Sketch Model Challenge

MMAE 432: Design of Mechanical Systems
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Abstract

The Sketch Model Challenge (SMC) was a project designed to get know team members and learn craftsmanship skills involved in a engineering process. The first step in the process was to generate the functional requirements needed for the team's model. Second, multiple concept ideas were generated and developed into 3D models in order to choose the best concept for the challenge. Third, analysis on the materials and model were conducted in order to determine if the the functional requirements had been met. Lastly, the weight cost of the model was to determined and competition ensued.

Introduction

The Sketch Model Challenge was a team challenge to build a device that was capable of being pushed/pulled by a driver such that a rider in/on the device did not touch the ground. The device was to be constructed mainly of paper, foam board, cardboard tubes, and other paper-products. The constructed device was to be designed such that it may be used in a dodgeball competition. The team decided on the name of the Raging Ducks, per a Google team name generator. The team was comprised of six members: Shannon, Joe, Ante, Kana, Jay, and Abe.

Concept Generation and Evaluation

Concept generation began after the group established the functional requirements that were deemed necessary of the device for the SMC:

- Device must support 102 kg (225 lb).
- Rider's height requirement: 5 ft to 6.5 ft.
- Ability to make 360 degree turn within 5 seconds.
- Maximum weight of the device: 6.8 kg (15 lb).
- Two different seating positions

The team's concepts for the SMC began with two different beginning ideas: a "Chariot-Tricycle" model (Figure 1) and the "Nascar" model (Figure 2). The team liked these concepts because of their stability and potential for quick turns and ease of pushing/pulling motions.

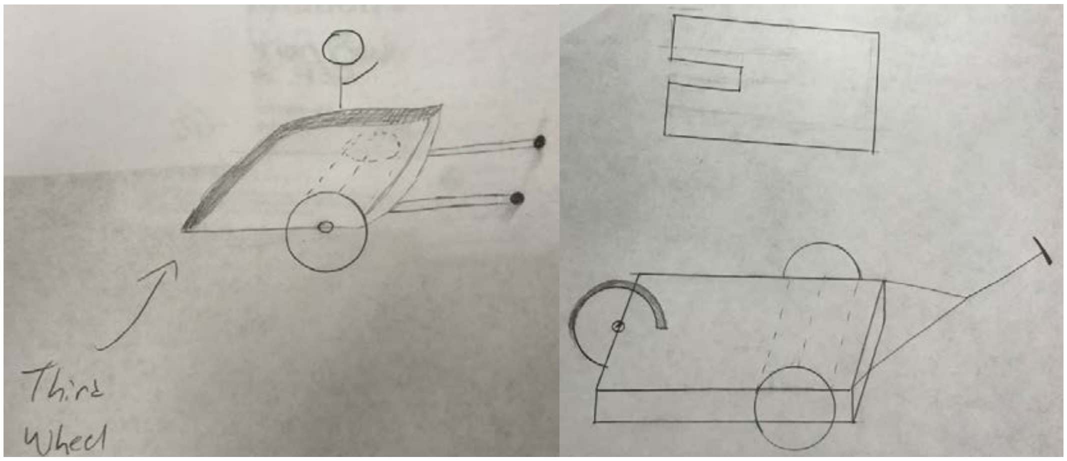


Figure 1: “Chariot-Tricycle” Model

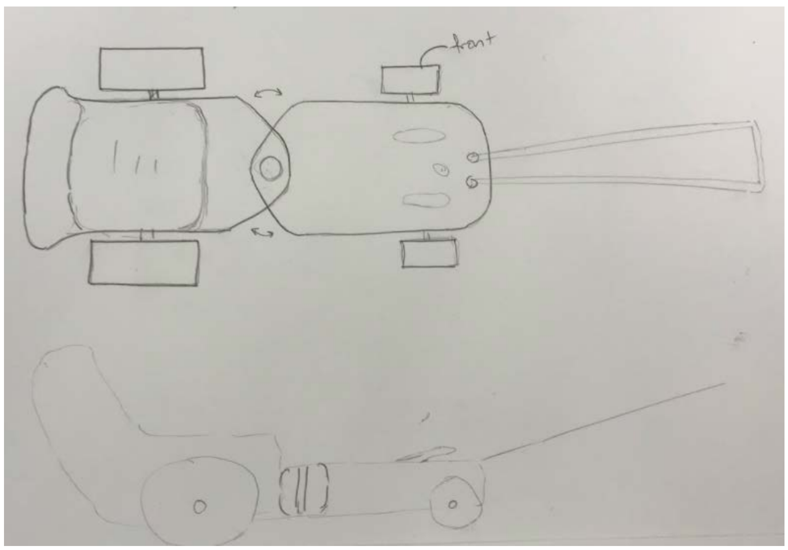


Figure 2: “Nascar” Model

The team decided on the first day of lab to continue forward with the “Nascar” Model since it seemed like it would be able to make tighter turns and be able to be pulled easier by the driver However, after a furthering the development of the “Nascar” Model it was deemed at a group meeting that the model was beginning to become a bit too complicated. The axles were difficult to design and the center joint was going to have too much stress placed upon it.

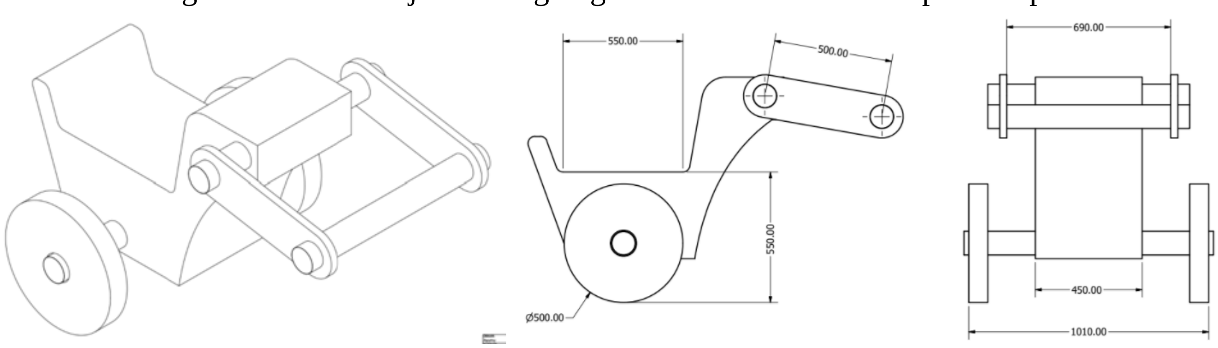


Figure 3: “Raging Duck Cart” Model

The next model that was produced was the “Raging Duck Cart”, shown in Figure 3. This model was designed with the idea that the duck style would be more supportive for the larger riders but still small enough so that the smaller riders would not be overwhelmed with the size. This model would also allow for the two wheels to spin independently of one another with a fixed axle, therefore allowing for tighter and faster turns. The handles on the “Raging Duck Cart” are designed to be higher up than the “Nascar” Model, allowing for less force on the cart and more ease of pulling for the driver. The team created a Pugh Chart, shown in Table 1, in order to confirm that the “Raging Duck Cart” model would be the best design, based on the team’s functional requirements and the SMC criteria.

Table 1: Pugh Chart for Three Designs

CRITERIA	**“Chariot-Tricycle” Model**	**“Nascar” Model**	**“Raging Duck Cart” Model**
Maneuverability	0	1	2
Ability to support different driver size	0	1	2
Level of ease for push/pull of cart	0	1	2
Simplicity of design/time to build	2	0	1
TOTAL	**2**	**3**	**7**

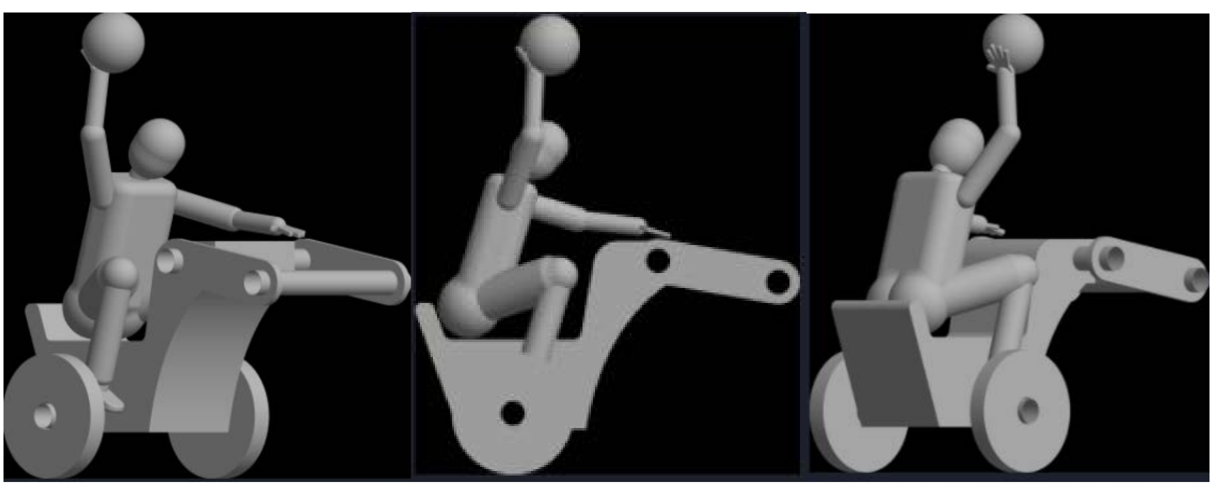


Figure 4: 3D Model of the “Raging Duck Cart” with a 5’10” Rider

Kana and Ante worked on 3D Models of the “Raging Duck Cart” so that is could be visualized before being cut by the CNC in the IDEA Shop. Jay and Ante worked on some physical testing of the materials for strength, while Kana performed stress testing electronically. Kana, the smallest rider, and Ante, the largest rider, both sat on a backwards chair in order to generate some ballpark numbers for the size of the cart. Based on the values found in the testing, and the ballpark numbers generated, the cart was designed with specific measurements, shown below in Figure 5.

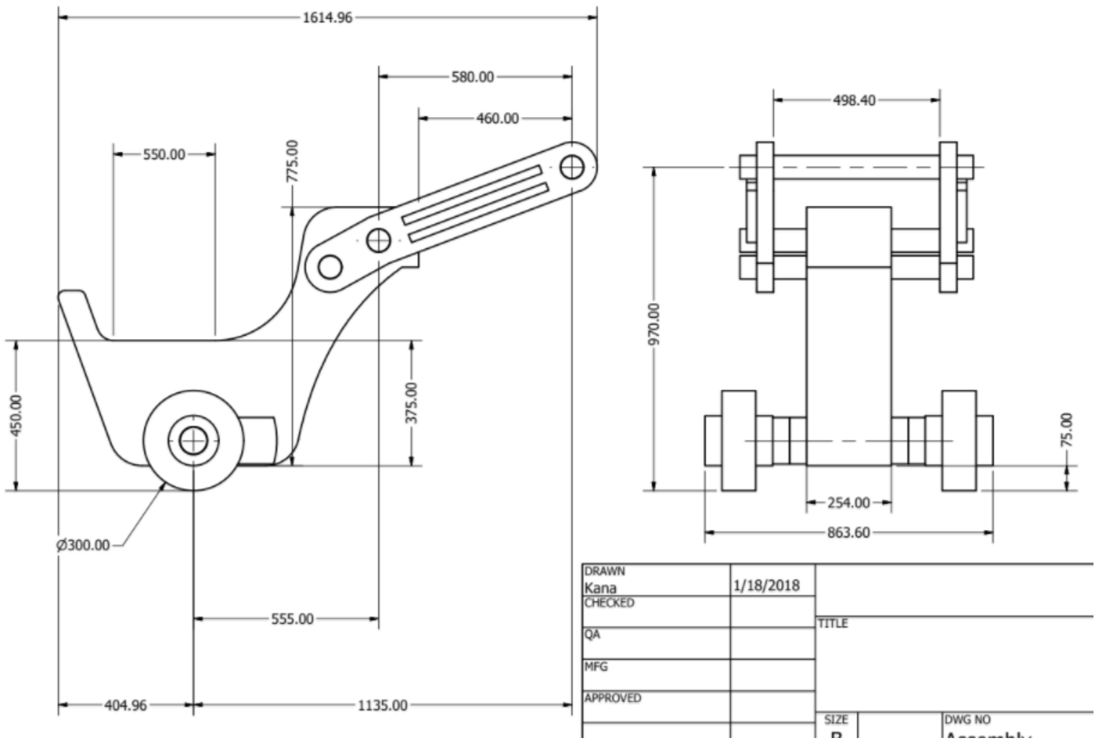


Figure 5: “Raging Duck Cart” Measurements for CNC Machine

The foam for the body and wheels was cut and were glued together with PL300 Foam Adhesive. Upon the first stages of the building and some simulated stress tests, it was deemed that the original design of the handles needed to be changed. The foam in the handles was going to be changed to cardboard tubes so that it would be more sturdy and easier for the driver to maneuver (see Figure 6 and 7).

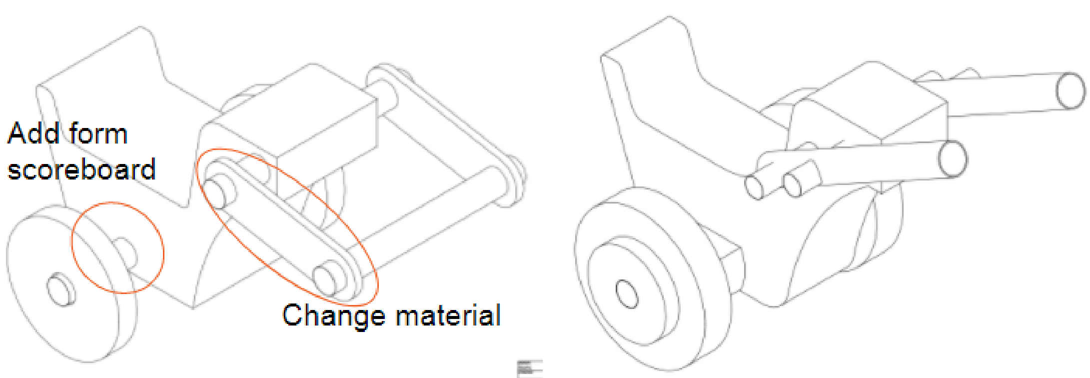


Figure 6: Change in the Material for the Handles

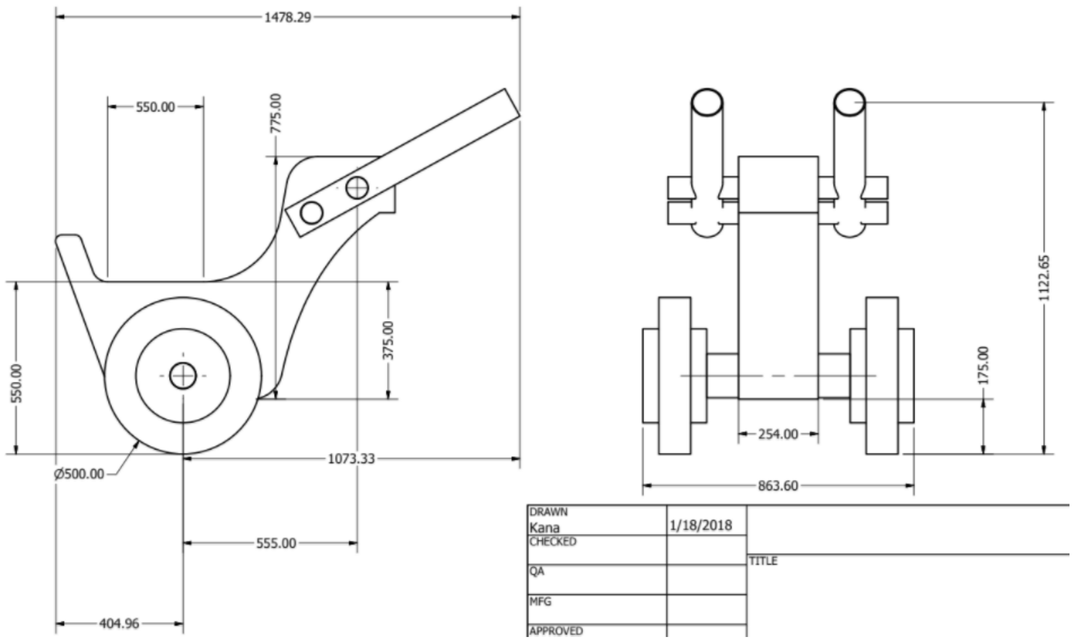


Figure 7: Dimensions of the Cart with the New Handle Design

This design would be carried through to the final design as the final cart was cut, glued, and taped together. Kana and Abe constructed the body from pink insulation foam and glue.. Joe and Shannon constructed the wheel and axle from pink insulation foam, glue, duct tape, and cardboard tubes. Ante and Jay constructed the newly designed handles from cardboard tubes and a power drill. The completed “Raging Duck Cart” that was brought to competition is shown below in Figure 8.

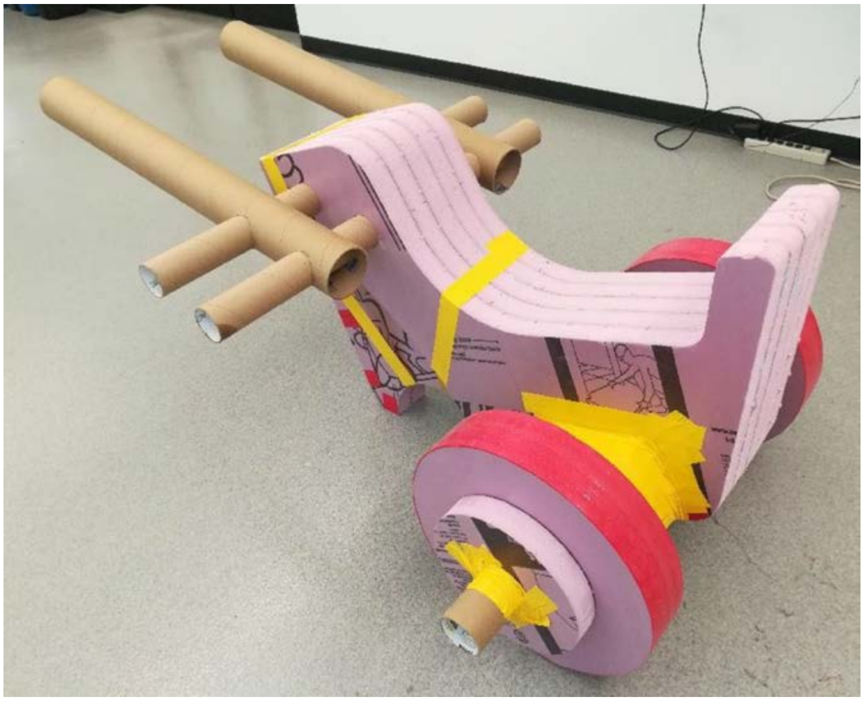


Figure 8: Completed “Raging Duck Cart”

Analysis

Analysis began by identifying the foam board and paper tube properties by carrying out experiments. The goal of the experiments were to find the elastic modulus (*E*), the stress of failure (σ), and the normal strain (ε) of both materials. The data collected from the experiments was used to calculate the maximum stress loading on the axis of the model, the maximum deflection of the axis, the compression of the wheel, and the moment in the body when the functional requirement weight was loaded. Then, the maximum weight that the model could support was determined.

A. Material Properties of Foam Board

To find the elastic modulus of foam board, the deflection of foam board was measured by performing a cantilever beam loading experiment (see Figure 9). The measured deflection from the experiment was then used into the following equation:

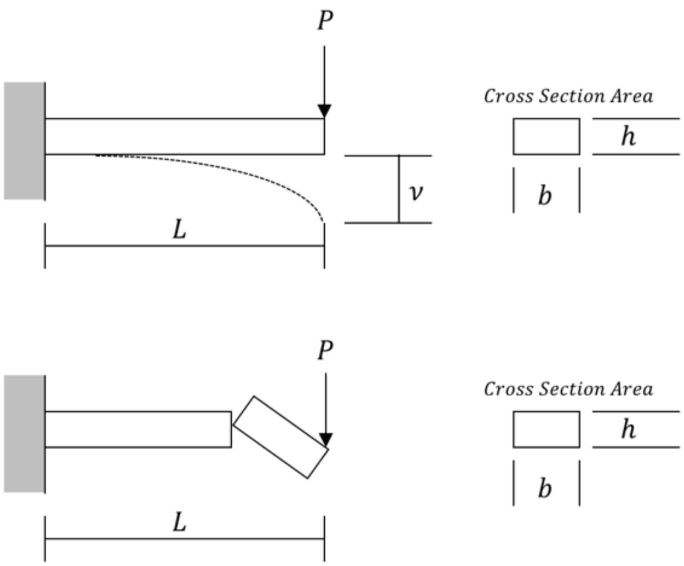
$$\nu = (-\square\square^{3})/(3\square\square) \quad (1)$$

where *v* is deflection (0.017 m), *P* is applied force (17.64 N), *L* is length (0.4 m), and *I* is moment of inertia (1.146E-06 $\square^{4}$). Thus, *E* is 19.32 MPa (see Table 2).

A similar experiment was carried out to find the failure stress of a foam board by using the equation:

$$\sigma_{\square\square\square} = (\square\square)/(\square) \quad (2)$$

where M is the maximum bending moment when a form board was broken (22.70 Nm), C is distance from neutral axis (0.025 m), and I is moment of inertia (1.146E-06 $\square^4$). As the result, $\sigma_{failure}$ is 0.495 MPa (see Table 2).



Find E	Form Board
L (m)	0.4
b (m)	0.11
h (m)	0.05
v (m)	0.017
I (m^4)	1.146E-06
P (N)	17.64
E (MPa)	19.32

Find Max stress	Form Board
P (N)	37.83
L (m)	0.60
b (m)	0.11
h (m)	0.05
I (m^4)	1.146E-06
M (Nm)	22.70
c(m)	0.025
σ (MPa)	0.495

Figure 9: Cantilever Beam Experiment for Foam Board
Table 2: Material Properties of the Foam Board

Normal strain is defined by the following equation:

$$\sigma = \square\square \qquad (3)$$

By manipulating Equation 3 and using the appropriate values of σ = 0.495MPa for the normal stress and E = 19.32 MPa for the elastic modulus, ε was found to be 0.0256.

Using this data, the Hooke's Law stress-strain curve was evaluated (see Figure 10). Foam board is very brittle so it broke rather easily. The break is shown where the curve discontinued.

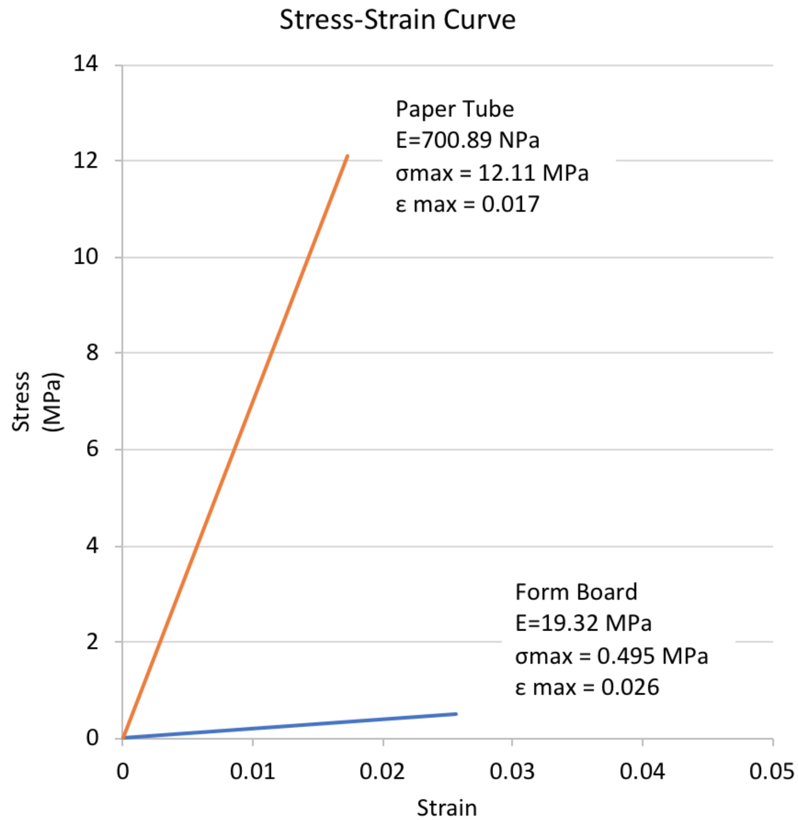


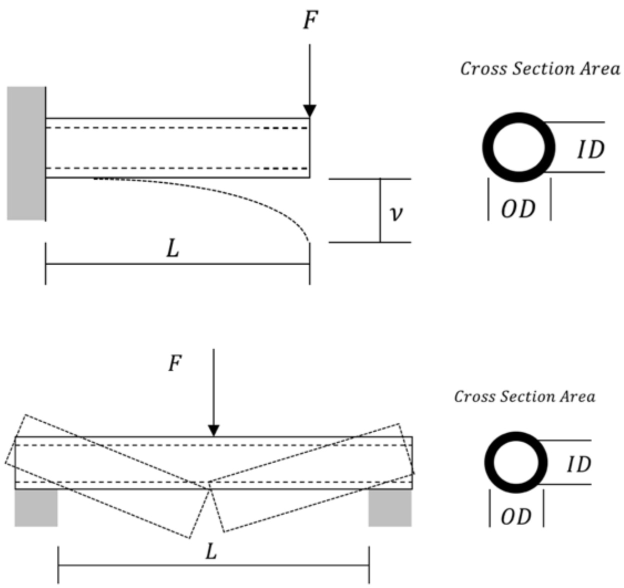
Figure 10: Stress-Strain Curve

B. Material Properties of Paper/Cardboard Tube

To find the elastic modulus of the paper tube, the same experiment that was used for the foam board was conducted with the paper tube (see Figure 11). The experimental value of deflection was applied to the Equation 1 where v is deflection (0.004 m), P is applied force (17.64 N), L is length (0.6 m), and I is moment of inertia (4.530E-07 □^{4}). As the result, E for the paper tube was determined to be 700.89 MPa (see Table 3).

Next, the experimental value was applied to the equation 2 to find the failure stress of the paper tube. M is the maximum bending moment (156.8 Nm), C is the maximum distance from neutral axis (0.035 m), and I is the moment of inertia (4.530E-07□^{4}). As the results, $\sigma_{failure}$ was determined to be 12.11 MPa (see Table 3).

Lastly, Hooke's law (equation 3) was used to find the normal strain. $\sigma$is the normal stress (12.11 MPa) and E is the elastic modulus (700.89 MPa), this ε was determined to be 0.0173. The paper tube was also very brittle, so the curve for paper tube also discontinues (see Figure 10). However, based upon the data, it was obvious that the paper tube was stronger than the foam board and thus the team deemed that the paper tube should be used in areas that had heavier loads.



Find E	Paper Tube
L (m)	0.6
OD(m)	0.07
ID (m)	0.062
v (m)	0.004
I (m^4)	4.530E-07
P (N)	17.64
E (MPa)	700.89

Find Max stress	Paper Tube
P (N)	392
L (m)	0.4
OD(m)	0.07
ID (m)	0.062
I (m^4)	4.530E-07
M (Nm)	156.80
c(m)	0.035
σ (MPa)	12.11

Figure 11: Experimental Setup for Paper Tube
Table 3: Material Properties of Paper Tube.

C. The Maximum Stress Loading on the Axle

From the functional requirements, the maximum load on the axle is 225 lbf, which is approximately 980 N. Due to the structure of the device, the force is distributed uniformly. Therefore, the distribution load can be calculated:

$$w = P/L \quad (4)$$

where *P* is the force (980 N) and *L* is the length of the axle (0.6 m). As a result, *w* is 1484 N/m.

Next, the maximum bending moment (see Figure 12) was computed. σ_{max} was found to be 3.92 MPa by using equation 2. Since the max stress was found to be smaller than the failure stress 12.11 MPa, the team’s device would not break when functional requirement weight was loaded. The device was evaluated further to have a safety factor of 3.

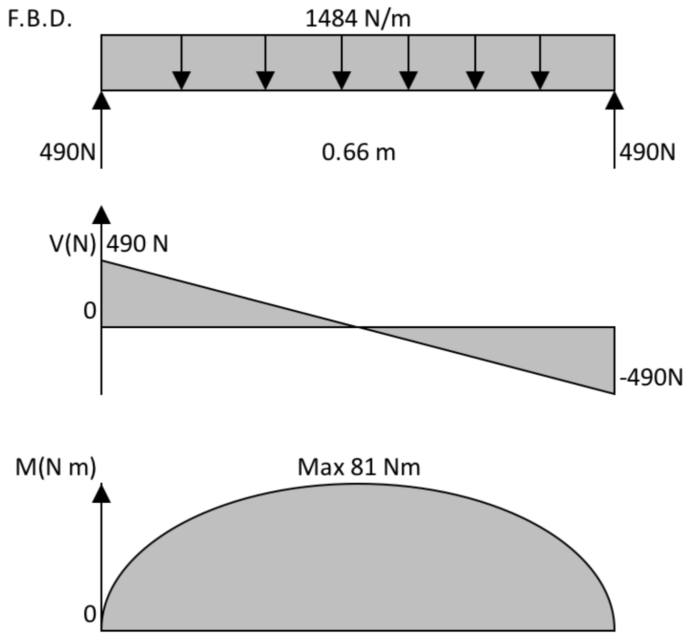


Figure 12: Force and Moment Diagram of the Axle

D. The Maximum Deflection of the Axle

To estimate the maximum deflection of the axle, an experiment was conducted by using the situation of a distributed load on a simply supported beam. Data was evaluated using the following equation:

$$\nu = (-5\square\square^{4})/(384\square\square) \qquad (5)$$

where *w* is distributed load (1481 N/m), *L* is the length (0.66 m), *E* is the elastic modulus (700.89 MPa), and *I* is moment of inertia (8.58E-07 $\square^4$). Thus, the deflection of the axle was found to be *v* = -6.1 mm.

E. The Compression of the Wheel

To verify the compression of the wheel, another experiment was conducted. The team made a foam board specimen with an area of 0.02 $\square^2$ and an applied compressive force of 930N. This is the same as 0.0465 MPa stress that was determined previously. It was observed that there was no deformation with the applied load. According to this calculation, the stress on the wheel was estimated to be 0.038 MPa (see Figure 13). The team determined that the wheel would not be crushed when the functional requirement load was applied to the cart sinc 0.038 MPa was smaller than failure stress of 0.495 MPa.

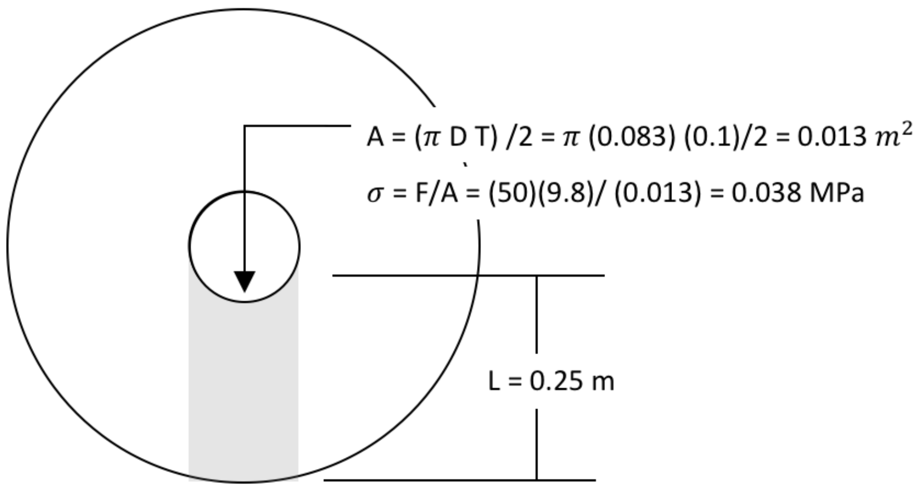


Figure 13: Wheel Compression Experiment

F. The Moment in the Body

It was assumed for experimental purposes that the force would be applied to the device's body when it was pushed or pulled. The weakest point was the thinness parts and the worst case was when the rider's center of mass was apart from the axis (see Figure 14). Using equation 2 where, *M* is 63.48 Nm, *C* is 0.095m, and I is 1.43E-04 □^{4}, the maximum bending stress was found to be 0.042 MPa. This value was smaller than the failure stress of 0.495 MPa and so it was determined the device would not break even at its weakest points.

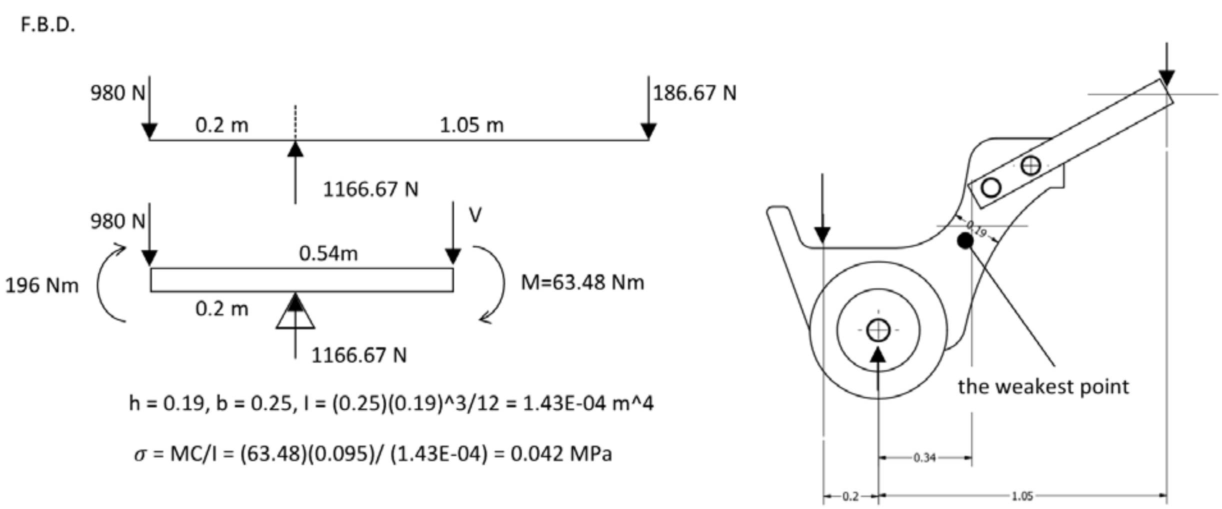


Figure 14: The Moment in the Body

G. The Theoretical Maximum Weight

This calculation was to determine the maximum that the axle could support before failure. Equation 2 gave the maximum bending moment where the failure stress (σ) is 12.11 MPa, *C* is 0.0415, and *I* is 8.58E-07□^{4}. As the result, □$_{□□□}$= 250 Nm, and the force which would break the axle was determined to be 3030 N. This value can be evaluated to be about

309.21 kg if it is divided by the acceleration due to gravity of 9.8 m/□^{2}. Since none of the team members were even close to this weight, the device was deemed safe enough for all riders of the group.

H. Weight Cost

The device that the team constructed did not use any material other than foam board, paper tube, glue, and tape so there was not any non-paper weight penalty. Therefore, weight cost was the gross weight of our model. The density of paper foam board and paper tube was determined by measuring the volume and mass of both materials' sample. Density of foam board was 0.027 g/□^{3}, and density of paper tube was 0.477 g/□^{3}. Total volume of the model was determined by CAD to be 0.153 □^{3}. From the total volume and density of both materials, the weight of the model was 5.8 kg. The weight cost of the device was submitted to the instructor prior to competition by using the follow equation provided in the SMC handout.

$$Weight\_cost = Gross\ weight\ (kg) + 30*non\text{-}paper\ weight\ (kg) \quad (6)$$

Reflection

The Raging Ducks worked really well together. The group came up with some really unique ideas. The team found that it was important to work together because different members have different strengths than others. During the competition the model worked very well. It was one of the only carts that did not have any failures while being used. If allotted more time, the team would have tried to run some more testing with the cardboard tubes and the foam in order to see the best way to design the wheels and axle. The team also would have liked to test out other types of adhesives and run some testing on those as well. Overall, the competition was very successful and a great learning experience.

Figure 15: Raging Duck Model Before and After Competition (no damage)

Sources

Budynas, R. G., Nisbett, J. K., & Shigley, J. E. (2011). *Shigley's Mechanical Engineering Design*. New York: McGraw-Hill.

Philpot, T. A. (2008). Mechanics of Materials: An Integrated Learning System. Hoboken, NJ: J. Wiley.