rod hung by the catfish line in Step (4).
6) Weights were deposited into the bucket, beginning with the largest masses. As the specimen approached the breaking point, smaller weights were used for a better resolution.

   Weights available for testing:
   - (1) 100 Newton
   - (2) 50 Newton
   - (6) 20 Newton
   - (4) 10 Newton
   - (5) 5 Newton
   - (6) 2 Newton
   - (1) 1 Newton

7) The test specimen was broken and the weight was recorded.

5. Wing Design

Based on the strength test results the plan form of a composite beam can be optimized. Assume that the pressure distribution along the wingspan can be approximated by the relation (see Figure 6a):

$$p(x) = p_0 \sqrt{1-\left(2x/L\right)^2}$$

where p_0 [force/area] is the pressure at the wing center and L is the span of the wing. Note, x and L are displayed in Figure 6a. In general, the force generated by the pressure distribution depends on the width *w(x)* of the beam (see Figure 1). Here, for the sake of simplicity, you may assume a uniform width of 4” to compute the distributed load per unit length of the wing. This approximate distributed load may be used for the rest of the analyses.

The pressure distribution results in a total lift Λ. The goal of the design problem is to minimize the weight of the beam and, at the same time, maximize the load bearing capacity of the beam. You need to find the optimal shape of the planform *w(x)* (see Figure 1) and maximize the lift Λ. To facilitate the numerical solution of such an optimization problem, you may consider *M* grid points $x_0, x_1, \ldots, x_M$ along the *x* direction (for sufficiently large *M*) and find the optimum width values $w(x_0), w(x_1), \ldots, w(x_M)$ (assume that $w(x=0)$ = 4”). These values may then be utilized to generate the continuous optimal width *w(x)* using interpolation.

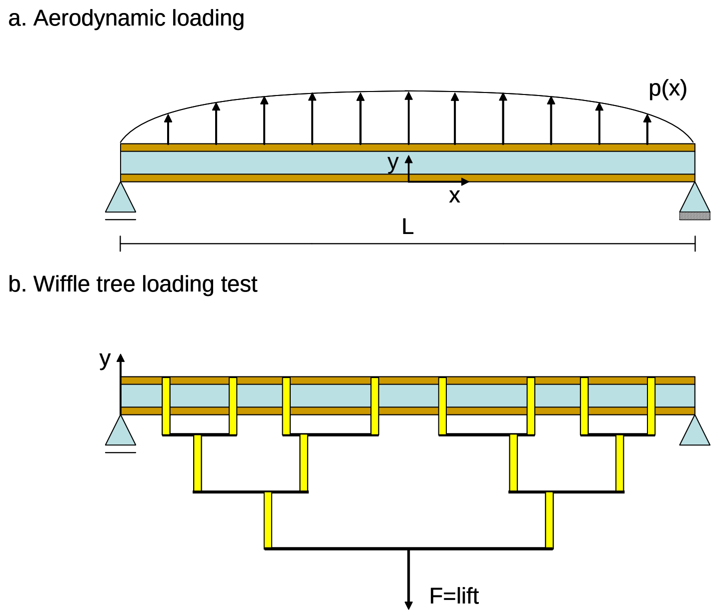

Figure 6: Aerodynamic and wiffle tree loading scenarios

5.1. Analysis and design

Like for any other engineering design problem, first you will need to model and analyze the structural response of the beam for the given loading. As you do not know the planform *w(x)* and the maximum lift force, you should keep the parameters as variables and determine their values only after you have a sufficient understanding of how the planform, total lift, wing failure, and weight of the wing depend on each other.

The analysis and design process should involve the following components:

- Shear force and moment diagrams (if needed, you may use *MATLAB's* symbolic functions for this purpose)
- Stress and failure analysis; consider failure in shear and bending
- Optimization of planform for minimum weight and maximum load bearing capacity

As you may want to study various planform shapes, it is strongly recommended to develop a *MATLAB* code that performs the above analysis tasks for a given plan form shape.

Test data on the failure of previously fabricated wings are available on D2L. Use this test data to estimate the failure normal and shear stress values for the wing and determine an appropriate safety factor based on the scatter of the data. Assume the nominal values for the thicknesses of the balsa and foam layers. Distinguish between random and systematic errors in the test data.

Once your design process has converged to a final solution, you will cut the wing out of the 36" x 4" composite plate you have fabricated earlier.

5.2. Wiffle Tree Test

Your analysis and design process was built upon several assumptions. Therefore it is necessary to experimentally test the optimized wing to failure. In contrast to the 4 point bending test preformed earlier, in this test you will need to "simulate" the aerodynamic loading conditions. You will design a so-called wiffle tree which approximates the distributed pressure load by applying multiple discrete forces to the wing (see Figure 6b). These forces are determined such that they reproduce a moment and shear force distribution in the beam that closely resembles the moment and shear force distributions generated by the aerodynamic pressure load.

In this lab you will design a wiffle tree, which applies discrete loads via straps at 8 points on the wing. You need to determine the locations of the straps on the wing and within the wiffle tree by analyzing the moment and shear diagrams generated by the wiffle tree and comparing these diagrams with the ones generated by the aerodynamic pressure load. The wiffle tree should be designed such that the errors between the corresponding moment and shear force diagrams are minimized. Define how you measure the error between the diagrams.

Before performing the experiment, you will have to present a test plan in which you need to specify and describe:

- design of optimized beam and wiffle tree layout
- moment and shear diagrams for aerodynamic loading and wiffle tree loading
- stress analysis and failure prediction for aerodynamic loading and wiffle tree loading
- loading procedure (in which increments will you apply the wiffle tree loads)

5.3. Testing procedure

<u>Materials for Testing:</u>

(1) *Composite Wing Specimen*
(2) *Lab Carts*
(1) *Wiffle Tree Kit containing:*
  - (2) *Steel Roller Supports*
  - (2) *Aluminum Supports*
  - (1) *Foam Pad*
  - (4) *Clamps*
  - (8) *Aluminum Loops*
  - (4) *6" Aluminum Bars*
  - (2) *12" Aluminum Bars*
  - (1) *18" Aluminum Bars*
  - (1) *Bucket*

Various Weights

Figure 7: Wiffle tree kit

<u>Testing Procedure:</u>

1) Locate one of the testing sections, which will have a wiffle tree kit provided. If any parts are missing, compared to Figure 7, check other stations nearby or get a lab assistant or TA. The kits are color-coded, so throughout testing, do not use parts that do not match your set.
2) If not already done, place the support beams near the edges of the two carts and clamp them down on both ends. Place the steel rollers on top.
3) Note that you can either move the attachments before or after placing the assembly on the wing. If doing so before, loosen the eyebolts and slide them where needed, then tighten them down in the correct location.
4) Slide your wing through the loops, then place it on the supports. The carts can be adjusted to get the correct distance. Center the foam under the wing.
5) Using the s-hooks attached to the loops, connect the four smallest bars as the next layer down. The eyebolts can be freely rotated to match orientations. The bars contain levels if needed.
6) Repeat step 4, using the two 12" bars, then the 18", as the next two layers. Hang the bucket from the hook on the longest piece. It should look like Figures 6 and 8.

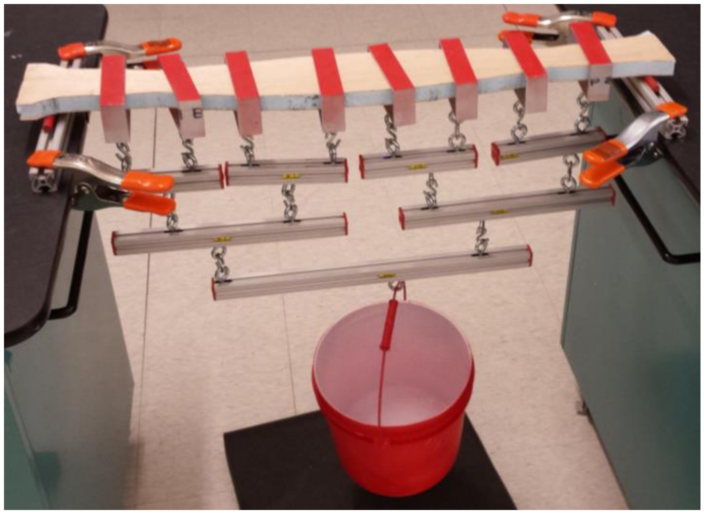

Figure 8: Fully assembled wiffle tree

7) If not already measured, slide the eyebolts to the required locations. The bottom bar must be centered with the bucket hanging in the middle of the bar.
8) Once everything is in place, begin loading the beam, starting with larger weights and then progressing to smaller ones for a better resolution. If the wing begins to break, it is safer to leave it alone for some time, to ensure the safety of other group members.
9) Place all the pieces of the assembly in the bucket, and weigh it to find the total failure weight for your wing.

5.4. Analysis and discussion of test results

After the wiffle tree test has been performed, compare the test results to your predictions. Among others, consider the following questions:

- In which mode did the beam fail?
- Which component (foam or balsa sheets) failed first?
- Discuss potential reasons which may have led to discrepancies between predicted and observed failure loads.

6. Writing a Group Report

Reports are due Friday December 9 at 7:00 am. An electronic copy needs to be uploaded to D2L.

The report must be word processed. The main body should be no more than 6 pages (this excludes the Title Page, Abstract, Graphs, and Appendices). The general guidelines for lab report writing can be found on D2L. The required format of the report is defined in a report template document that can also be found at the D2L course web page.

Your Lab 3 report should more specifically include:

Title Page. (see guidelines)

Abstract. (see guidelines)

Introduction. Discuss the objectives of the lab as you see them. This should include background "theory" as described in the guidelines.

Strength Analysis. Describe and discuss the analysis and experiment performed under Section 4.

Wing Design. Describe and discuss the analysis and experiment performed under Section 5. This section should include the analysis and design of the composite beam as well as the wiffle tree.

Discussion. As usual, the discussion section should include your observations of agreement and disagreement of the experimental and theoretical portions of the lab. Focus in particular on the failure modes observed versus modeled. Discuss which additional failure modes one would need to take into account for a more realistic wing model which may include for examples mounts for engines and landing gears etc. How could one analyze and predict such failure modes?

Conclusions. (see guidelines)

References. List of references cited in the body of the report, e.g. the textbook or experimental description document. References should be cited in the text by numbers enclosed in square brackets. Example: "the experimental procedure provided on page 4 of [3] is used."

Appendices. (see guidelines)

Note. For sections such as the introduction it is recommended that a key rule of technical writing: "context before content", be followed. That is, briefly state what the objectives are and which approach was followed to meet the objectives, before entering into the technical content.

Addendum I - Report Grading

The score assigned to the lab report includes technical content (80%) and presentation (20%). This is a more detailed breakdown of the weights:

Category	Weight	Score	Contribution
Abstract	0.05		
Introduction	0.10		
Strength Analysis	0.20		
Wing Design	0.30		
Discussion	0.10		
Conclusions	0.05		
Organization	0.05		
Flow and style	0.05		
Grammar, spelling and typos	0.05		
Referencing	0.05		
Total	1.00		

"Flow" measures smoothness of reading from start to finish and correlation of material from section to section, as well as adherence to guidelines of technical writing.

The score within each category ranges from 0 to 100%. For example if the score for "strength analysis" is 80%, it contributes 0.20 * 80% = 16% to the overall score.