

A photograph of three students working at a table in a classroom or workshop. The students are focused on their work, with one student in the foreground wearing a blue shirt and another in the background wearing a grey and black shirt. The table is cluttered with papers, a box, and other materials. The background features a blue door, a yellow safety poster, and a bookshelf filled with books. The text "Final Wing Design File" is overlaid in large, bold, black letters across the center of the image.

# Final Wing Design File

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Period 1B

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## Abstract

During the wing strength design process at Aviation High School, Shawn Stern was the design engineer, Emilia Keylin was the project manager, and Derek Diaz was the test engineer. During the design process, three iterations of wings were designed, built and tested. For each iteration:

- The design process is discussed
- The building process is documented
- The testing data is presented and analyzed

After each iteration, the lessons learned from testing are discussed, and proposals for improving wing efficiency are addressed.

The wings in round one had efficiencies of 55.692 Nm/kg, the major design feature being balls of newspaper; 38.683 Nm/kg, the major design feature being a triangle; and 92.243 Nm/kg, the major design feature being an interior <|> shape.

The wing in round two had an efficiency of 84.89 Nm/kg, the major design feature being spars leaning against each other.

The wing in round three had an efficiency of 419.3 Nm/kg, the major design feature being exterior spars.

The testing model's strengths and limitations are evaluated, and applications to actual wing design are discussed.

## **Initial Designs**

After developing 9 designs, the three below were chosen for the corresponding reasons.

NOTE: All designs are 24" x 4" x 1.5" (Length, Width, Height)

- Wing Z because it is strong, only marginally complicated, and resistant in many ways to the stresses that will come in the trial.
- Wing X because it is very simple, yet very strong; which is good for this project considering the amount of time required to make 3 wings.
- Wing Y because it is the simplest, and should be easy to complete, leaving time to complete the other two wings.

Design Z:

This design was the only design that held a fair amount of weight during testing. It had an extremely strong core structure, but failed due to the thin shell, poor interface, and lack of time for construction.

Design X:

This design was utterly useless in terms of holding weight, as it crumpled the instant the actuators were added; mainly because it was assembled only to meet the 3-wing quota.

Design Y:

This design was partially successful at supporting the actuators and the bucket, but collapsed at that time. This was due to the fragile supports and thin shell.

**High quality schematics of the wings are available in the Appendix**

## **Building Process**

### **Outer shells:**

This was the easiest, but messiest part of the wing construction. Three “2x4”s were wrapped in aluminum foil, and successively wrapped with layers of paper drenched in starch to create papier-mâché.

### **Wing Cores:**

In this step the outer shells were cut open, and wing supports were inserted.

Wing Z: Originally, cardboard strips were cut to the exact dimensions required for the design. The strips were then covered in foil and wrapped in starched newspaper like the wing shells were. At the point where they were inserted into the wing it was discovered that the supports were too large to fit in the way they had been intended to do so. Therefore the design was modified to accommodate a larger interior design, and some supports had to be removed from the design (resulting in the design listed in the Design Selection section of this file). The new design was created, and is pictured below.



Wing Y: The design was so simple and easy that construction went smoothly compared to Wing 1, and there were no mishaps. The construction process was the same for this wing, minus the design modifications.



Wing X: By the time Wings 1 and 2 were finished, there was no time to create the large cylinder imperative for this wing and still meet the 3-wing minimum for testing. A compromise was made, and the shell was quickly stuffed with starch-coated balls of starched paper, a procedure that took less than 5 minutes, but resulted in a questionable wing.



## **Lessons Learned**

Design: The only lesson learned in respect to wing design was that spar thickness has to be taken into account when making the measurements for the moulds.

Building: The team learned that the wing needs to be wrapped tighter during casting, and better measurements should be taken when assembling the wing, since most measurements are off while blueprints were drawn.

Testing: Nothing really to learn here, except that pictures should be taken instead of movies, and that it's a good idea to have the test engineer present during testing.

Process: The most prominent lesson learned is that pictures are a must for the building process, and many should be taken at each stage of construction.

## Round 1 Testing

1. The wings were loaded 15 cm onto a 2 x 4 interface.
2. Two small blocks of wood were used to clamp the wing to the interface. The blocks of wood were placed on the outside of the wing where the 2 x 4 interface ended.
3. Actuators were loaded at 10 cm, 20 cm, 30 cm and 40 cm from where the interface ended.
4. A lower spreader was added to the actuators.
5. A bucket was added to the lower spreader.
6. Water was added to the bucket until the wing failed.

Round 1 test results are shown below:

Wing	Wing Mass (kg)	Failure Load Moment (Nm)	Efficiency (Nm/kg)	Failure Mode
X	.1211	6.744	55.692	Compression
Y	.1748	6.744	38.583	Compression
Z	.2098	19.353	92.243	Compression

## Observations:

**Wing X-** The wing stayed straight as the actuators were put on. It buckled and bent when the bucket attachment was put on (not the bucket).

**Wing Y-** Same results as X, except it lasted a few seconds longer.

**Wing Z-** Wing did very well. It held all attachments and the bucket was filled to 6.5cm of water before the wing began to bend (didn't break). High quality design.

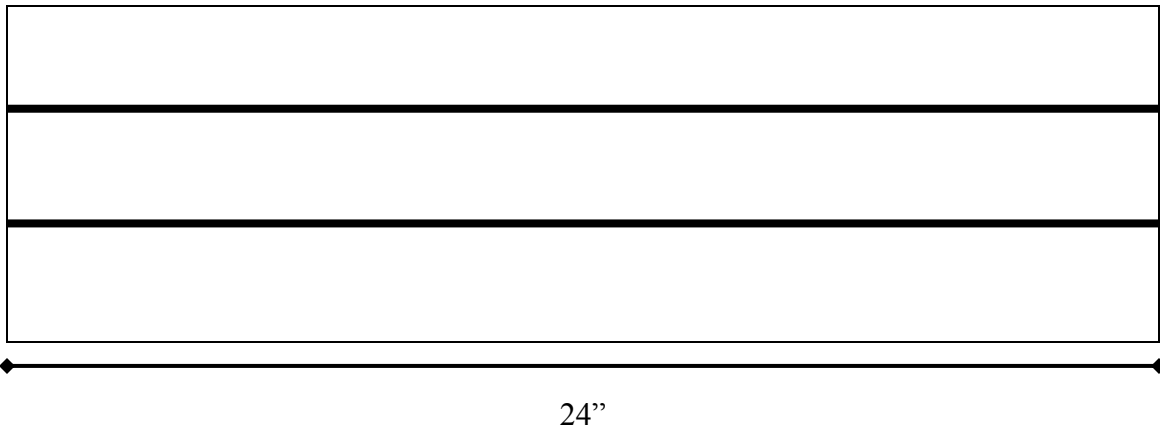
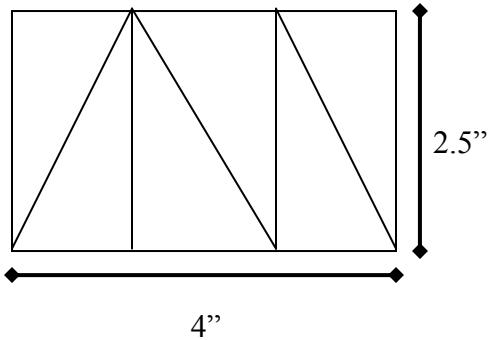
## Probable Cause of Failure:

The probable cause of failure for all of the wings was most likely poor construction. At the time, it was thought that wing Z's design was a good design. These wings were the first 3 wings that were made and were very weak. Wings X and Y failed due to compression at the root with only half of the actuators in place. The interior designs for these two wings were poorly constructed, and the support at the wing was most likely weak. Wing Z failed at the root, also due to compression. The interior design was a better construction. Wing Z received the most attention to detail out of the three.



## Second Design

For this round of testing the wing was dubbed “Fatty” for identification purposes during testing. The design was based off of data from the last round of testing. It was selected because it has a strong internal structure resistant to compression, and is easily produced.

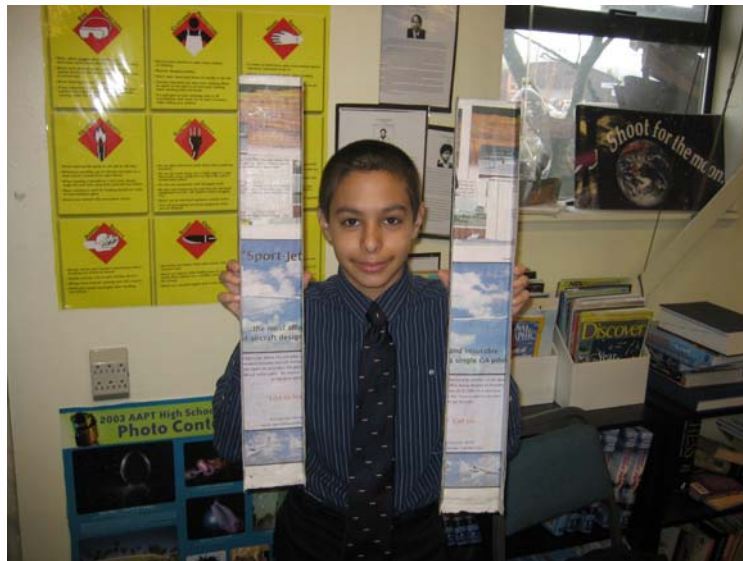


\*\*A side view is not supplied because there is nothing to draw from a side perspective

**Higher quality schematics of this wing are available in the Appendix**

## Building Process

**Outer Shells:** This step of the building process was simple, but messy. A “2x4” was wrapped in aluminum foil, and many, many layers of starch-drenched paper were applied to it. The result was an extremely solid, hollow ‘wing’.



**Wing Core:** While the shell was drying on the racks, the interior supports for the wing were constructed. Using a method similar to the wing construction, pieces of cardboard were wrapped in foil and had the starched paper applied. This resulted in a set of different sized spars, 3 of them for the diagonal supports and 2 for vertical support (vertical spars weren't as wide, since the area they had to fill was smaller than that of the diagonal supports).



After the supports and wing shell were dry, the wing was split open with an exacto knife. Then the supports were carefully placed inside the wing and glued in place. After the supports were solidly in place, the top shell was placed on the wing, and the wing was wrapped with more starched paper to compensate for the wing being cut open.



## **Lessons Learned**

**Design:** A lesson learned in this respect was that the wing requires a much simpler design that has a better margin for error, since this wing had exact calculations for its planning, and the constructs that were made weren't exact in size.

**Building:** No lessons were learned in regards to building the wing because the building went smoothly, and any errors were due to design.

**Testing:** As with last time, more pictures need to be taken during testing at critical points.

**Process:** The only lesson learned was that the wing planning has to have more room for error, and that the shell probably shouldn't be cut open, since there is no need for it in the first place, cutting the shell weakens the wing, and it also generates more work since the wing has to be re-wrapped in order to work correctly.

## Round 2 Testing

1. The wings were loaded 15 cm onto a 2 x 4 interface.
2. Two small blocks of wood were used to clamp the wing to the interface.  
The blocks of wood were placed on the outside of the wing where the 2 x 4 interface ended.
3. Actuators were loaded at 10 cm, 20 cm, 30 cm and 40 cm from where the interface ended.
4. A lower spreader was added to the actuators.
5. A bucket was added to the lower spreader.
6. Water was added to the bucket until the wing failed.

Round 2 test results are shown below:

Wing	Wing Mass (kg)	Failure Load Moment (Nm)	Efficiency (Nm/kg)	Failure Mode
Fatty	.5429	46.087	84.89	Compression

### Observations:

Fatty: The wing was completely dry when it was tested. When slid onto the 2X4 it fit loosely, meaning the dimensions were slightly off. Fatty was clamped down at 15cm, and each actuator was placed 10cm apart after that. It held the total weight of the actuators well. Around 15cm of water, Fatty started to bend. Fatty failed at the interface of the wing and held 23cm of water.



### Probable Cause of Failure:

Fatty's biggest problem was its weight. The actuators alone made it slightly bend. The most probable cause of failure was the weight being held up by the interface. It was just too heavy.

## **Final Design**

This final design was based on the data from all of the previous tests, and input from a Boeing engineer named Dan Hrehov. It was decided that the wing design should stray from the cantilever designs used up to this point, and instead rely on a strong shell and exterior supports to resist both tension and compression. Another reason this design was produced is that it is very easy to replicate, as there is no interior structure to assemble, and the exterior supports are extremely simple to create.

**High quality schematics of the wing are available in the Appendix**

## **Building Process**

**Outer Shell:** Because the design of this wing was cantilever, a strong outer shell was crucial. As with previous wings, a “2 x 4” was wrapped in a layer of aluminum foil, and successively wrapped in many layers of paper drenched in starch. As this wing had a non-cantilever design the thickness and strength of the shell was imperative. Thus the shell for this wing had many more layers than all of the previous wings. Due to the attention to detail and tightness, the first shell was so strong and tight that it was impossible to extract the “2 x 4” with the tools available without compromising the shell by cutting it open. Thus a second shell was produced and had the same results. A third shell was then produced, this time the “2 x 4” had two layers of foil that could slide on each other for extraction, and the wrapping of the paper was looser to ensure the possibility of actually getting a useable shell; this was successful, but the shell was significantly weaker compared to the original because of this.

**Structure:** Once a shell was available, the external supports for the wing could be created. For this phase of construction three, meter sticks were wrapped in foil and then wrapped in starched paper, in a fashion similar to the shell construction. Two of the meter-long struts were planned to be measured and cut into correctly sized pieces to be attached to the shell at the planned points. The final strut was wrapped much thicker, and was intended to act as a support for inside the wing, but was scrubbed from the design

because it weighed too much for what it added and failed to dry early enough to be added to the wing.

Assembly: Now that all of the components for the wing were dry and available, the wing was assembled. This was accomplished by laying each of the exterior support struts in their correct places, cutting strips of paper, covering each in starch, and tightly wrapping each around the supports in an X shape at the root of the wing, and the opposite end of the wing. This attached the struts to the wing, added strength, and changed the direction of the stresses on the wing by providing an alternate direction for the forces to go.

### **Lessons Learned**

Design: A huge lesson was learned in this case. In all previous tests the wings were cantilever, and had low efficiencies to a maximum of 90 grams per gram of wing. This final wing however wasn't cantilever, and had an efficiency close to 420 grams per gram of wing. With this lesson in mind, any future wings aimed at efficiency will have even stronger versions of this wing's exterior structure.

Building: With the strength of this wing in mind, and the immense strength of the original shell many lessons were learned with regards to wing construction. The first consideration to be made is that the tighter the paper is wrapped around the "2 x 4" the stronger the wing is. However, this is limited because if the wraps are too tight the wing can't be used because the "2 x 4" won't be extractable. Another lesson is related to the integrity of the shell. In the first two rounds of testing the wings were cut open, the structures inserted, and the wing was re-wrapped to try and hold the wing together. In hindsight this is an obvious error, and by keeping the shell intact throughout the whole process, a much stronger wing could be produced with much less weight.

Testing: With regards to testing only one lesson was learned. This lesson is that pictures should be taken during testing instead of a live movie. This is because several times there have been errors preventing access to the movie, therefore removing any

chances to extract still pictures to place in the design file or for review of the failure point of the wing.

Process: No lessons were learned in this case, because the process behind designing, building, and testing the wings has been perfected with only minor exceptions due to the limitations of the facility and the limitations inherent in constructing wings with papier-mâché.

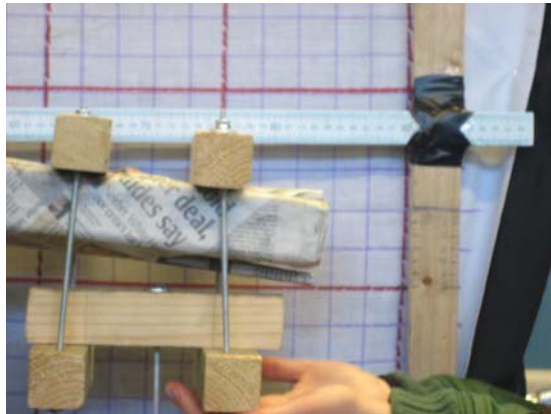
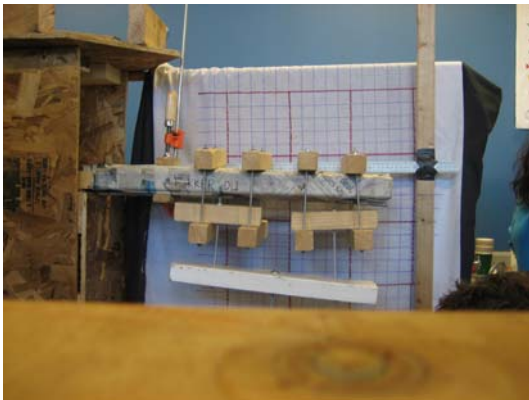
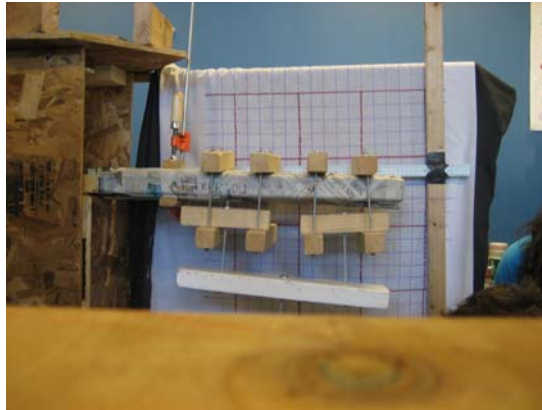
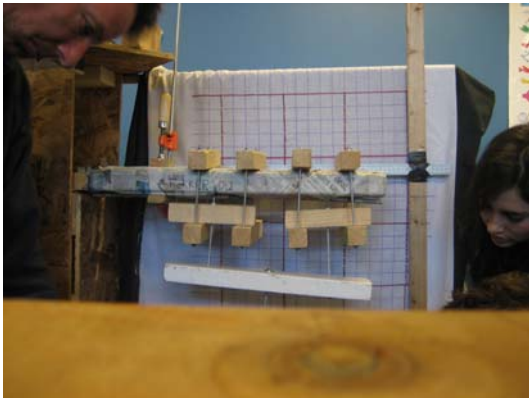


## Round 3 Testing

1. The wings were loaded 15 cm onto a 2 x 4 interface.
2. Two small blocks of wood were used to clamp the wing to the interface.  
The blocks of wood were placed on the outside of the wing where the 2 x 4 interface ended.
3. Actuators were loaded at 10 cm, 20 cm, 30 cm and 40 cm from where the interface ended.
4. A lower spreader was added to the actuators.
5. A bucket was added to the lower spreader.
6. Water was added to the bucket until the wing failed.

Round 3 test results are shown below:

Wing	Wing Mass (kg)	Failure Load Moment (Nm)	Efficiency (Nm/kg)	Failure Mode
Fokker D-12	.331	138.788	419.3	Compression





### **Observations:**

Fokker D-12: This was the final wing. There was plenty of time to make it, and it was remade three times. It was a very carefully crafted wing. The wing performed much, much better than expected. The wing was marked correctly where the actuators would be put. The actuators were placed in the correct spots, 10cm, 20cm, 30cm, and 40, from the end of the 15cm interface. The wing was loaded until the wing reached the “breaking” point which was 6 cm below the tip of the wing. The failure point of the wing was 14 cm from the interface. After the weight was removed from the wing, it straightened back out and no evidence of a buckle was visible.

### **Probable Cause of Failure:**

The Fokker D-12 never actually snapped. It bent down to the point where it was considered failed. When the weights were removed it straightened back out. If there was anything that prevented the Fokker D-12 from being any stronger it would be that there was no interior.

## Conclusions and Evaluation

During each round of wing testing, the efficiency improved. We contribute the improvements to:

- More careful craftsmanship
- Better design selection
- Improved building process

To further improve the design of the wings, the wings should:

- Have further exterior support
- Papier-mâché should be cast tighter and with more starch to improve strength
- Have exterior and interior support
- Be lighter

The papier maché model wings and testing apparatus are useful models for real wings in the following ways:

- They simulated the vertical stresses on the wings during flight.
- They simulated the design process and how improvements are made during that process.

The data gathered from the papier-mâché model wings and testing apparatus have the following limitations:

- Wings were not constructed with materials common to real wings.
- Testing was confined to vertical stresses, real testing examines wing performance in both vertical and horizontal stresses.
- Wings were made of papier-mâché, which isn't a stable substance for making a precise construct.

## Appendix:

To test the wings' strength, the wing was slid onto the 15-cm interface and clamped into place. Each wing was loaded with four (4) actuators spaced at 10-cm intervals from the root. (See diagram on next page.) A siphon and spigot were used to slowly add water to a bucket hanging from the actuators until the wing failed.

The depth of the water ( $d$ ) and the radius of the bucket, ( $r$ ) were measured.

The volume was calculated with the following formula:

$$V = \pi r^2 h$$

The density of water is  $\rho_{\text{water}} = 1 \text{ g} / \text{cm}^3$ .

Knowing the relationship between mass, volume and density, the mass of the water was calculated:

$$m_{\text{water}} = V \rho_{\text{water}}$$

The mass of the water and the mass of the hanging fixtures were added.

$$m_{\text{total}} = m_{\text{water}} + m_{\text{hanging fixtures}}$$

Knowing the total mass and the acceleration due to gravity ( $a_{\text{gravity}} = 9.81 \text{ m/s}^2$ ), the force acting on the wing, or total applied load was calculated using the following formula:

$$F_{\text{total}} = ma$$

Because the actuators split the force equally, the force on each actuator was calculated with the following formula:

$$F_{\text{actuator}} = F_{\text{total}} / 4$$

The bending moment experienced at the root from each actuator was calculated by using the following formula:

$$\tau = Fd$$

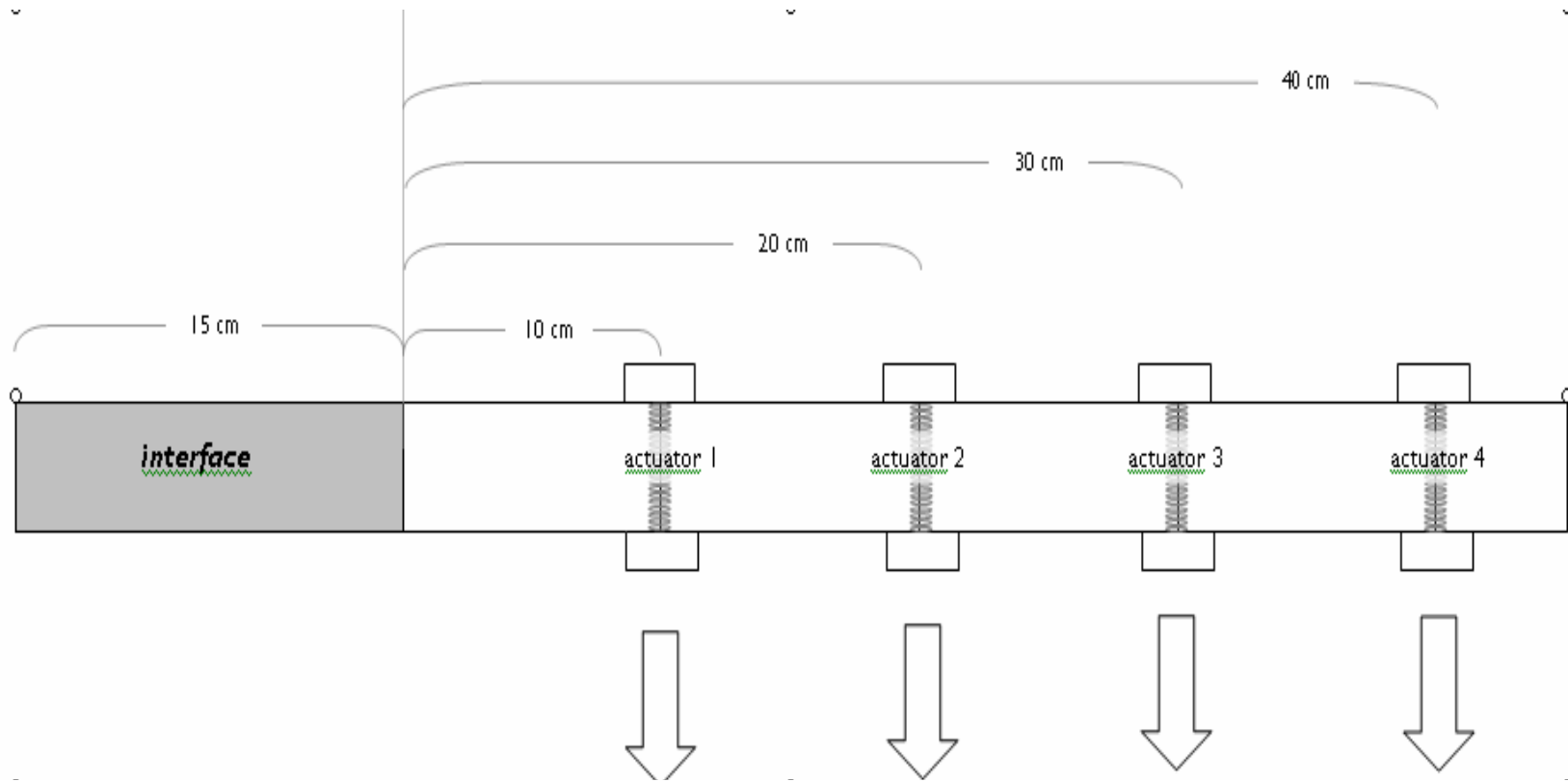
Adding those bending moments together resulted in the total bending moment.

$$\tau_{\text{total}} = \tau_1 + \tau_2 + \tau_3 + \tau_4$$

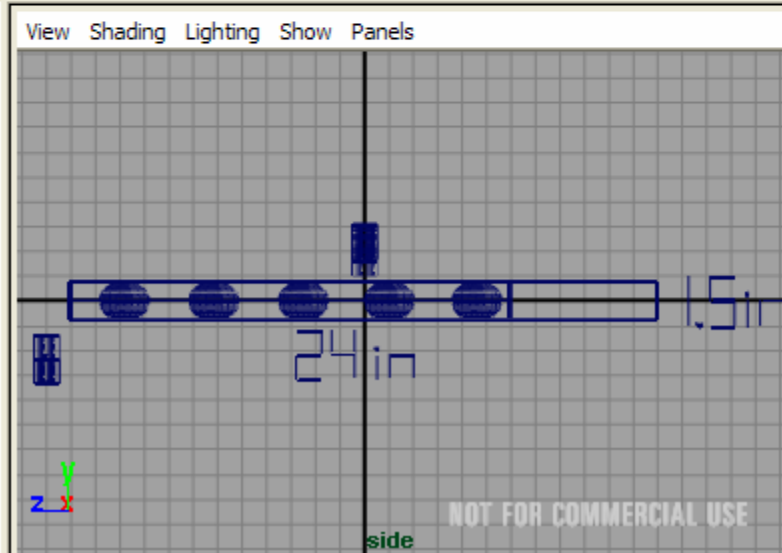
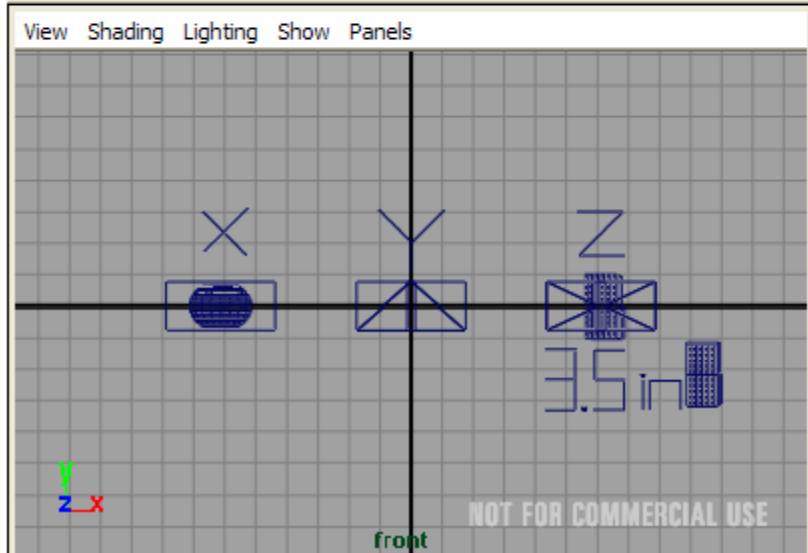
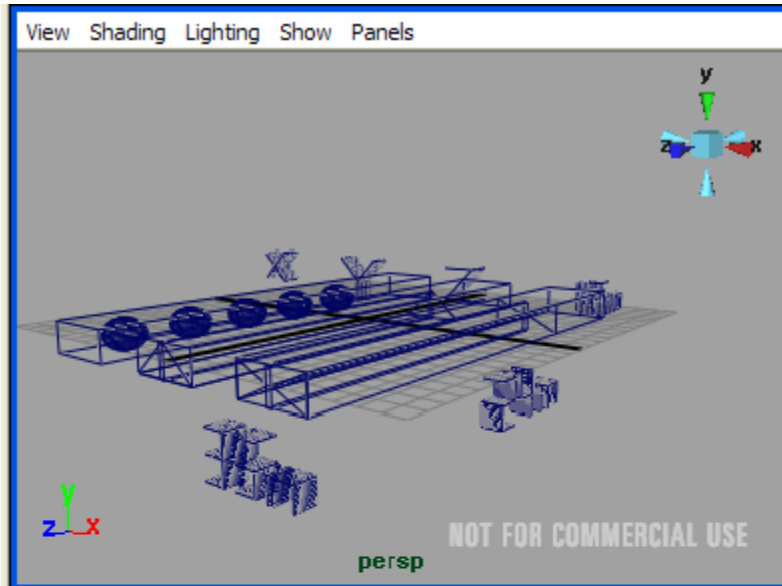
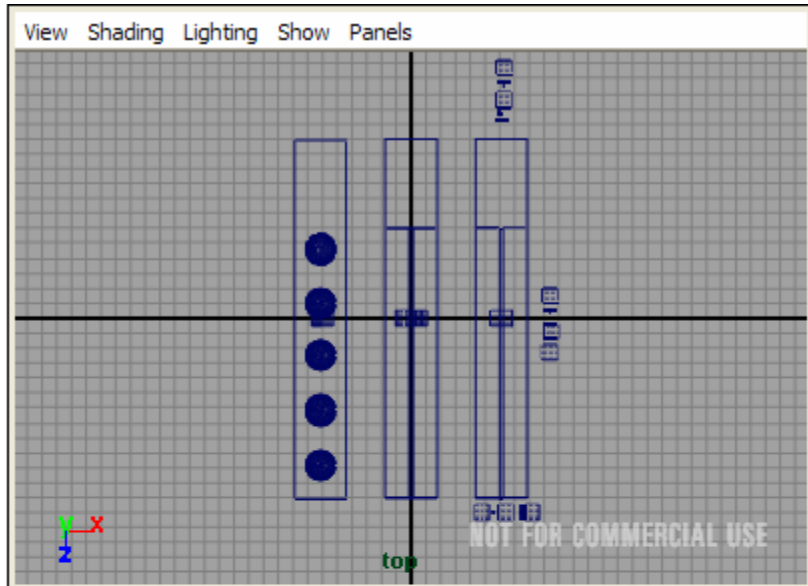
Data for the wing tests is summarized below. NOTE: Refer to the appendix for description of formulas and testing apparatus.

Wing	Wing Mass (kg)	Mass of Attachments (kg)	Added Water						Total Applied Load (N)	Failure Load Shear (N)	Failure Load Moment (N*M)	Efficiency (N*M/kg)
			Depth (cm)	Radius (cm)	Volume (cm <sup>3</sup> )	Density (g/cm <sup>3</sup> )	Mass of Water (g)	Mass of Water (kg)				
X	.1211	2.75	0	14.5	0	1g/cm <sup>3</sup>	0	0	26.98	26.98	6.744	55.692
Y	.1748	2.75	0	14.5	0	1g/cm <sup>3</sup>	0	0	26.98	26.98	6.744	38.583
Z	.2098	3.6	6.5	14.5	4291.2	1g/cm <sup>3</sup>	4291.2	4.291	77.41	77.41	19.353	92.243
Fatty	.5429	3.6	23	14.5	15192	1g/cm <sup>3</sup>	15192	15.192	184.349	184.349	46.087	84.89
Fokker D-12	.331	3.6	24.5	14.5	16182.74	1g/cm <sup>3</sup>	16182.74	16.182	555.152	555.152	138.788	419.3

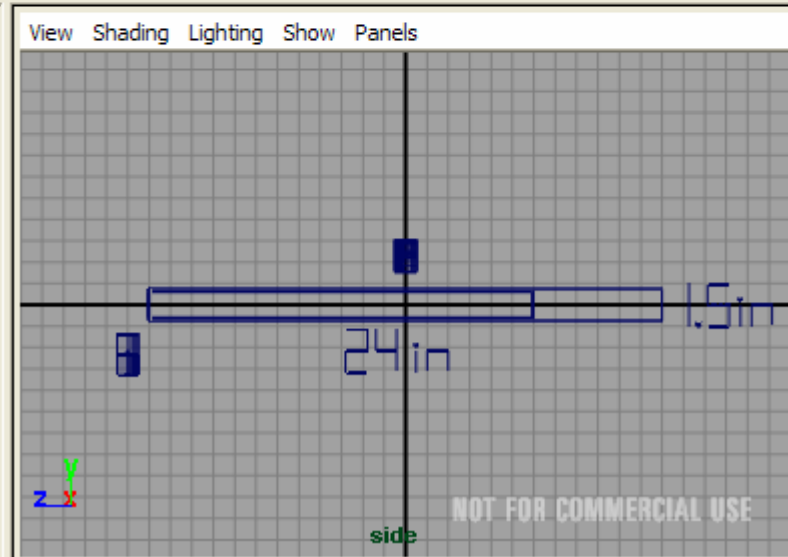
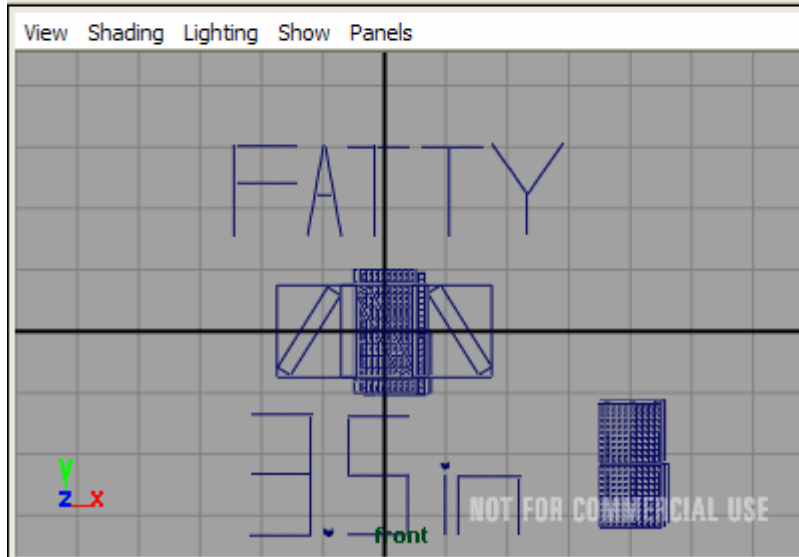
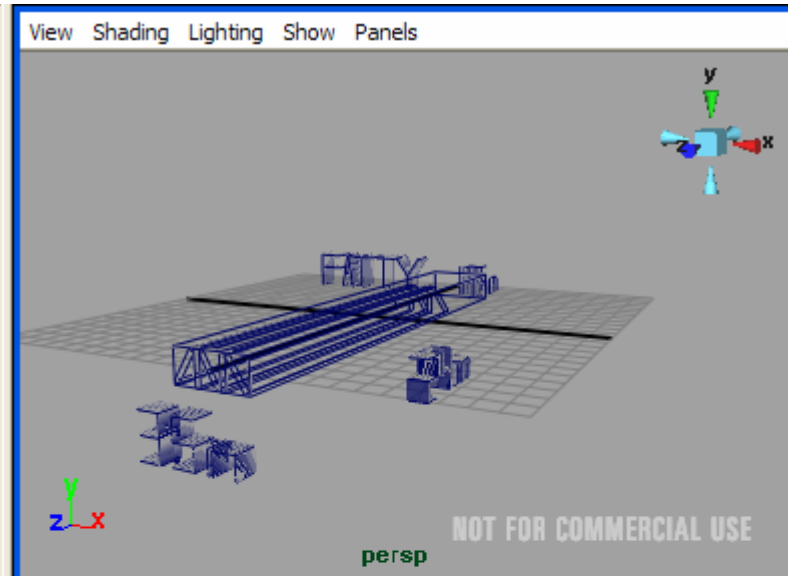
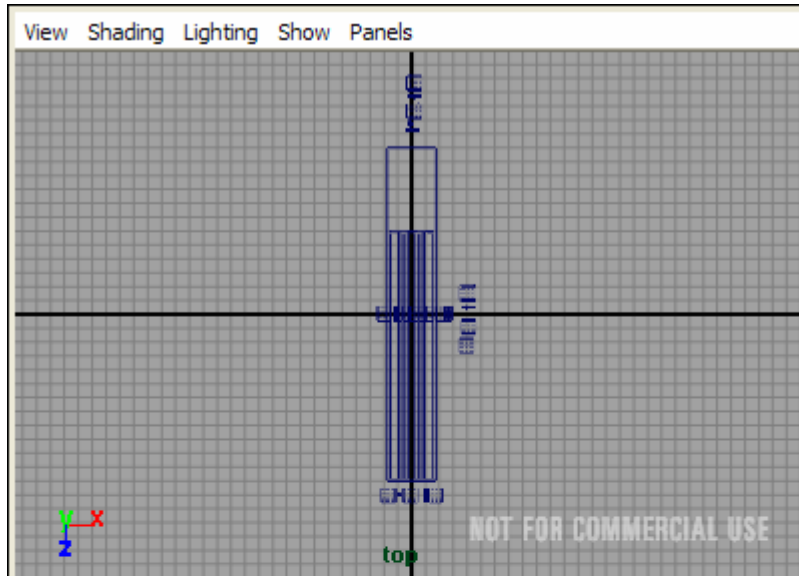
NOTE: Fokker D-12 held 34.808kg of extra weight after the bucket of water was full (5 science books, a 2 X 4, and all the diving weights), resulting in a change in the Total Applied Load from 213.681N to 555.152N. This change also affected the Failure Load Moment and Efficiency. The chart shows the corrected numbers.



# Round 1

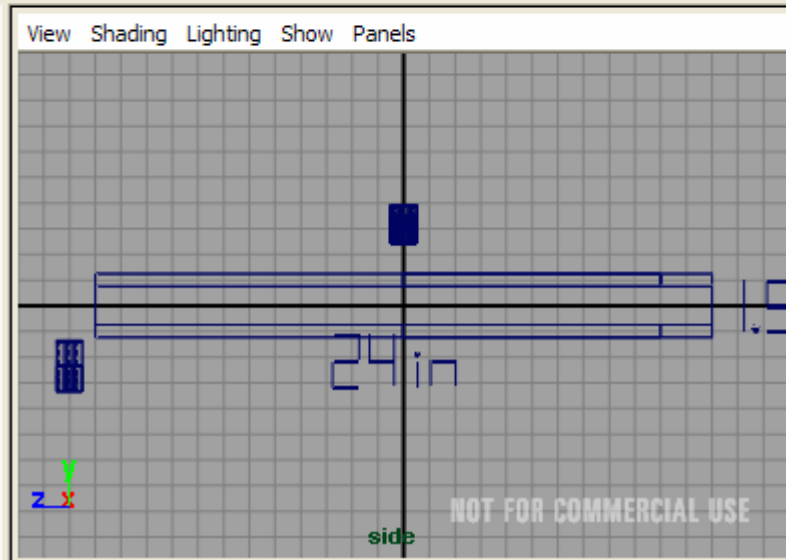
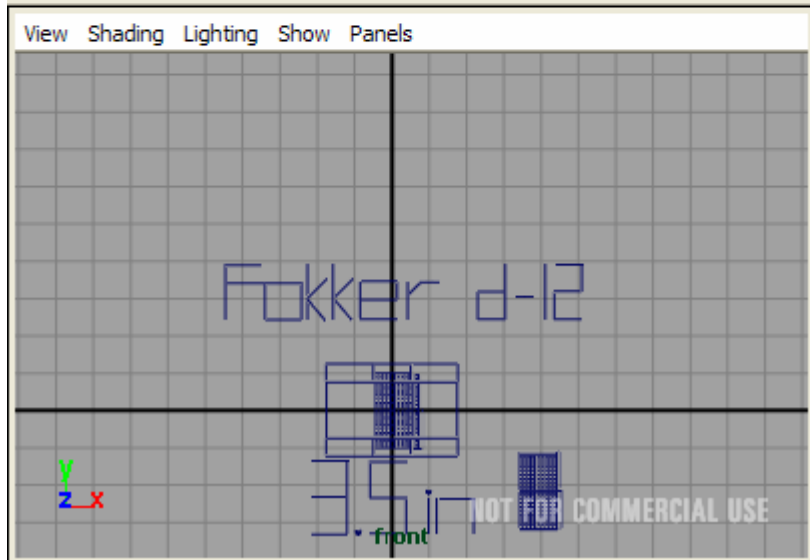
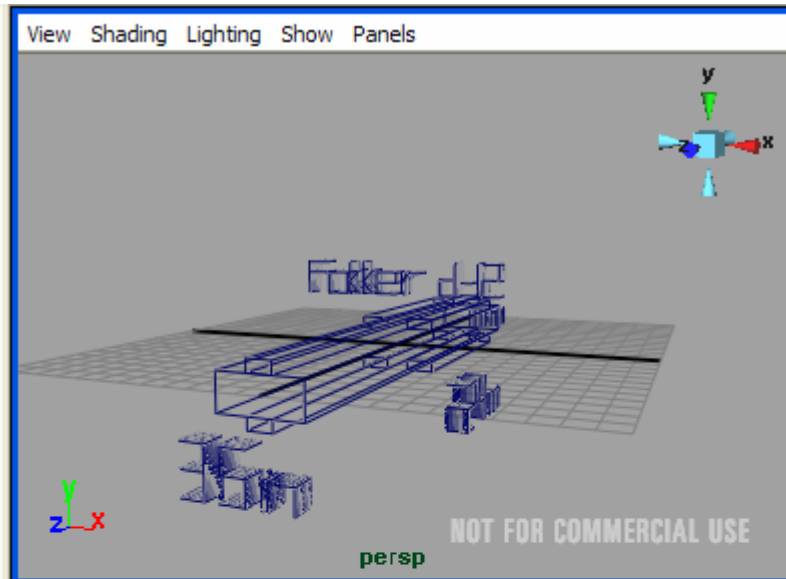
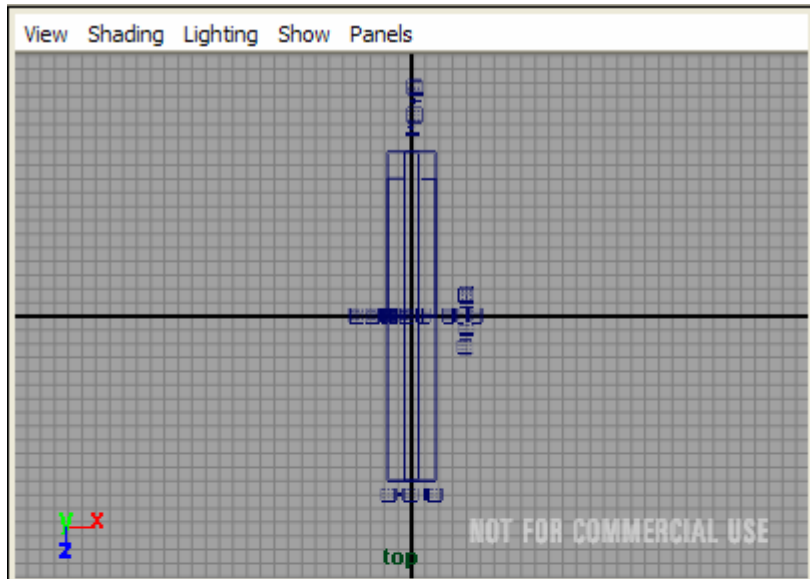


## Round 2





# Round 3



Wing Design Efficiency

## Wing Design Efficiency

