2013

Reliance: Herreshoff Marine Museum

Arnold Robinson
Community Partnerships Center, cpc@rwu.edu

George Dalton

Sean Damico

Eric Doremus

Brian Fortier

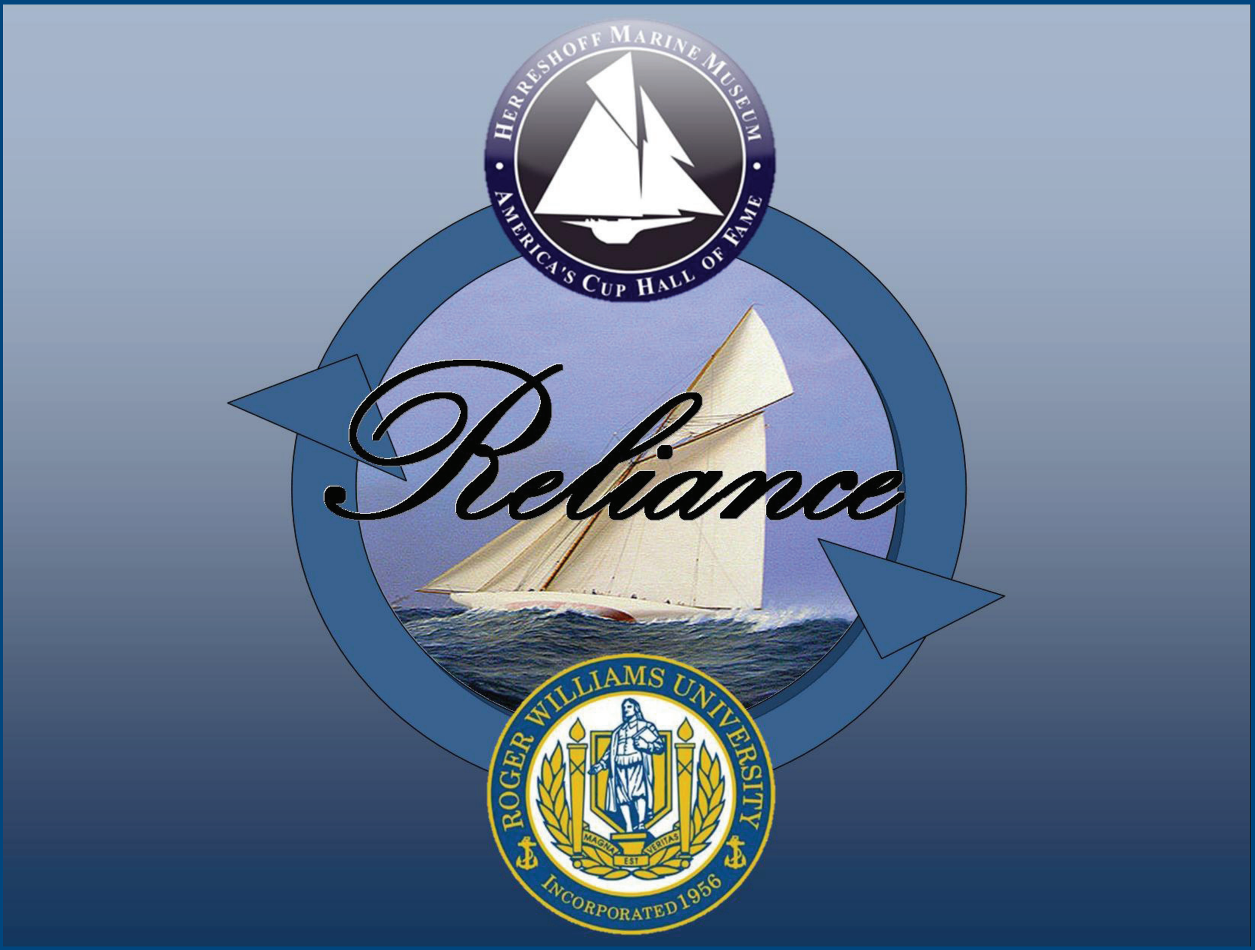
See next page for additional authors

Recommended Citation

Robinson, Arnold; Dalton, George; Damico, Sean; Doremus, Eric; Fortier, Brian; Goncalo, Jeffrey; and Lee, Arthur, "Reliance: Herreshoff Marine Museum" (2013). *Engineering and Construction Management.* Paper 1.
http://docs.rwu.edu/cpc_ecm/1

Authors
Arnold Robinson, George Dalton, Sean Damico, Eric Doremus, Brian Fortier, Jeffrey Goncalo, and Arthur Lee

Roger Williams University
Reliance Team
2012



The Roger Williams University Community Partnerships Center

The Roger Williams University (RWU) Community Partnerships Center (CPC) provides project-based assistance to non-profit organizations, government agencies and low- and moderate-income communities in Rhode Island and southeastern Massachusetts. Our mission is to undertake and complete projects that will benefit the local community while providing RWU students with experience in real-world projects that deepen their academic experiences.

CPC projects draw upon the skills and experience of students and faculty from RWU programs in areas such as:

- Architecture and Urban Design
- Historic Preservation
- Law
- Justice Studies
- Business
- Education
- Engineering and Construction Management
- Environmental Science and Sustainability
- Community Development
- Visual Arts and Digital Media
- Marketing and Communications
- Graphic Design
- Political Science
- Psychology
- History
- American Studies
- Finance
- Public Administration
- Public Relations
- Writing Studies
- Sustainable Studies

Community partnerships broaden and deepen the academic experiences of RWU students by allowing them to work on real-world projects, through curriculum-based and service-learning opportunities collaborating with non-profit and community leaders as they seek to achieve their missions. The services provided by the CPC would normally not be available to these organizations due to their cost and/or diverse needs.

CPC Project Disclaimer: The reader shall understand the following in regards to this project report:

1. The Project is being undertaken in the
public interest;

2. The deliverables generated hereunder are intended to provide conceptual information only to assist design and planning and such are not intended, nor should they be used, for construction or other project implementation. Furthermore, professional and/or other services may be needed to ultimately implement the desired goals of the public in ownership of the project served.

3. The parties understand, agree and acknowledge that the deliverables being provided hereunder are being performed by students who are not licensed and/or otherwise certified as professionals. Neither RWU nor the CPC makes any warranties or guarantees expressed or implied, regarding the deliverables provided pursuant to this Agreement and the quality thereof, and Sponsor should not rely on the assistance as constituting professional advice. RWU, the CPC, the faculty mentor, and the students involved are not covered by professional liability insurance.

4. Neither RWU, the CPC, the faculty mentor, nor the students involved assume responsibility or liability for the deliverables provided hereunder or for any subsequent use by sponsor or other party and Sponsor agrees to indemnify and hold harmless RWU, the Center, the Faculty Mentor, and the Center's student against any and all claims arising out of Sponsor's utilization, sale, or transfer of deliverables provided under this Agreement.

Community Partnerships Center
Roger Williams University
One Old Ferry Road
Bristol, RI 02809
cpc@rwu.edu
http://cpc.rwu.edu

Community Partnerships Center
At Roger Williams University

ENGR 490
Fall 2012

Building a Museum Quality, 1/6th Scale Replica of the 1903 Americas Cup Defender,

Submitted: 12/14/2012
Lead Engineers: George Dalton | Sean Damico | Eric Doremus | Brian Fortier | Jeffrey Goncalo
Client: Arthur Lee | Herreshoff Marine Museum
Faculty Supervisor: Dr. William Palm
Technical Mentor: Dr. Gilbert Brunnhoeffer
In Partnership With: Herreshoff Marine Museum, Bristol RI

Abstract

The Roger Williams University Reliance team is working in cooperation with the Herreshoff Marine Museum in Bristol, RI to create a 1/6th scale model of the 1901 Americas Cup defender, the Reliance. The project can be broken up into two sub-projects. The first, to design a museum-quality cradle to hold the 24ft fully rigged model at a 15O angle. The second sub-project is to perform full strength/structural analysis of all the critical components on the model to ensure that their strength is great enough to withstand the applied forces. This second sub-project is going to be the focus of the spring 2013 semester while the Fall 2012 semester focused on the cradle design.

After determining our final cradle design, structural analysis validated the use of two square channel 4"x4"x0.5" steel columns for the 'legs' of the cradle, while 3/8" bolts secured C 3x3.5 A36 steel outrigger beams to the center beam constructed of American Standard S 3x5.7 A36 steel.

Table of Contents

List of Figures

List of Tables

List of Acronyms

RWU	Roger Williams University
HMM	Herreshoff Marine Museum
MFA	Museum of Fine Arts

Introduction

Our client and project manager, Sandy Lee from the Herreshoff Marine Museum (HMM), proposed a design project to the students of the Engineering Design course at Roger Williams University to assist the HMM in the building of a 1/6th scale replica of the 1901 Americas Cup Defender, the *Reliance*. This project includes structural analysis of the critical components on the model, as well as design and analysis of a cradle that will hold the model at a 150 angle. The original Reliance yacht measured 205ft from the tip of the bowsprit to the end of the boom and 220ft from the bottom of the keel to the tip of the topmast. Our 1/6th scale replica will measure roughly 33ft from tip to tip and 37ft from keel to tip of topmast. This scaled model will be fully rigged with sails and all the rigging components will be produced using similar materials to those that were used on the original yacht.

Looking deeper into the designing of a cradle and structural analysis of critical components, for ease of construction, the HMM would also like expertise on structural adhesives that may be used on the model and cradle designs. Our goal is to develop the cradle design in such a manner that it meets all requirements of the client including but not limited to portability, display angle, and above all safety.

After reviewing what needed to be done to complete the design project, our team broke down the work for the 2012 fall and 2013 spring semester. It was determined that the most practical approach would be to finalize a cradle design by the end of the fall semester and perform all structural analysis on the model during the spring semester.

At the beginning of our fall semester the HMM and Mr. Lee seemed to have a very clear vision of what they wanted for the cradle design. After extensive communication between the group and Mr. Lee, we found our list of customer needs growing with each meeting. Through our meetings with Mr. Lee we formed a list of cradle design constraints and assumptions, as shown below, to guide our team in the formulating of our designs.

1. Cradle Design Constraints
    a. Needs to be portable
    b. 15 degree tilt
    c. Structurally sound
    d. Aesthetically pleasing
    e. Low cost
    f. Less obtrusive is better
2. Assumptions
    a. Model will never be placed in the water or sailed
    b. Model will never be displayed without the cradle
    c. Model will be indoors at all times

One of the key objectives of our project was to have displays of the hull, deck and spars in time for this year's July 4th activities that will take place in Bristol.

To ensure our team is staying on task we have adopted the following mission statement:
"The 2012-2013 Herreshoff Marine Museum Senior Design project encompasses numerous tasks to assist the Herreshoff team in the structural design and analysis of a 1/6th scale model of the *Reliance* with safety and quality at the highest priority."

Throughout the year we plan to look back on our mission statement to ensure we have not lost sight of our goals and ensure we are working to satisfying the needs of our client, the Herreshoff Marine Museum. We are happy to provide aid to a local non-profit organization to establish a partnership between Roger Williams University and the local community to hope to build on this relationship in the years to come.

Project Planning

The RWU Reliance team is composed of 5 senior civil engineering students as well as two faculty mentors and supervisors. George Dalton, Sean Damico, Eric Doremus, Brian Fortier, and Jeffrey Goncalo make up the student portion of the group. The team's technical mentor is Dr. Gilbert Brunnhoeffer while Dr. William Palm acts as the team's supervisor.

George Dalton has engaged a lead role in creating SolidWorks models of various parts of the model, such as the boom, gaff, and spars, as well as deriving a process to calculate the center of gravity of the hull. He worked with Eric Doremus to present at the 2012 RI-ASCE Spain dinner in Narragansett, RI and has made a major contribution towards the final cradle design specifications.

Sean Damico has taken the role as the student project manager. His expertise in SolidWorks has been put to use to create several drafts of the many cradle designs that developed during the course of this project. He has organized the team, using resources such as Microsoft Project to keep the team on track and on schedule. In addition to this, Mr. Damico has put forth a major effort in milestone reports as well as analysis and design of the final cradle design.

Eric Doremus has assumed the responsibility of drafting a 3D model of the hull in SolidWorks and drafting the initial team PowerPoint presentations. He has also been put in charge of the team's binder as well as putting together the final report, making sure that all important documents, emails, and meetings are accounted for. His knowledge and experience of 3D printing technology as well as SolidWorks experience has been put to use during the course of this project.

Brian Fortier created his own unique cradle design as well as worked hand in hand with Mr. Dalton to calculate the center of gravity of the model hull. He has played a major role in the completion of the various Milestone Reports and has made many contributions towards finalizing the member sizing in our final cradle design.

Jeffrey Goncalo put forth a major effort to calculate the center of gravity of the upper rigging of the model. He has put forth a major effort towards the creation of PowerPoint's, milestone reports, as well as revisions to finalize the cradle design.

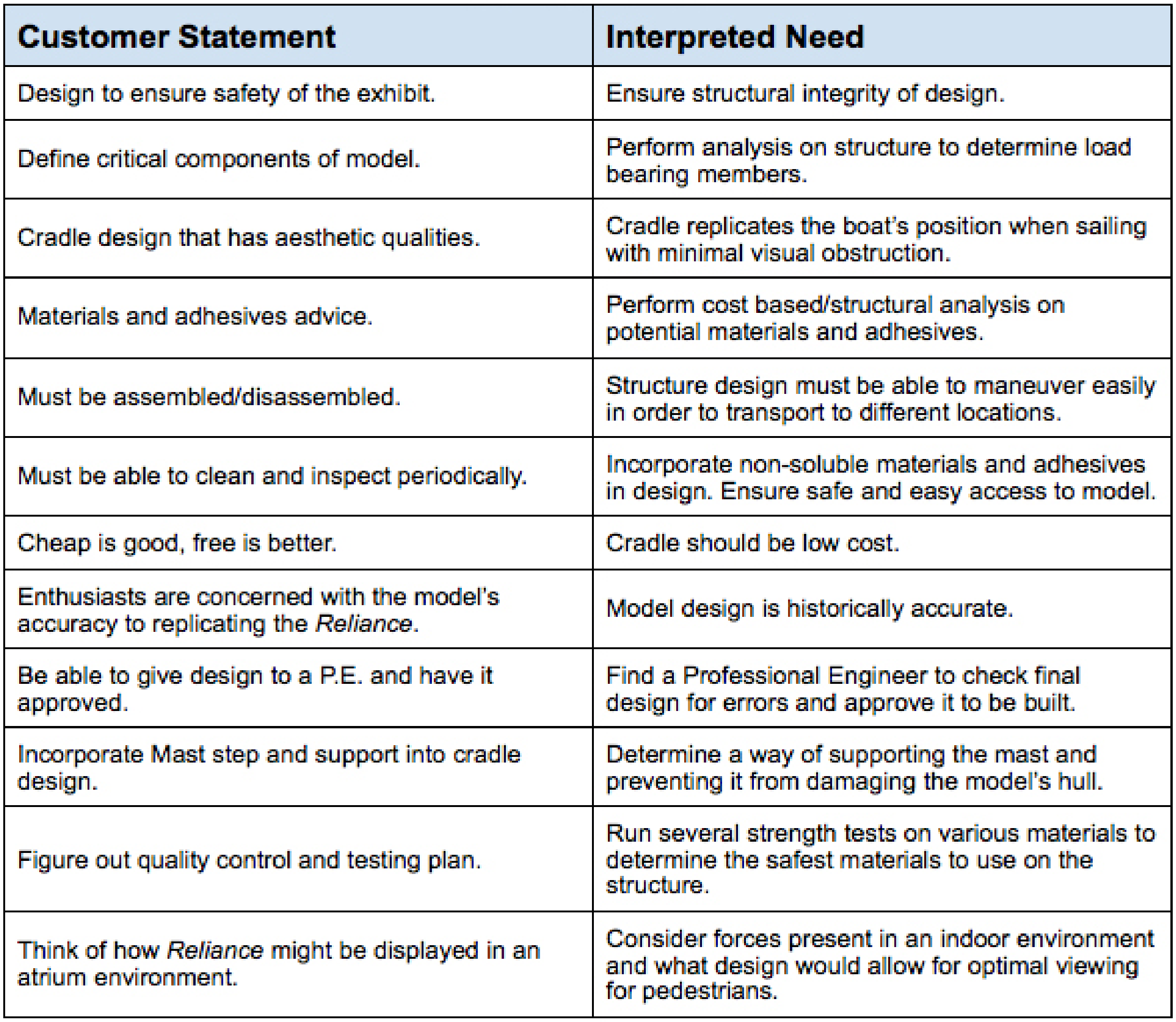
Customer Needs Analysis

Data Collection Approach

Upon receiving our initial project statement on September 17th, an interview with Mr. Lee, the HMM Reliance Project Manager, was immediately established for September 20th. In preparation for the meeting our group composed several questions that were emailed to Mr. Lee for our meeting. During our meeting, Mr. Lee relayed his answers in great detail including what he would like to see as the final outcome of our year-long project. At the meeting we observed the layout of the museum, the proposed location of the display, and the actual hull of the *Reliance* model. Mr. Lee also presented copies of the original *Reliance* plans for construction. After determining the team's objectives, it was recognized that the project was going to require a great deal of information regarding the specifications of the model. It was communicated to Mr. Lee that it would be necessary for the team to acquire extensive plans in order to successfully analyze the model and create an effective cradle design. Mr. Lee was able to scan what plans he had onto a disk as well as draw several views of the model in detail. The disks and drawings were transferred to Mr. Damico on Saturday, September 29th. The team continued to stay in contact with Mr. Lee for future required data including, but not limited to, the weight of the model, center of gravity, weight of mast, material of mast, hull cross sections, and the thickness of the hull.

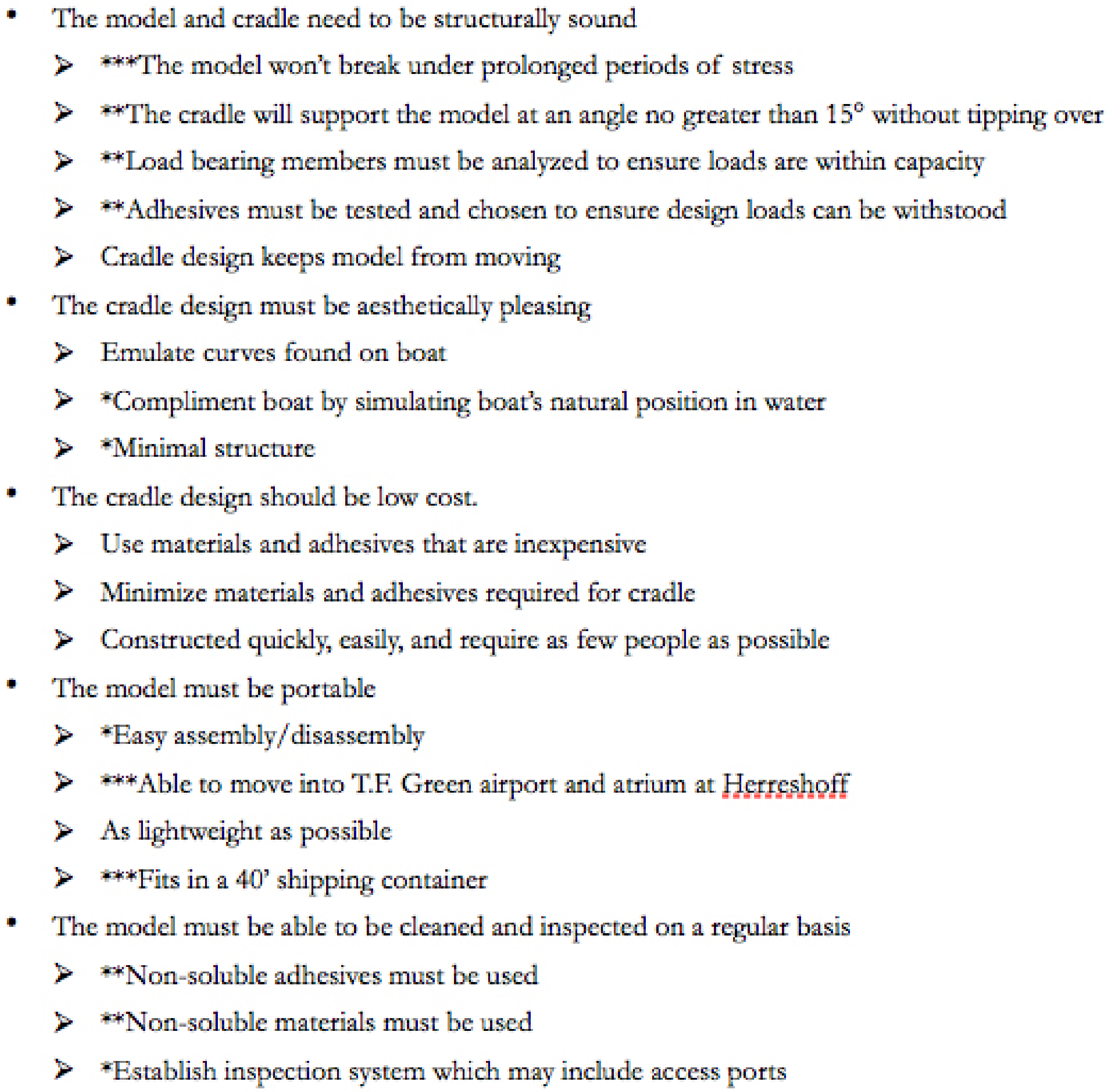
Summary of Raw Data

Table 1: Customer Needs



Customer Statement	Interpreted Need
Design to ensure safety of the exhibit.	Ensure structural integrity of design.
Define critical components of model.	Perform analysis on structure to determine load bearing members.
Cradle design that has aesthetic qualities.	Cradle replicates the boat's position when sailing with minimal visual obstruction.
Materials and adhesives advice.	Perform cost based/structural analysis on potential materials and adhesives.
Must be assembled/disassembled.	Structure design must be able to maneuver easily in order to transport to different locations.
Must be able to clean and inspect periodically.	Incorporate non-soluble materials and adhesives in design. Ensure safe and easy access to model.
Cheap is good, free is better.	Cradle should be low cost.
Enthusiasts are concerned with the model's accuracy to replicating the *Reliance*.	Model design is historically accurate.
Be able to give design to a P.E. and have it approved.	Find a Professional Engineer to check final design for errors and approve it to be built.
Incorporate Mast step and support into cradle design.	Determine a way of supporting the mast and preventing it from damaging the model's hull.
Figure out quality control and testing plan.	Run several strength tests on various materials to determine the safest materials to use on the structure.
Think of how *Reliance* might be displayed in an atrium environment.	Consider forces present in an indoor environment and what design would allow for optimal viewing for pedestrians.

Hierarchical List of Primary and Secondary Needs



- The model and cradle need to be structurally sound
  - ***The model won't break under prolonged periods of stress
  - **The cradle will support the model at an angle no greater than 15° without tipping over
  - **Load bearing members must be analyzed to ensure loads are within capacity
  - **Adhesives must be tested and chosen to ensure design loads can be withstood
  - Cradle design keeps model from moving
- The cradle design must be aesthetically pleasing
  - Emulate curves found on boat
  - *Compliment boat by simulating boat's natural position in water
  - *Minimal structure
- The cradle design should be low cost.
  - Use materials and adhesives that are inexpensive
  - Minimize materials and adhesives required for cradle
  - Constructed quickly, easily, and require as few people as possible
- The model must be portable
  - *Easy assembly/disassembly
  - ***Able to move into T.F. Green airport and atrium at Herreshoff
  - As lightweight as possible
  - ***Fits in a 40' shipping container
- The model must be able to be cleaned and inspected on a regular basis
  - **Non-soluble adhesives must be used
  - **Non-soluble materials must be used
  - *Establish inspection system which may include access ports

Importance ratings for the secondary needs are indicated by the number of *'s, with *** denoting critically important needs.

Reflections on Results and Process

We have interacted with the client a great deal since the beginning of the project. Through these exchanges, we have discovered numerous design objectives the client would like us to achieve. The needs of our customer were prioritized by what Mr. Lee discussed when asked what he wanted us to accomplish. Since our cradle design will be seen by the general public, safety is of the utmost importance. All of the structural needs were based off of the idea of making it safe, whereas all of our other needs dealt with the structure's aesthetic appeal. Some aspects of the structure's aesthetics were determined more important than others based on what Mr. Lee stressed multiple times. Furthermore, we realized that these objectives will be hard to achieve if we are not given numerous specifications relating to the model. We will be working with Mr. Lee periodically to ensure all desired model information is acquired.

To gain an even greater understanding of the customers' needs, we could interact with people other than our project manager, Mr. Lee. The *Reliance* model is being built for museum visitors, so their input is also very important. We could interview these museum visitors or have them fill out a survey to get an understanding of what they would like to see. In order to get possible overlooked information on the *Reliance*, we could talk to the Herreshoff Museum staff, volunteers, or the *Reliance* enthusiasts that Mr. Lee has mentioned to us. While we feel we have a great understanding of what our customers' needs are, our team needs to make sure everyone affected by this project's voice is heard.

Target Specifications

Executive Summary

The target specifications were concluded by analyzing customer needs, constraints, and various similar designs on the market today. Although numerous metrics already exist within our project due to the lack of alterations to the model, we comprised a list based on the needs and design goals given to us by our client. The metrics are compared to those in similar projects in the maritime and marine modeling field. However, due to the nature of this project being a custom build many typical applications do not closely coincide with those found in this project. Ultimately from our analysis we were able to determine the key metrics that will prove to define the success of our work as it relates to meeting and or exceeding our client's needs.

Introduction

The following analysis is based upon the needs presented to us by our client Mr. Lee from the Herreshoff Marine Museum. Most needs were generated from specific lines of work necessary to the success of the overall project. Others have stemmed from these to cover all necessary work to be completed. From these needs a system of metrics were developed to account for necessary standards and means by which our design and analysis must adhere to for overall success of the desired requirements. In Table 4 a comparison of each metric is made to their designated need.

In the subsequent Tables the costumers needs and their respective metrics have been benchmarked to those of similar projects and or practices currently found in the field today. The *Reliance* project has been compared to the Americas Cup Exhibit at the MFA in Boston, The *Defiant*, currently on exhibit outside the HMM, and standardized boat supports found at the Newport Boat Yard. From these three outside sources we are able to gain a greater understanding of both the importance of each need as it pertains to similar projects and how well each source correlates by means of metrics.

Benchmark Comparisons

The Americas Cup exhibit at the MFA in 2005 showed two full size Americas Cup sailboats tilted at a slight angle to replicate the looks as if they were under sail. Although these boats were placed outside and were not rigged with any sails, we were inspired by the fact that they were only supported by cables. The 1992 Americas Cup contender, the Defiant is currently placed outside on a permanent, upright structure in front of HMM. This International Americas Cup Class boat is 75ft long and does not have any sails rigged at the time. Although this boat is not placed at an angle, it gave us a good idea on how we could possibly support the model. Standard boat supports, which can be seen at any boat yard, are typically used for short term storage. We have ruled these out of our possible cradle design because of their bulkiness and limited ability to place the boat at an angle. Since our design is so unique, it is hard to compare it with the benchmarks listed above. Our project stands out on its own because of the fact that HMM is trying to replicate a boat from 1903, using the same or similar materials that would have been found on the boat. The hull does not hold the normal structural integrity that the actual boat would have, so a unique cradle design with an internal support is necessary to provide structure to the model.

Methods and Results

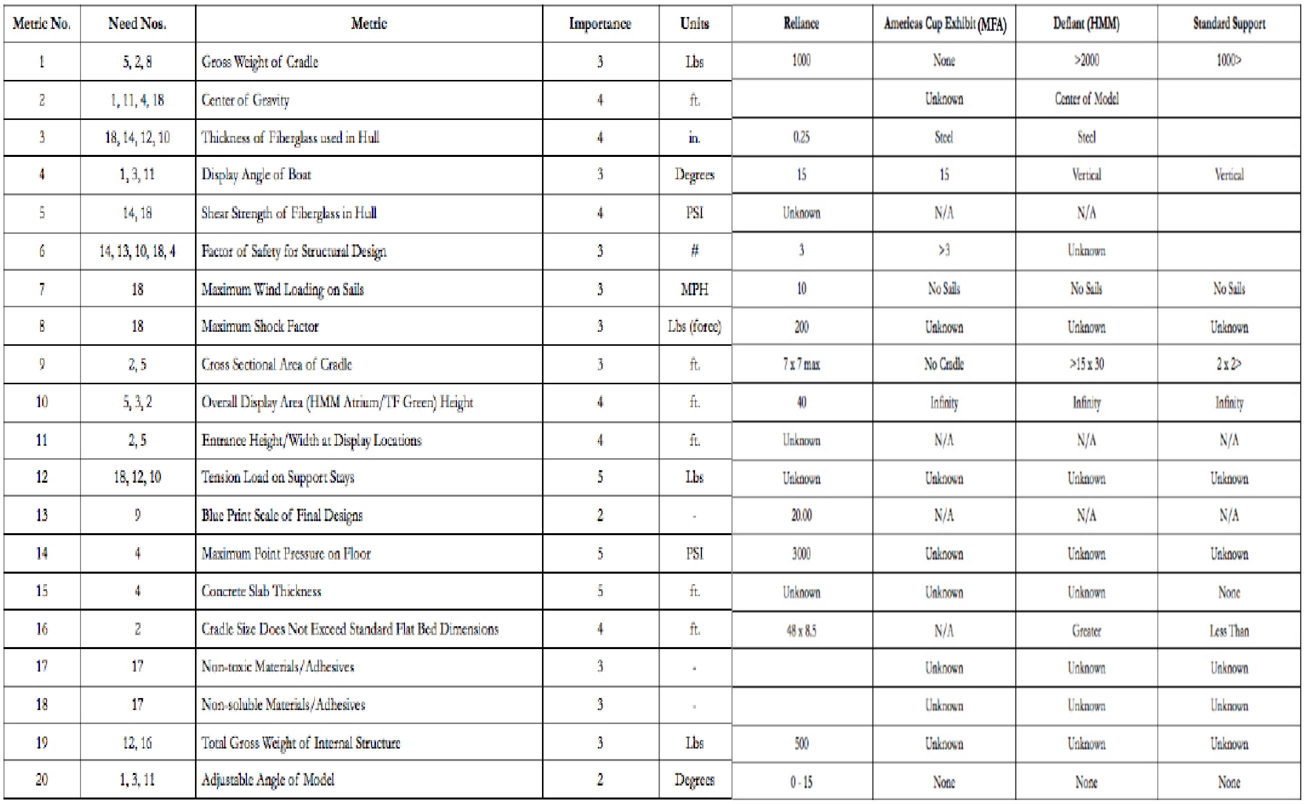
Specifications were established through a multi-step process which translated customer need into design specifications. First, a customer needs table was created and the importance of each need was ranked on a scale of one to five as displayed in Table 2. The customer needs were established through client meetings in which our group was briefed on their overall vision of the project. The importance rating assigned to each need was determined by considering the clients stress on the individual need as well as its importance to the overall outcome of the project.

Table 2: Project Metrics based upon customer needs as listed in Table 1. Each metric is related to specific needs and ranked by importance. Units have been provided for each metric in the quantity in which they are evaluated.

Metric No.	Need Nos.	Metric	Importance	Units
1	5, 2, 8	Gross Weight of Cradle	3	Lbs
2	1, 11, 4, 18	Center of Gravity	4	ft.
3	18, 14, 12, 10	Thickness of Fiberglass used in Hull	4	in.
4	1, 3, 11	Display Angle of Boat	3	Degrees
5	14, 18	Shear Strength of Fiberglass in Hull	4	PSI
6	14, 13, 10, 18, 4	Factor of Safety for Structural Design	3	#
7	18	Maximum Wind Loading on Sails	3	Lbs (force)
8	18	Maximum Shock Factor	3	Lbs (force)
9	2, 5	Cross Sectional Area of Cradle	3	ft.
10	5, 3, 2	Overall Display Area (HMM Atrium/TF Green) Height	4	ft.
11	2, 5	Entrance Height/Width at Display Locations	4	ft.
12	18, 12, 10	Tension Load on Support Stays	5	Lbs
13	9	Blue Print Scale of Final Designs	2	-
14	4	Maximum Point Pressure on Floor	5	PSI
15	4	Concrete Slab Thickness	5	ft.
16	2	Cradle Size Does Not Exceed Standard Flat Bed Dimensions	4	ft.
17	17	Non-toxic Materials/Adhesives	3	-
18	17	Non-soluble Materials/Adhesives	3	-
19	12, 16	Total Gross Weight of Internal Structure	3	Lbs
20	1, 3, 11	Adjustable Angle of Model	2	Degrees

Next, a list of metrics surrounding the project was generated from the customer needs. The list consists of general specifications that will be needed to successfully complete the project since the Reliance consists of several hundred minor specifications that branch from those listed. The metrics were then linked to their correspondent customer needs in a needs-metrics matrix displayed in Table 3.

Table 3: Metrics Benchmarking. All metrics found in Table 2 are compared to three outside sources. As seen above many of the metrics do not correlate from the Reliance project to other models and or standards found in the field today.



Metric No.	Need Nos.	Metric	Importance	Units	Reliance	Americas Cup Exhibit (MFA)	Defiant (HMM)	Standard Support
1	5, 2, 8	Gross Weight of Cradle	3	Lbs	1000	None	>2000	1000>
2	1, 11, 4, 18	Center of Gravity	4	ft.		Unknown	Center of Model	
3	18, 14, 12, 10	Thickness of Fiberglass used in Hull	4	in.	0.25	Steel	Steel	
4	1, 3, 11	Display Angle of Boat	3	Degrees	15	15	Vertical	Vertical
5	14, 18	Shear Strength of Fiberglass in Hull	4	PSI	Unknown	N/A	N/A	
6	14, 13, 10, 18, 4	Factor of Safety for Structural Design	3	#	3	>3	Unknown	
7	18	Maximum Wind Loading on Sails	3	MPH	10	No Sails	No Sails	No Sails
8	18	Maximum Shock Factor	3	Lbs (force)	200	Unknown	Unknown	Unknown
9	2, 5	Cross Sectional Area of Cradle	3	ft.	7 x 7 max	No Cradle	>15 x 30	2 x 2>
10	5, 3, 2	Overall Display Area (HMM Atrium/TF Green) Height	4	ft.	40	Infinity	Infinity	Infinity
11	2, 5	Entrance Height/Width at Display Locations	4	ft.	Unknown	N/A	N/A	N/A
12	18, 12, 10	Tension Load on Support Stays	5	Lbs	Unknown	Unknown	Unknown	Unknown
13	9	Blue Print Scale of Final Designs	2	-	20.00	N/A	N/A	N/A
14	4	Maximum Point Pressure on Floor	5	PSI	3000	Unknown	Unknown	Unknown
15	4	Concrete Slab Thickness	5	ft.	Unknown	Unknown	Unknown	None
16	2	Cradle Size Does Not Exceed Standard Flat Bed Dimensions	4	ft.	48 x 8.5	N/A	Greater	Less Than
17	17	Non-toxic Materials/Adhesives	3	-		Unknown	Unknown	Unknown
18	17	Non-soluble Materials/Adhesives	3	-		Unknown	Unknown	Unknown
19	12, 16	Total Gross Weight of Internal Structure	3	Lbs	500	Unknown	Unknown	Unknown
20	1, 3, 11	Adjustable Angle of Model	2	Degrees	0 - 15	None	None	None

In order to compare the specifications of the Reliance Project with similar projects a metrics competitive benchmarking chart was created as shown in Table 4. Metrics of the comparative projects were determined through research of the projects. After establishing metrics of similar projects, the customer needs of our project were related to the comparative projects and ranked by importance. The customer needs importance of the related projects was determined through analysis of assumed goals of the respective designs.

Table 4: Needs Benchmarking. Each need as seen in Table 1 above has been compared to those in the three outside sources as seen in the last three columns. From this table we are able to see how the needs of our project correlate to those in other previously completed projects. This will allow us to easily find resources for problems that may develop among our specified needs and look into different means by which they were overcome.

No.	Field	Need	Importance	Americas Cup Exhibit (MFA)	Defiant (HMM)	Standard Support
1	Cradle	Tilts Model to Allow Viewing of Deck/Full Sails	4	*****	*	*
2	Cradle	Portable for Transfer to and from TF Green	5	*****	**	****
3	Cradle	Aesthetically Pleasing	3	******	***	*
4	Cradle	Supports Weight of Model	5	**	******	*****
5	Cradle	Minimal Structure	2	******	**	**
6	Cradle	No Movement of Model - All Around Safety	5	****	****	****
7	Cradle	Easy Assembly and Disassembly for Portability	3	***	**	****
8	Cradle	Light Weight	2	***	*	****
9	Cradle	Blue Prints For Final Review	4	*****	****	*
10	Model	Won't Break Under Prolonged Periods of Stress	5	******	*****	******
11	Model	Supported at Desired Angle Without Tipping	5	******	*****	******
12	Model	Analysis of All Load Bearing Members	4	****	****	*
13	Model	Adhesive Testing to Ensure Design Loads Can be Withstood	3	*	*	*
14	Model	Materials Testing to Ensure Design Loads Can be Withstood	4	****	****	*
15	Model	Establish Inspection Program	2	**	**	*
16	Model	Full Structural Analysis	4	****	****	*
17	Model	Ability to be Cleaned With Generic Products	2	****	****	****

Concept Generation

Executive Summary

Stemming from our client's needs and external visits, concept designs were constructed and compared. The client needs were then used to establish selection criteria and the concept designs were compared to determine how well they met the criteria. Each design was then given a rating for how well it met each selection criteria and a weighted rating system was constructed based on the importance of the criteria. The data concluded the hybrid designs met the most client needs and therefore should be examined further.

Introduction

Concept Designs have been formed by analyzing various criteria included in the customer needs and constraints. The concepts were all designed with the client's desires in mind, but take different approaches in doing so.

From our initial meeting with Mr. Lee on September 20th 2012, until our group meeting on October 18th, 2012, every member of our group brainstormed design ideas individually. Everyone was responsible for drafting a design for the cradle that would hold up the model. Throughout the process of identifying customer needs and developing target specifications, the group took unique measures of getting inspiration to come up with a creative solution to our design problem.

After our initial meeting on September 20th, Mr. Lee was kind enough to take the group on a tour of the Herreshoff Marine Museum and the workshops on the museum's grounds. We were able to see other large models of boats and how they were put on display. Although the display for the *Reliance* model will be unique to the other models currently at museum, we were able to see how a cradle enhances the viewing of the model. On the tour we were also able to see the hull of the *Reliance* model for the first time. Once seeing it in person, we were able to understand the grandeur this model will project once it is completed.

In front of the Herreshoff Marine Museum, is the International America's Cup Class boat, the *Defiant*. The boat is 75 feet long and is held upright. It is visible from Route 114, which the *Reliance* model will be too, once it is completed. The boat gave us on idea of how massive the rigging will be on our model in comparison to the hull.

On Saturday, September 22nd, the group took a trip to Newport, Rhode Island, to visit the Newport Shipyard. There were many different shapes, sizes, and types of ships that were in the water and held upright on land. While most of the ships were held upright by the standard steel blocks that are held placed around the hull, some required extra support to keep it up straight. One of the ships in particular, used a very thick rope tied from the top of the topmast to a large concrete block on the ground. This inspired the idea of cable stabilizers that appeared in a few of the early concept designs.

On October 18th, all members of the group came together in the Shawmut Construction Room in Roger Williams' Engineering building with our design concepts. We drew all of our designs on a giant whiteboard and went through the idea behind each design. We discussed what we liked about each design and what we thought wasn't pragmatic. As a group, we voted on three designs to move forward with and present to our project manager, Mr. Lee.

Concept Designs

Cantilever Cradle

Concept Design #1 allows for the model to be fully supported with minimal obstruction to the hull from the frontal view as shown below in Figure 1.

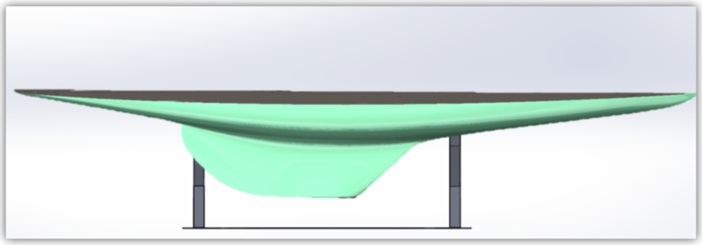


Figure 1: Cantilever Cradle front viewer's perspective

In this design the active rigging components tie directly into the internal structure and the hull itself is supported along the outside edge of the deck. This will ensure that there are no forces that will jeopardize the integrity of the fiberglass and that the mast and rest of the rigging components rely purely on the structural integrity of the internal structure, displayed below in Figure 2.

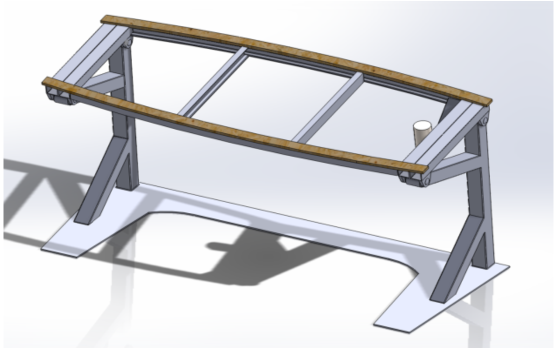


Figure 2: Cantilever Cradle internal structure and frame.

Looking into the internal structure itself we see that the mast is supported by a steel frame. The design of sailboats makes it so that at the mast connection point there are only direct compressive forces and the active stays are pure tensile forces. Because of this, the mast support frame will be acting against the compressive force exerted and the stays will be attached to the outer edge of the frame to take all of the tensile forces exerted. Ultimately by this concept we are completely removing the fiberglass hull from the model's structural integrity and the cradle itself could display the mast and the rest of the rigging without the hull in place.

To counteract the moment created by the cantilever design the rear of the upright structure will be bolted to the ground or in the case this is unobtainable, weight will be added to the rear of the base plate. As for the portability of the cradle the internal structure can be detached from the base and uprights by means of pins. This will allow for the two members to become completely separate from one another to enable ease of transportation and a smaller profile for access into the TF Green airport and other buildings in which it may end up before its final home at HMM.

Free Floating

Our second concept design is based off a previous display of America's Cup boats at the Boston Museum of Fine Arts by Roger Martin Design. This design is supported by a single steel column placed near the center of mass and connected to a ball and socket joint, as shown in Figure 3.

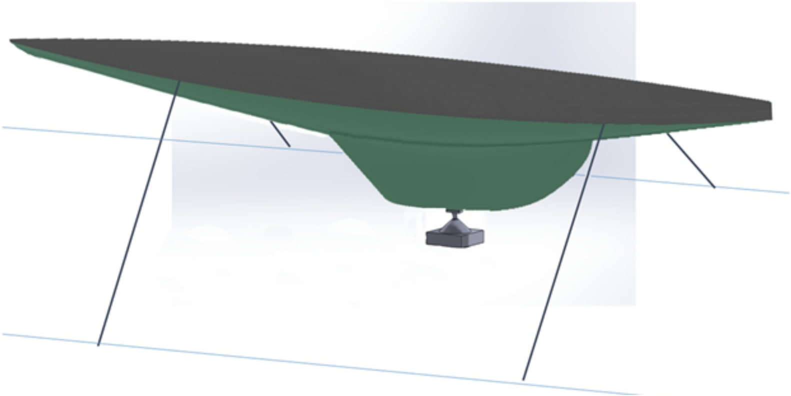


Figure 3: Free Floating viewer's perspective

Four stabilizing cables, two at the bow and two at the stern will be tied into a center column I-beam, which runs the length of the hull. A support cable connected to a wall or surface running parallel to the I-beam will act as additional support for the structure, as shown in Figure 4.

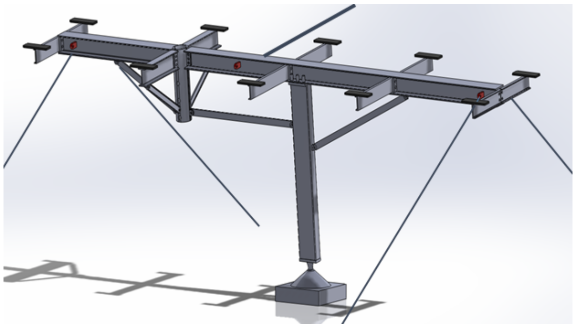


Figure 4: Free Floating internal structure

The internal structure will consist of a steel I-Beam extending the length of the hull, equipped with 5 C-channels and 1 I-Beam at the mast location. These beams will act as support for the hull having the deck rest on the rubber padding at the ends of the beams as well as support for the main riggings which will be tied into the C-channel to take the load off the hull. The mast is to be supported by a steel mast sleeve having a steel plate bolted into the I-Beam and braced to give extra support. The center column will be bolted into the bottom of the I-Beam and also braced to give extra support. The structure will then be placed in a ball and socket joint, which is mounted by a concrete footing, allowing the boat to rotate and adjust the angle if necessary. The purpose of this design is to give the model an aesthetically appealing look by appearing to be free floating and supported by a cost effective minimal structure.

Natural Surroundings

For Concept Design 3 we took a different approach by incorporating the boat's natural surroundings into the cradle. The Reliance will be held at a 10° angle to portray the boat cutting through the ocean while under sail as shown in Figure 5 and Figure 6

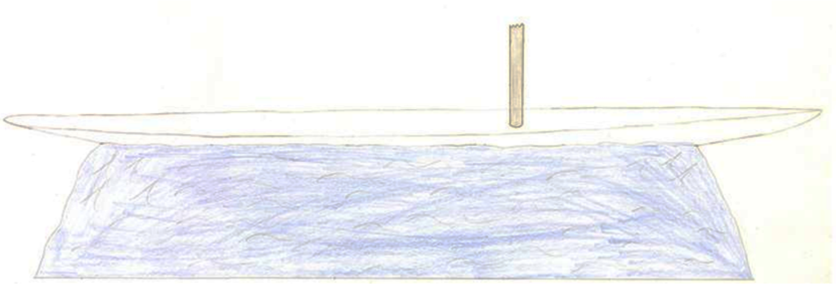


Figure 5: Natural Surroundings
front viewer's perspective

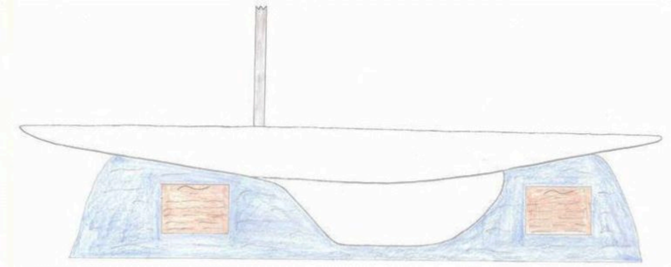


Figure 6: Natural Surroundings
back viewer's perspective

The approach of the design treats the hull and mast as completely separate loads supported by their own individual structures as shown in Figure 7.

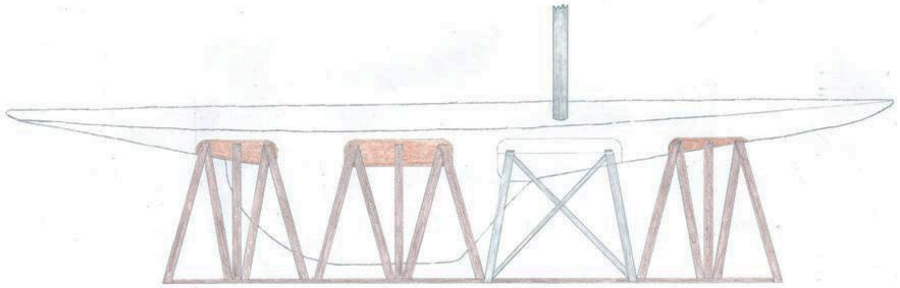


Figure 7: Natural Surroundings
hidden structural supports

The design as a whole will not be lightweight, but the individual parts such as the 3 cradle supports and the mast support will be light enough on their own to be lifted under man power. To cut costs the cradle supports will be made of standard 2x4 construction with plywood distributed loading pads. The mast support will be constructed of roughly 2" box channel structural steel and the front side of the hull will be equipped with a French door hidden underneath the water structure to enable the mast support structure to be taken out of the hull for easy transport.

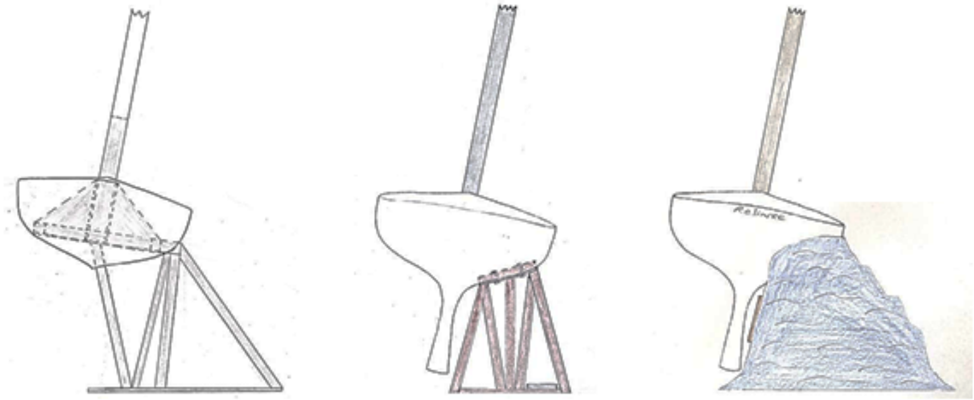


Figure 8: Natural Surroundings respective side views of mast support, hull support, and viewer's perspective

The mast support, as shown in Figure 8, will incorporate a frame, cone, and mast sleeve. The mast will be placed over the sleeve. Additionally the sleeve will wrap the outer edge of the mast inside the hull to help stabilize the mast. The sleeve will then be supported by a steel cone welded to the frame. The hull structural support will involve a sandwich method in which an exterior sheet of plywood will be through bolted to an interior sheet of plywood. The structure will then be hidden by an artificial water structure. The water structure will be made into multiple parts to enable easy transport and will be constructed of a ¼" aluminum tubing frame wrapped in aluminum chicken wire which is then spray coated with a polyvinyl plastic cocooning.

Conclusion

For our project, our clients played an integral role in the concept selection process. By working together, our group was able to produce three concept designs that met most, if not all, of the target specifications.

Concept Selection

Introduction

Each concept design had its strengths and weaknesses, so when we presented our designs to our clients we found out which specifications were most important to them. After a lengthy discussion of our designs and clarifying any questions or concerns they had expressed, they liked the minimal exposed structure of the free floating design, and the support and durability that the cantilever cradle offered. We quickly came up with a design that combined features of the cantilever cradle and free floating design. They seemed to like this idea, so we decided to come up with three "hybrid" designs that incorporated our customer's additional constraints and desires.

Hybrid #1

To reduce intrusion of the hull from the supporting arms and their attachment points to the upright support an alternative design has been devised. To support the main cantilever arms a cable will be attached at the outermost edge and run through the square channel to the main attachment point as shown in Figure 9.

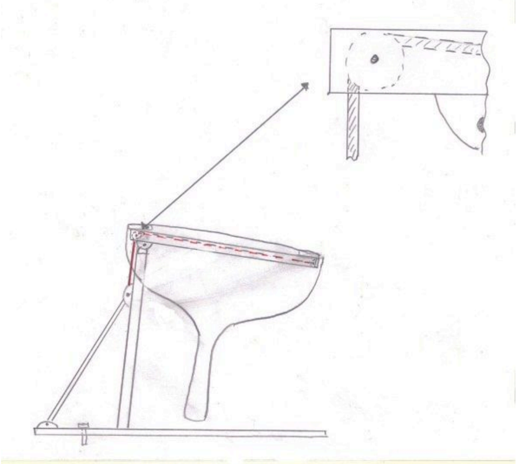


Figure 9: Hybrid #1 side structural

At this point the cable will be redirected by means of a pulley and attached to the backside face of the vertical support. It is at this connection point that the main stabilizer of the upright support will also be attached. The main stabilizer will consist of a tie rod that will fasten to the base plate of the cradle. The critical points of the cradle design will be found in the tensile stresses of the support cable and tie-rod. Stemming from this it can also be assumed that the shear stresses in the pulley through bolts and bolts at all connection locations will be substantial.

Hybrid #2

One of the main issues that developed with the Free Floating design was portability. Due to the anchor cables needing a substantial platform to be mounted to, the versatility of display locations is limited. To solve this issue and option has been added to the Free Floating design to give it the ability to stand alone.

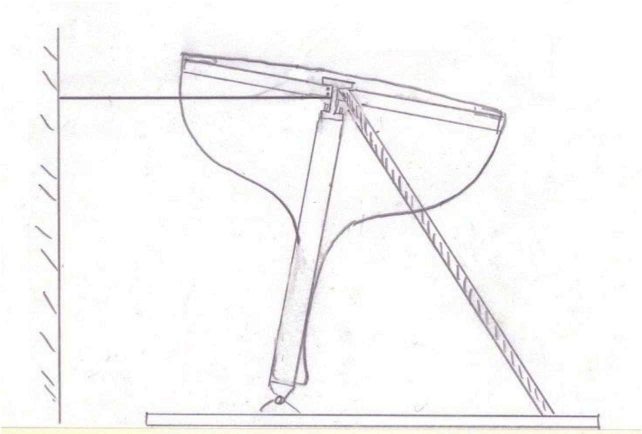


Figure 10: Hybrid #2 side structural

As shown in Figure 10 a base plate has been added which will provide a foundation for the ball and socket joints to fasten to. Two supports will attach the internal structure to the baseplate, acting as cross members. These two supports will keep the hull upright at a fifteen-degree angle and counter act the high center of gravity of the model. This design will increase the portability and versatility of the cradle design. When the model reaches its final destination in the HMM atrium the base plate and supporting rods can be removed. The design of the new atrium should account for the required anchor supports of the design, which includes a concrete support foundation and anchoring wall.

Hybrid #3

Hybrid #3 is combination of the Cantilever Cradles base support with the internal structure of the Free Floating design. The main difference in this design is that the mast support is an extension of the front base support as shown in Figure 11.

Figure 11: Hybrid #3 frame

By incorporating the mast sleeve into the base support, Hybrid #3 is the most minimal structure. Using the leg design of the cantilever cradle, the structure will also be portable since the foundation will consist of legs mounted to a baseplate and no tension cable requirements.

Screening and Scoring

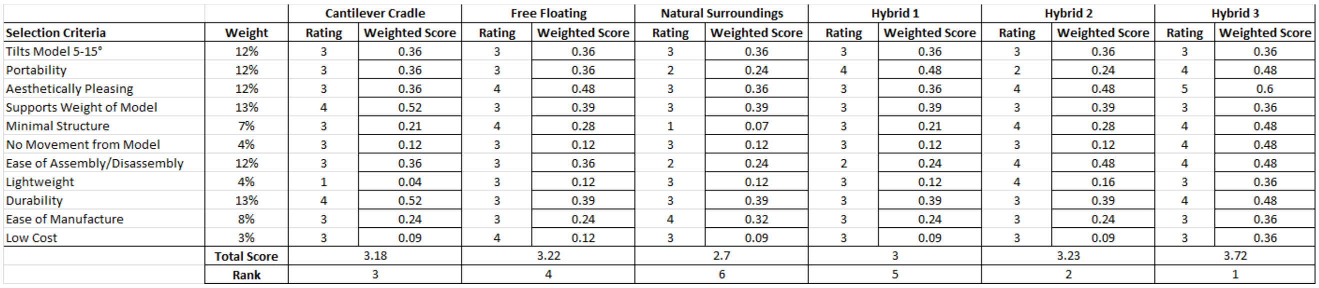
In order to assess the concept designs on an equal platform a screening matrix was constructed. The screening matrix enables us to see the advantages and disadvantages of each design in a side by side comparison. By designating one design as the reference for each selection criteria and assigning it a zero, other models could then be compared to the reference by a plus or minus. The pluses and minuses for each concept were then summed to provide a score for each design, as shown in Table 5.

Table 5: Concept Screening Matrix used to identify concepts requiring further examination or discontinuation

Selection Criteria	Concepts					
	Cantilever Cradle	Free Floating	Natural Surroundings	Hybrid 1	Hybrid 2	Hybrid 3
Tilts Model 5-15°	0	0	0	0	0	0
Portability	0	-	-	0	-	+
Aesthetically Pleasing	0	+	0	0	0	+
Supports Weight of Model	0	0	0	0	0	0
Minimal Structure	0	+	-	0	+	+
No Movement from Model	0	0	0	0	0	0
Ease of Assembly/Disassembly	0	0	-	0	0	0
Lightweight	-	+	0	+	+	+
Durability	+	0	0	0	0	+
Ease of Manufacture	0	0	+	0	0	0
Low Cost	0	+	0	0	0	0
Sum +'s	1	4	1	1	2	5
Sum 0's	9	7	7	9	7	6
Sum -'s	1	0	3	0	1	0
Net Score	0	3	-2	1	1	5
Rank	4	2	5	3	3	1

A concept scoring sheet was then devised to determine concept rankings in terms of weighted sums on selection criteria. Each selection criteria was given a weighted factor on the overall design and the concepts were given a rating between one and five as to how well they met each criterion. Scores for each design concept were then constructed by summing the weighted scores of each criteria associated with each design, as shown in Table 6.

Table 6: Concept Scoring Matrix used to determine concept rankings



		Cantilever Cradle		Free Floating		Natural Surroundings		Hybrid 1		Hybrid 2		Hybrid 3	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Tilts Model 5-15°	12%	3	0.36	3	0.36	3	0.36	3	0.36	3	0.36	3	0.36
Portability	12%	3	0.36	3	0.36	2	0.24	4	0.48	2	0.24	4	0.48
Aesthetically Pleasing	12%	3	0.36	4	0.48	3	0.36	3	0.36	4	0.48	5	0.6
Supports Weight of Model	13%	4	0.52	3	0.39	3	0.39	3	0.39	3	0.39	3	0.36
Minimal Structure	7%	3	0.21	4	0.28	1	0.07	3	0.21	4	0.28	4	0.48
No Movement from Model	4%	3	0.12	3	0.12	3	0.12	3	0.12	3	0.12	4	0.48
Ease of Assembly/Disassembly	12%	3	0.36	3	0.36	2	0.24	2	0.24	4	0.48	4	0.48
Lightweight	4%	1	0.04	3	0.12	3	0.12	3	0.12	4	0.16	3	0.36
Durability	13%	4	0.52	3	0.39	3	0.39	3	0.39	3	0.39	4	0.48
Ease of Manufacture	8%	3	0.24	3	0.24	4	0.32	3	0.24	3	0.24	3	0.36
Low Cost	3%	3	0.09	4	0.12	3	0.09	3	0.09	3	0.09	3	0.36
	Total Score	3.18		3.22		2.7		3		3.23		3.72	
	Rank	3		4		6		5		2		1	

In theory, by having a weighted score assigned to each design we can determine which design best suits the needs of the client. It also enables us to decide on which design concepts to discontinue or examine further.

Conclusion

After presenting our updated Hybrid designs to Mr. Lee and others at HMM, the Hybrid 3 design was chosen as the best cradle. Our client liked the minimal structure and portability that Hybrid 3 offered. It also allows for a complete 3600 viewing perspective, with little to no obstruction to the public. It is interesting to note that in Table 6, Hybrid 3 also scored the highest total score.

Concept Testing Plan

Executive Summary

A concept testing plan has been developed to ensure the feasibility and integrity of the final design. The final design has been approved for further testing by both customer and design team based upon the preliminary drawings and design concepts. The testing plan is established around a series of uncertainties and risks that cannot be accurately determined from the preliminary design and dimensions. The risks and uncertainties have been further developed into a series of questions which drive a system of different tests from which answers will be concluded. Table 3 correlates each question to the specific means of testing that will ensure feasibility and ultimately deem the design acceptable. The purpose, experimental plan and schedule for each respective test are summed up in Table 10 through Table 12. Based upon the proposed schedule, all testing and further analysis will be finalized by December 2nd, 2012 given no significant errors arise during testing. From our analysis we will be able to determine the sizing of the structural components of the cradle design and furthermore deem the overall design ready for construction.

Risk and Uncertainties Assessment

The preliminary design of the final proposed concept goes into great detail to describe the methods by which the cradle will house and support the Reliance model in its given orientation. However, the cradle design has yet to undergo theoretical calculation and/or SolidWorks analysis to determine the structural member's integrity. To this point all dimensions and member sizing have been strictly based upon clearance requirements that are provided via the hull's geometry. Major risks are found in the member's ability to remain structurally sound given the loading requirements. To assess these risks, two means of analysis can be conducted. First we can determine whether or not the present sizing will hold the given load. Alternatively, we can determine the maximum sizing necessary to support the loading requirements while still allowing for a factor of safety of 2.5. Ultimately we are hoping that both sizing requirements and loading needs can be met with the current design. If this becomes an issue further design will need to be developed to meet the given necessities.

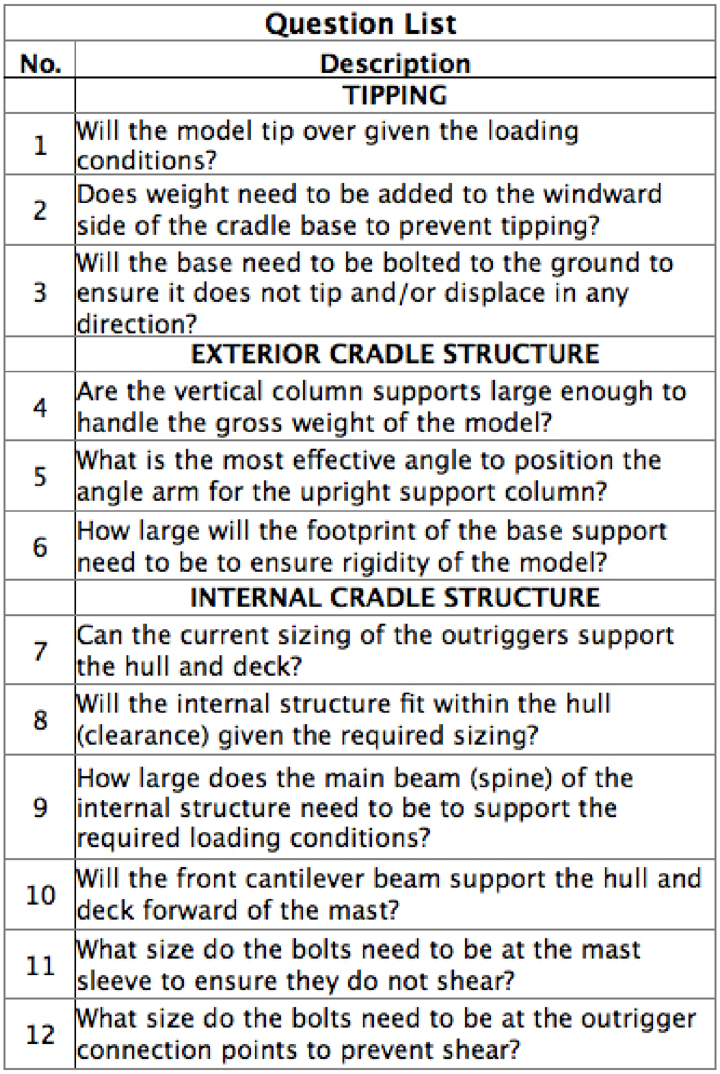
Given the desire to have the model displayed at a 15 degree angle, the cradle will undergo a large tipping force making the entire structure want to heel over and drop. To counteract this, the cradle has been designed to work against this tipping force. In preliminary design, different ideas were developed that would ensure the model would not tip. Testing will allow us to determine which method will be necessary and/or if any precautions will need to be taken to alter the base of the cradle to ensure the model remains upright.

Our ultimate goal is to eliminate risk from the design by determining the requirements of the cradle given the foreseeable conditions in which the cradle and model will be on display. At no point can the model become a risk to the public and/or staff that will be around it. Like the name itself, *Reliance*, we want the designed cradle to be reliable and uphold its integrity over its lifetime.

Design Testing

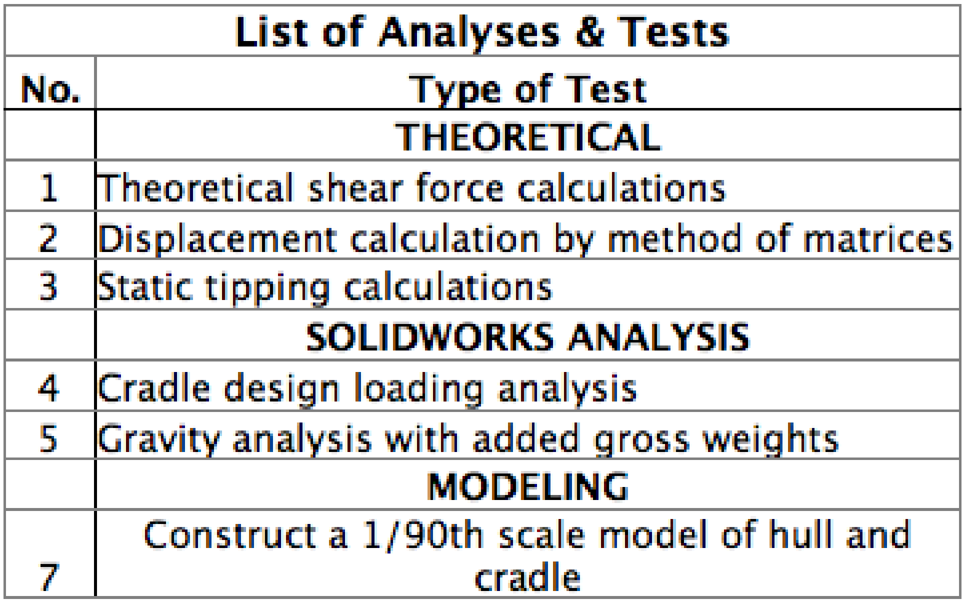
To determine a means of testing the proposed cradle design a series of questions were developed to act as a foundation by which the cradle will be rated. The questions as seen in the list below were established from the risks and uncertainties as noted before. Once the tests and analysis have been conducted we will be able to develop answers to each question and determine whether the design is indeed feasible or further alterations to the cradle need to be made.

Table 7: List of questions based upon risk and uncertainty assessment. Each question is numbered and falls under its specific category within the cradle design.



Question List	
No.	**Description**
	TIPPING
1	Will the model tip over given the loading conditions?
2	Does weight need to be added to the windward side of the cradle base to prevent tipping?
3	Will the base need to be bolted to the ground to ensure it does not tip and/or displace in any direction?
	EXTERIOR CRADLE STRUCTURE
4	Are the vertical column supports large enough to handle the gross weight of the model?
5	What is the most effective angle to position the angle arm for the upright support column?
6	How large will the footprint of the base support need to be to ensure rigidity of the model?
	INTERNAL CRADLE STRUCTURE
7	Can the current sizing of the outriggers support the hull and deck?
8	Will the internal structure fit within the hull (clearance) given the required sizing?
9	How large does the main beam (spine) of the internal structure need to be to support the required loading conditions?
10	Will the front cantilever beam support the hull and deck forward of the mast?
11	What size do the bolts need to be at the mast sleeve to ensure they do not shear?
12	What size do the bolts need to be at the outrigger connection points to prevent shear?

Table 8: Analyses and testing list developed from needs as seen in Table 1.



List of Analyses & Tests

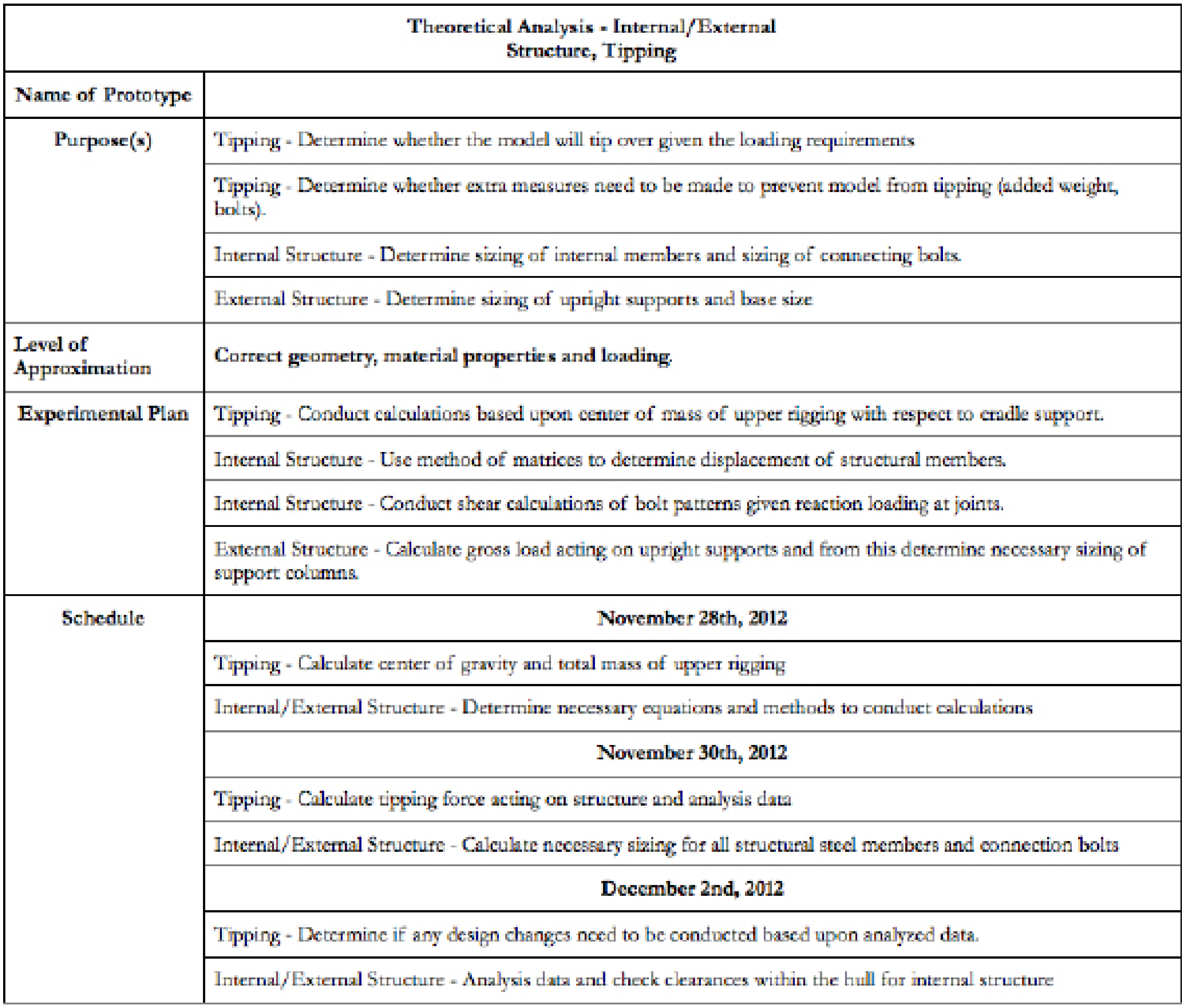
No.	Type of Test
	THEORETICAL
1	Theoretical shear force calculations
2	Displacement calculation by method of matrices
3	Static tipping calculations
	SOLIDWORKS ANALYSIS
4	Cradle design loading analysis
5	Gravity analysis with added gross weights
	MODELING
7	Construct a 1/90th scale model of hull and cradle

Table 9: Comparison table linking each question to their respective means of testing. By testing a majority of the questions by more than one means the conclusions that are made can be considered to be accurate

		List of Analyses and Tests								
		No.	1	2	3		4	5		7
		Type of Test	Theoretical sheer force calculations	Displacement calculation by method of matrices	Static tipping calculations		Cradle design loading analysis	Gravity analysis with added gross weights		Construct a 1/90th scale model of hull and cradle
		THEORETICAL				SOLIDWORKS ANALYSIS			MODELING	
No.	**Questions**									
	TIPPING									
1	Will the model tip over given the loading conditions?				X			X		
2	Does weight need to be added to the windward side of the cradle base to prevent tipping?				X			X		
3	Will the base need to be bolted to the ground to ensure it does not tip and/or displace in any direction?				X			X		
	EXTERIOR CRADLE STRUCTURE									
4	Are the vertical column supports large enough to handle the gross weight of the model?			X			X			
5	What is the most effective angle to position the angle arm for the upright support column?			X			X			
6	How large will the footprint of the base support need to be to ensure rigidity of the model?							X		
	INTERNAL CRADLE STRUCTURE									
7	Can the current sizing of the outriggers support the hull and deck?			X			X			
8	Will the internal structure fit within the hull (clearance) given the required sizing?						X			X
9	How large does the main beam (spine) of the internal structure need to be to support the required loading conditions?			X			X			
10	Will the front cantilever beam support the hull and deck forward of the mast?			X			X			
11	What size do the bolts need to be at the mast sleeve to ensure they do not shear?		X				X			
12	What size do the bolts need to be at the outrigger connection points to prevent shear?		X				X			

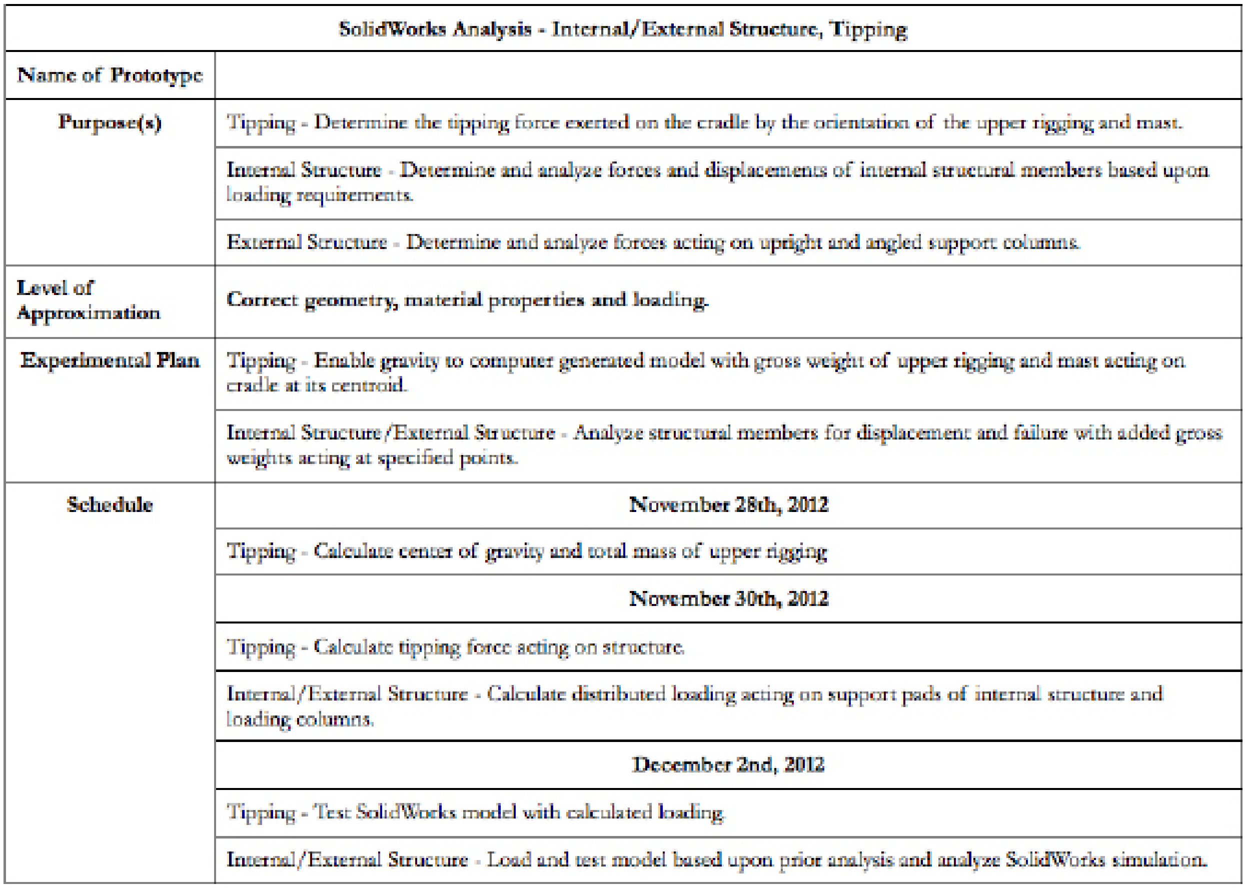
Testing Overview

Table 10: Theoretical Testing and Analysis.



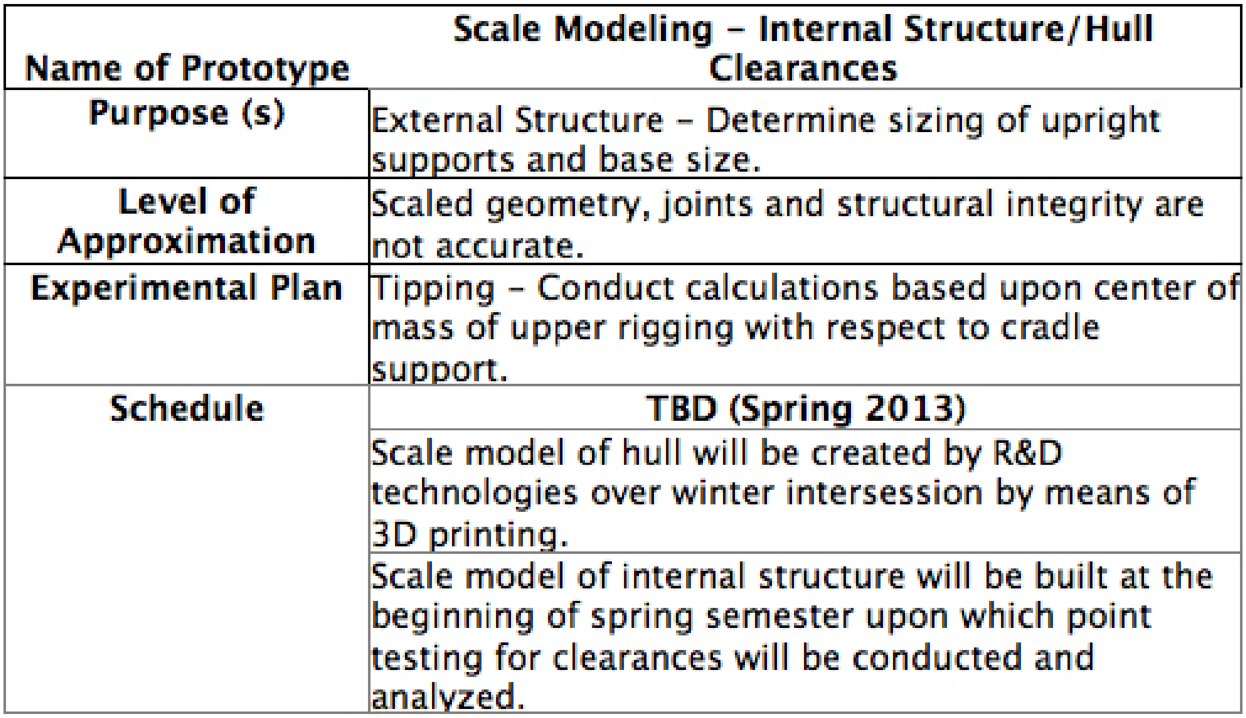
Theoretical Analysis - Internal/External Structure, Tipping	
Name of Prototype	
Purpose(s)	Tipping - Determine whether the model will tip over given the loading requirements
	Tipping - Determine whether extra measures need to be made to prevent model from tipping (added weight, bolts).
	Internal Structure - Determine sizing of internal members and sizing of connecting bolts.
	External Structure - Determine sizing of upright supports and base size
Level of Approximation	**Correct geometry, material properties and loading**
Experimental Plan	Tipping - Conduct calculations based upon center of mass of upper rigging with respect to cradle support.
	Internal Structure - Use method of matrices to determine displacement of structural members.
	Internal Structure - Conduct shear calculations of bolt patterns given reaction loading at joints.
	External Structure - Calculate gross load acting on upright supports and from this determine necessary sizing of support columns.
Schedule	**November 28th, 2012**
	Tipping - Calculate center of gravity and total mass of upper rigging
	Internal/External Structure - Determine necessary equations and methods to conduct calculations
	November 30th, 2012
	Tipping - Calculate tipping force acting on structure and analysis data
	Internal/External Structure - Calculate necessary sizing for all structural steel members and connection bolts
	December 2nd, 2012
	Tipping - Determine if any design changes need to be conducted based upon analyzed data.
	Internal/External Structure - Analysis data and check clearances within the hull for internal structure

Table 11: SolidWorks Modeling and Analysis.



SolidWorks Analysis - Internal/External Structure, Tipping	
Name of Prototype	
Purpose(s)	Tipping - Determine the tipping force exerted on the cradle by the orientation of the upper rigging and mast.
	Internal Structure - Determine and analyze forces and displacements of internal structural members based upon loading requirements.
	External Structure - Determine and analyze forces acting on upright and angled support columns.
Level of Approximation	**Correct geometry, material properties and loading.**
Experimental Plan	Tipping - Enable gravity to computer generated model with gross weight of upper rigging and mast acting on cradle at its centroid.
	Internal Structure/External Structure - Analyze structural members for displacement and failure with added gross weights acting at specified points.
Schedule	**November 28th, 2012**
	Tipping - Calculate center of gravity and total mass of upper rigging
	November 30th, 2012
	Tipping - Calculate tipping force acting on structure.
	Internal/External Structure - Calculate distributed loading acting on support pads of internal structure and loading columns.
	December 2nd, 2012
	Tipping - Test SolidWorks model with calculated loading.
	Internal/External Structure - Load and test model based upon prior analysis and analyze SolidWorks simulation.

Table 12: Scaled Model Prototype to determine clearances within hull with respect to internal structure.



Name of Prototype	Scale Modeling – Internal Structure/Hull Clearances
Purpose (s)	External Structure – Determine sizing of upright supports and base size.
Level of Approximation	Scaled geometry, joints and structural integrity are not accurate.
Experimental Plan	Tipping – Conduct calculations based upon center of mass of upper rigging with respect to cradle support.
Schedule	TBD (Spring 2013)
	Scale model of hull will be created by R&D technologies over winter intersession by means of 3D printing.
	Scale model of internal structure will be built at the beginning of spring semester upon which point testing for clearances will be conducted and analyzed.

Conclusion

From our testing analysis we will be able to determine whether or not the final proposed concept is feasible. Up to now all structural analysis and design specifications have been purely based off of theoretical concepts, clearance requirements driven by the model, and educated assumptions. By testing the cradle design by multiple means and methods we are able to gain accurate insight into the unknowns and potential risks that could prove to be a hazard upon final construction. Our analysis will give both the design team and the HMM proof of integrity and feasibility for the design enabling the project to move towards construction. In the case that the results prove the design inadequate to handle the given loading conditions, alterations will be made to the design to fix the given issue. Once the cradle is redesigned, it will be tested again by the same methods to ensure that the alterations meet the necessary conditions and fall within safety factors as specified by the client. In conjunction with structural analysis testing of the upper rigging structure/components (to be completed spring semester 2013) the final analysis of the cradle design will give HMM a strong foundation from which to complete the 1/6th scale *Reliance* model.

Concept Testing

Executive Summary

The main objective of the design was to build a cradle capable of supporting the applied loads with minimal deflection. To do so, it was necessary to theoretically split the boat into multiple sections, including the upper rigging, hull, and internal structure. The weight of each section had to be calculated based on unit weight and volume of material. After calculating the weights and center of mass of each section, we had to solve for the reaction forces acting on each loading pad and outrigger of the cradle. Once this was complete, the sizing of the outriggers and center spine beam could be determined. Once beam sizes were resolved, the bolt sizes required to safely connect each outrigger to the center spine needed to be found. After the sizing of all loading members that would be acting on the support column was determined, the sizing of the support columns could be calculated to achieve the desired minimal deflection. Finally, after verifying that the structure would be capable of supporting the applied loads, it was necessary to perform analysis on the model as a whole to determine that the model would not be subject to tipping. The methods below explain our logic and approach used to verify the structure will be capable of safely supporting the applied load.

Introduction

After receiving the specific design criteria from our client, our concept designs were narrowed down to one cradle design. To prove the concept would work, it was necessary to perform a detailed analysis on all load bearing members to ensure structural integrity. The following report explains the thought process and methods used to verify the quality of the proposed cradle design.

Methods

When determining the size of the members in the internal structure, an analysis of the hull was completed. Since the forces of the upper rigging are acting directly down the main mast into the forward column, there was no need to incorporate it into calculating the sizing of the beams and outriggers. The points at which the stays will be tied in will exert minimal positive load, which will reduce the deflection acting on the outriggers and therefore were excluded from calculations. The determination of the hull's mass was calculated first by the use of the hull's original blue prints. The hull was separated into five sections by dividing the distances between the outriggers. This was done because the outrigger positions are specifically placed to directly connect stays or other rigging components to the cradle that would otherwise imply heavy loads into the hull. These sections were then broken into several common shapes in order to find the surface area of each of the sections for both the deck and right view of the yacht's blue prints then scaled down to the model's actual size. A loss factor was applied to the side sections since the areas were analyzed as if they were flat and not curved, as the model. Then, from an assumption taken from our client regarding the thickness of the hull (3/16"), the volume of each section was determined. The total volume was found by adding up all the sections to create the solid hull. From this, the percent volume of both the deck and side was then calculated. Through the use of SolidWorks, the unit weight of the densest readily available fiberglass was obtained and used in determining the total mass of the hull and the mass of each section. From this the point loads acting on the hull per section were obtained by adding the deck and side view loads. The location of these point loads were determined by finding the centroids for each of the sections. This was done by obtaining the centroids of each of the common shapes used in determining the areas and combining them through means of geometric decomposition, where the sum of the areas multiplied by the centroids were divided by the sum of the areas. This can be summed by Equation 1 displayed below. An example of the results for this equation can be visualized in Figure 12.

$$C_x = \frac{\sum C_{i_x} A_i}{\sum A_i}, C_y = \frac{\sum C_{i_y} A_i}{\sum A_i}$$

Equation 1

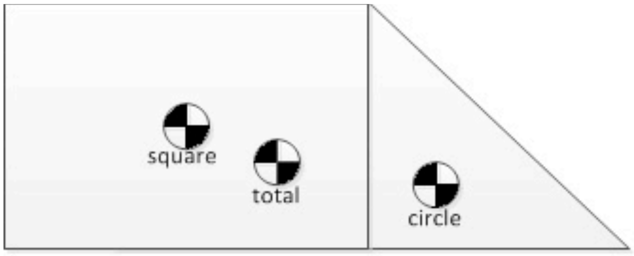


Figure 12: Visual of geometric decomposition

To determine the reacting forces acting on the outrigger pads, the three moment equation was used, as shown in Equation 2.

$$M1L_1 + 2M_2(L_1 + L_2) + M_3L_2 + \frac{6A_1\bar{a}_1}{L_1} + \frac{6A_2\bar{b}_2}{L_2} = 6EI\left(\frac{h_1}{L_1} + \frac{h_3}{L_2}\right)$$

Equation 2

Equation 2 expresses a general relation among moments at any three points in a beam, hence it is known as the three moment equation. Since points 1, 2, and 3 are on the same level in the deflected beam, the heights h_1 and h_3 become zero. therefore the right hand side of the equation also becomes zero. The three points selected in applying the equation to continuous beams are the points at the supports, assuming it is a rigid body; the equation was used to determine the bending moments in the beam over the supports. Since there are five reaction forces A-E, the equation was used three times, once each for A-C, B-D, and C-E. Moments B, C, and D were then found by the use of matrices. From this, the beam was then analyzed again with the moments and the reaction forces were determined. Since this method determined the reaction forces as if it was placed directly down the middle of the hull's center line, the forces where the outriggers were placed were simply divided in half since each outrigger is equidistance apart from the center beam. The determination of member sizing for the center beam and outriggers were calculated through means of determining the maximum deflection. Defelection was determined by methods of integration of the beams moment equation, with the first integration resulting in slope, and the second integration resulting in deflection. This is hown in Equation 3, Equation 4, and Equation 5 below.

$$EI\frac{d^2y}{dx^2} = Moment$$

Equation 3

$$EI\frac{dy}{dx} = Slope$$

Equation 4

$$EIy = Displacement$$

Equation 5

The longest outrigger with the largest load was checked for the chosen C-channel beam. This was analyzed as a cantilever beam having a point load on one end and fixed on the other with a distributed load for the mass of the beam itself. In order to determine the sizing of the center beams, it was necessary to split the cradle into two separate beams since the beams are connected by a mast sleeve. There was a cantilever beam reaching out for the front support of the hull and a rear beam being dual supported. The forward beam was analyzed the same way as the outriggers except multiple forces were analyzed. The rear dual support beam had to be analyzed by a different method since there was a support roughly two thirds of the length. The reaction forces on this beam had to be determined first then analyzed instead of having a boundary condition being the whole length of the beam as if it was a cantilever beam.

When determining the sizing of the support columns, the column supporting the mast was analyzed since this will be supporting the largest load. First, the loads of the entire internal structure, hull, and upper rigging were calculated to find the load needed to be supported. Then the load was drawn on a free body diagram to show the load acting vertically against the angled column. The load was then found in the X and Y-direction with respect to the 15 degree heel angle, the x-axis running parallel to the mast. Since the load in the X-direction was acting directly down the column it was ignored and only the load acting in the Y-direction was analyzed just as a cantilever as explained before. The deflection was found to check that the correct sizing for the column was chosen.

The bolt sizing for the internal structure was evaluated by checking the bolt shear force on the bolt supporting the largest load. Bolt shear was determined by using Equation 6, where the tau allowable is given by using the maximum shear stress known for the size bolt and a factor of safety of 2.5 for common building codes.

$$\tau_{Actual} \leq \tau_{Allow} = \frac{\tau_y}{F.S.}$$

Equation 6

T_{actual} was determined by taking the load and dividing it by the area. This is shown below in Equation 7. Then T_{actual} and $T_{allowable}$ were compared to check that the actual does not exceed the allowable.

$$\tau_{Actual} = \frac{P}{A}$$

Equation 7

Finally, the determination of whether or not the model would tip was checked by means of a basic tipping calculation using the center of mass of the upper rigging, hull, cradle, and base plate. The center of mass for the upper rigging was determined by first setting the bottom of the main mast as the origin of the system. After the centroid of each part of the upper rigging (i.e. sails, booms, spars, gaff, clubs...) was located with respect to the origin, they were combined through means of geometric decomposition as done in Equation 1. The center of mass of the cradle and hull were already calculated and explained previously in this section. The baseplate was treated as a symmetrical shape having the center of mass directly between the two column supports. The forces applied to the center of mass of the upper rigging and hull were then combined and compared to the sum of the forces applied to the internal structure and base plate to check that the model would not tip with the applied load found.

Results

The results for the internal structure member sizing and load forces acting on the structure are shown below in the following tables. These results were calculated as stated above in the methods section. Table 13 and Table 14 display the results from calculating the sections of the hull from the prints. The calculations for finding the areas of the sections can be seen in Figure 13 and Figure 14 in the appendices. From this the volumes were determined and percent volume of the whole hull, finally determining the force acting on each section.

Table 13: Calculated weight of deck sections

Deck						
Location	original area of drawing	Original area of boat (sqft)	area on model (sqft)	Volume	% volume	Weight (lb)
0-1	76.67	76.67	2.13	0.03	1%	5.75
1-2	396.11	396.11	11.00	0.17	5%	29.73
2-3	749.06	749.06	20.81	0.33	10%	56.22
3-4	127.24	904.80	25.13	0.39	12%	67.91
4-5	31.08	221.01	6.14	0.10	3%	16.59

Table 14: Calculated weight of side profile sections

Side Profile									
Location	original area of drawing	Original area of boat (sqft)	area on model (sqft)	Both Sides	Loss Factor	Total Area	Volume	% Volume	Weight (lb)
0-1	6.47	46.00	1.28	2.56	1.52	3.88	0.06	1.87%	10.50
1-2	23.92	170.07	4.72	9.45	1.58	14.93	0.23	7.20%	40.34
2-3	69.94	497.33	13.81	27.63	1.65	45.59	0.71	22.00%	123.18
3-4	110.75	787.59	21.88	43.75	1.61	70.45	1.10	33.99%	190.34
4-5	11.87	84.37	2.34	4.69	1.53	7.17	0.11	3.46%	19.38

From adding up the areas for each section the total area was determined and from this the total volume was found. Through the use of SolidWorks the unit weight for fiberglass was obtained and the estimated total weight of the hull was calculated. These values are displayed below Table 15.

Table 15: Total weight of hull

total area	207.23 ft^2
total volume	3.24 ft^3
Unit Weight	0.10 in$^{3/lb}$
Weight	559.93 lb

After determining the loads acting on each section they were placed at the centroid of the section and the sections where outriggers were located the load was divided in half since the riggers are symmetrical. These values are shown in Table 16 below, and the calculations for the centroids of each section are shown in Figure 13 and Figure 14 found in the appendices.

Table 16: Loads applied on internal structure determined from hull section centroids

Point Loads			
Location	Centroid from left edge of shape (ft)	Pt load (lb)	Pt load per rigger (lb)
0-1	1.70	16.25	16.25
1-2	2.34	70.07	35.03
2-3	3.28	179.40	89.70
3-4	1.55	258.25	129.13
4-5	1.68	35.97	17.98

Through the use of the three moment method explained above, the loads acting on the loading pads at the end of each outrigger were determined. Table 17 displays this data having member “D” having the largest force of 160.5lb acting on each of the loading pads. This calculation for determining the loads acting on the pads is visualized in Figure 15 and Figure 16 located in the appendices.

Table 17: load applied to each loading pad on end of outriggers

Reaction Forces	loads determined from 3 moment method (lb)	Final Loads on each rigger (lb)
Ay	9.47	9.47
By1	6.78	19.36
By2	31.94	
Cy1	38.13	89.28
Cy2	140.43	
Dy1	297.22	160.47
Dy2	23.71	
Ey	12.25	12.25

After determining the point loads acting on all outriggers, the reaction forces of the support columns were calculated and included the weight of the upper riggings. The upper rigging acting solely on the front support made it possible to only analyze that support since it would be supporting a higher load than the rear support. After determining the load applied to the support column, the angle of the force was accounted for to calculate the load that would be applied across the x-axis of the beam as shown in Table 18.

Table 18: determination of load applied to front “mast” column

Front "Mast" Column	
Load applied	659.00 lb
angle of load	15°
torqueing load	428.50 lb

When checking to see if the chosen members sizing would suffice the forces that are going to be applied, the members under the most force were checked for deflection. Since the outriggers are going to all be the same size member "D" was chosen and deflection calculated was only -4.5E-03in proving that the beam selected for the outriggers for the internal structure are suffice. This calculation is shown in the appendices under Figure 18. The check for the center beam's members of the internal structure was also checked through means of deflection. The rear beam having the largest load applied only incurred a deflection of -1.34E-01in and the forward beam having a smaller deflection of -8.76E-02in. This proof is shown in the appendices under Figure 19, Figure 20, and Figure 21, where the calculation for deflection is displayed. The final check for member sizing was for the mast column since the support column underneath the mast was supporting more of a load since the mast and upper rigging load was acting down it this was the only column necessary for analysis. After calculating deflection, which can be seen in Figure 23, the deflection calculated was -3.08E-04in proving that the column size chosen would support the load acting on it. All calculated deflections previously stated are displayed below in Table 19.

Table 19: chosen members and their maximum deflection

Member	Beam	Weight of Beam (lb/ft)	Length of Beam (inches)	Weight of Load (lb)	Elongation € (pascals)	Moment of Inertia (I) inches ^{4}	Deflection (inches)
Outrigger	C3x3.5	3.50	24.60	160.50	2.90E+07	1.57	-4.50E-03
Rear Center Beam	S3x5.7	5.70	155.52	524.97	2.90E+07	2.52	-1.34E-01
Forward Center Beam	S3x5.7	5.70	103.56	5.70	2.90E+07	2.52	-8.76E-02
Mast Column	4X4X1/2	20.88	26.16	428.50	2.90E+07	11.40	-3.08E-04

The final calculation made was the determination of the bolt size. This was done by choosing a nominal bolt size and checking the shear stress it was undergoing to the allowable shear stress that the bolt can handle. When doing this the bolt location chosen was where the most force is going to be applied. This location is where the rear center beam is connected to the mast sleeve. After determining the shear force on the bolt the T_{actual} was determined and compared to the $T_{allowable}$. Since the actual was less than the allowable the sized bolt checks for the applied load. These values are shown below in Table 20 and the calculations are displayed in the appendices under Figure 24.

Table 20: displays the bolt shear force exerted on the bolt undergoing the most load

Bolt Shear					
Bolt Size (inches)	**Factor of Safety**	**Yeild Stress (psi)**	**$\tau_{allowable}$ (psi)**	**Shear Force Acting on Bolt (lb)**	**τ_{actual} (psi)**
0.38	2.5	4903.5	1961.4	48.64	440.39

Discussion and Conclusion

In examining our results it was discovered that the weight of the hull was much higher than originally thought. It was also determined that the strength of steel is very high and we were able to use the smallest of S-beams, C-channel, and box beams to hold the weight of the model. Not only will this decrease weight, but it will also decrease cost. We also learned that a boat hull is one of the hardest structures to analyze due to the unconventional shape as compared to standard structures.

The analysis of the cradle design, which meets all target specifications, has determined that it will be capable of safely supporting the applied loads of the upper rigging, hull, and its own weight. Outriggers constructed of C 3x3.5 A36 steel will be capable of supporting the design load acting on the loading pads located on the outer edge of each outrigger to provide an acceptable level of deflection with the maximum being 0.0045 inches. The outriggers will be attached to the center spine which will be American Standard S 3x5.7 A36 steel beams providing a maximum deflection of 0.134 inches. After determining the sizing of the outriggers and spine, it was determined that the original plan of using a 4”x4”x.5” column would be more than capable of supporting the load as the deflection would be minimal at .0003 inches. It was then verified that ¼” bolts would be capable of supporting the applied loads, but for length requirements and product availability it was decided to use 3/8” bolts. After it was confirmed that the structure is structurally sound, a tipping calculation was done in which it was determined that in order for the cradle to tip, it needed to have a total weight of 2025lb. As of now, we are safely under that limit at 667lb. Therefore, the structure will stand and support all applied loads.

Looking into the future, additional testing will be required as more information comes in. Additional testing will include the design of the loading pads to ensure they will not puncture through the hull. The sizing of the pads can be adjusted to achieve a desired pressure on each pad. Furthermore, all calculations were based on weights determined from unit weights and volumes of parts pulled from drawings and therefore are subject to change. The complete analysis of the cradle design will likely be complete by March of 2013.

Final Specifications

At the midway point of the Fall semester target specifications were set based upon a compilation of the client's needs and project goals. To date, there are still numerous specifications that have yet to be finalized due to either its placement falling under the Spring schedule completion of work or schedule postponements from the Herreshoff Museum. Many of the specifications were not critical to the scheduled completion of work for this semester and have been held until required next semester. As for HMM delays we are still waiting for the model hull and other model components to be moved to the Herreshoff workshop at which point quantities for items such as model hull weight will be determined.

Table 21 displays all of our final specifications as of the end of the Fall 2012 semester. As noted before, some specifications have yet to be obtained which is denoted as unknown in Table 1. As not to delay our project schedule, we are moving forward by making theoretical assumptions or calculated values to enter into our testing and analysis. We have conducted our testing in a manner so that once information is presented the calculations conducted prior can be re-run with the new numbers in Excel formatted worksheets. This will reduce the time substantially to redo the calculations with the correct values.

When we developed a system of metrics back in early Fall, an analysis was generated to determine how well other model cradles and designs met our needs. For this report we have created Table 22 in a similar fashion to rate how our design has ultimately met the client's needs in the end. This table allows us to see if there have been certain needs that were overlooked and/or areas in which improvements can be made before finalizing the design. At its current standings the design meets the majority of the needs with high ranks.

Table 21: Initial and Final Specifications for Cradle Design

Metric No.	Need Nos.	Metric	Importance	Units	Reliance (Initial)	Reliance (Final)
1	5,2,8	Gross Weight of Cradle	3	Lbs	1000	Unknown
2	1,11,4,18	Center of Gravity	4	ft		Unknown
3	18, 14, 12, 10	Thickness of Fiberglass used in Hull	4	in.	0.25	3/16ths
4	1, 3, 11	Display Angle of Boat	3	Degrees	15	15
5	14, 18	Shear Strength of Fiberglass in Hull	4	PSI	Unknown	Unknown
6	14, 13, 10, 18, 4	Factor of Safety for Structural Design	3	#	3	2.5
7	18	Maximum Wind Loading on Sails	3	MPH	10	10
8	18	Maximum Shock Factor	3	Lbs(force)	200	200
9	2,5	Cross Sectional area of cradle	3	ft	7 x 7 max	4.5 x 5
10	5,3,2	Overall Display Area (HMM Atrium/ TF Green) Height	4	ft	40	40
11	2,5	Entrance height/width at Display Locations	4	ft	Unknown	Unknown
12	18,12,10	Tension Load on Support Stays	5	Lbs.	Unknown	Unknown
13	9	Blue Print Scale of final desings	2	-	20.00	20
14	4	Maximum Point Pressure on Floor	5	PSI	3000	3000
15	4	Concrete Slab Thickness	5	ft	Unknown	Unknown
16	2	Cradle size does not exceed standard flat bed dimensions	4	ft	48 x 8.5	4.5 x 5 x 10.5
17	17	Non-toxic Materials/Adhesives	3	-		None
18	17	Non-soluble Materials/Adhesives	3	-		None
19	12,16	Total gross weight of internal structure	3	Lbs	500	Unknown
20	1,3,11	Adjustable Angle of Model	2	Degrees	0 - 15	None

Table 22: How well Final Specifications met Customer's Needs

No.	Field	Need	Importance	Reliance Final Cradle Design
1	Cradle	Tilts Model to allow viewing of deck / full sails	4	•••••
2	Cradle	Portable for transfer to and from TF Green	5	••••
3	Cradle	Aesthetically Pleasing	3	••••
4	Cradle	Supports weight of Model	5	•••••
5	Cradle	Minimal Structure	2	••••
6	Cradle	No movement of model - All around safety	5	•••••
7	Cradle	Easy assembly and dissasembly for portability	3	•••
8	Cradle	Light Weight	2	•••
9	Cradle	Blue prints for final review	4	••••
10	Model	Won't break under prolonged periods of stress	5	•••••
11	Model	Supported at desired angle without tipping	5	•••••
12	Model	Analysis of all load bearing members	4	••••
13	Model	Adhesive testing to ensure design loads can be withstood	3	••••
14	Model	Materials testing to ensure design loads can be withstood	4	•••••
15	Model	Establish inspection system	2	•••
16	Model	Full structural analysis	4	•••••
17	Model	Ability to be cleaned with generic products	2	•••••

Preliminary Project Cost Analysis

Executive Summary

At the end of the Fall 2012 semester a wide range of work has been completed that encompasses project tasks such as model cradle design and testing. During the course of this semester a final design has been generated and preliminary testing for its feasibility has been conducted. For the 2013 Winter intercession and Spring 2013 semester, we will be transitioning into detailed testing and analysis of both the designed cradle and *Reliance* model. This stage includes refining and optimizing our cradle design as well as assigning and fixing the cradle's design details. We will be performing a structural analysis of the model's critical components, including both theoretical analysis and failure testing to remove risk and ensure the model's structural integrity. By the completion of the 2013 spring semester we are hoping to have all project objectives and goals completed including a finalized cradle design and structural analysis of the *Reliance* model.

Estimated Costs

Due to the fact that our portion of the *Reliance* project is strictly design, there are few costs associated with our work. By acquiring volunteer work from Roger Williams University faculty and students, the Hereshoff Marine Museum has saved a substantial amount of money. Table 23 displayed below, demonstrates the costs that the museum could have expected to pay if they were unable to acquire volunteer work for the design.

Table 23: Estimated Labor Costs

	Hours per Week/Person	$'s per Hour (estimated)	Total Weeks Spent on Project	Estimated Labor Cost
Each Team Member (5 total)	15 hrs	$25.00	14 weeks	**$5,250**
Supervisor: Dr. William Palm	3 hrs	$45.00	14 weeks	**$1,575**
Technical Mentor: Dr. Gilbert Brunnhoeffer	1 hrs	$45.00	14 weeks	**$630**
			Estimated Total Labor Costs:	**$28,455**

The only costs we see in the future for our design team are associated with prototyping. It is expected that the cost to print a 3D model of the hull will be approximately $320. We estimate that an additional $80 will be needed for the construction of a cradle prototype for a total prototype cost of about $400.

At the end of our project, we are planning on donating any remaining funds to the HMM for use towards the cost of the reliance project. Since the HMM runs purely on donations from outside sources, we would like to be able to help out as much as we can to insure the success of the reliance project and future exhibits at the museum.

Downstream Development Analysis

Executive Summary

The Fall semester's accomplishments include the completion of designing a cradle to display the model, performing a preliminary structural integrity analysis on the finalized design, and researching the potential incorporation of 3D printing and structural adhesives into the construction of the model boat. During the spring semester, the group will be primarily focused on performing structural analysis on the model's critical components, refining the cradle design, and completing in depth analysis of the entire structure.

Detailed Design

One component of the project is to ensure that during the scaling down process, the fully rigged model will not fail or break. In order to accomplish this, we will be performing a structural analysis of the model's critical components, which includes a theoretical analysis and physical failure testing to remove risk and ensure the model's structural integrity. Some of the critical components include the blocks, halyards, and pad eyes. We will be performing failure testing on these parts by using the universal testing machine located in room 119 of the School of Engineering, Computing, and Construction Management at Roger Williams University. By using this machine, we will be able to determine the maximum tensile and shear force on the components to make the component yield and/or fail. By comparing our results to our theoretical analysis of the model we will be able to conclude whether the component will be able to handle the required loading conditions.

A side project that was looked into this semester encompassed the idea of using structural adhesives in the model construction. The client believed that there may be an application for the use of adhesives that would make for an ease of constructability. It has been concluded that an acrylic adhesive would be best for the model boat if instituted. Since fiberglass is simply a glass-strengthened plastic, a plastic bonder such as an acrylic adhesive would be the best choice. Next semester we will be determining which specific one will be best. We have already received a free sample from the company Permabond and are hoping to test other adhesives from other companies to determine the best for the given application.

Functional Prototype

During the 2013 winter intersession, Eric will look into 3D printing a 1/90th scale prototype of *Reliance* hull based upon the specs of the fiberglass hull made for the model. The prototype, 3D printed at R&D Technologies, will be approximately twenty inches long and made out of a photopolymer acrylic. Furthermore, we are planning on constructing a scale model of the cradle out of balsa wood to use in conjunction with the hull. The prototypes will allow us to gain a greater sense for clearances within the closed hull as well as provide insight as to how to gain access into the hull for construction of the cradle's internal structure.

Complete Design Documentation

Upon completion of testing and analysis of the cradle design our team will be documenting the final design to submit to the Herreshoff Marine Museum. The final cradle design and results from our structural analysis will be documented in a prototype and final report, which will include design drawings and fabrication specifications. The final design results will also be communicated to our clients by an oral presentation, which will be aided by a PowerPoint deck containing results from our final report.

Design Competitions

The team is currently planning on entering our cradle design, and all the work we've completed for this project, into two collegiate engineering design competitions. The first one is the 2013 Structural Engineering Institute student structural design competition. Any team of undergraduate civil engineering students is eligible to submit a structural design whose innovative project demonstrates excellence in structural engineering. Three finalist teams will be invited to present their designs at the Structures 2013 Congress in Pittsburg, Pennsylvania, May 2nd – 4th, 2013. The submission is due by January 15, 2013.

The second design competition the team plans on entering is the NCEES Engineering Award. NCEES invites ABET accredited programs from all engineering disciplines to submit collaborative projects that demonstrate a meaningful partnership between professional practice and education. Entries must be received by May 6th, 2013, and the grand prize is $25,000.

Finally our team will be entering our design into the 2013 Roger Williams University Academic Showcase. The Academic Showcase is an annual event that celebrates the creative achievements and interests of any currently-enrolled full-time student. This weekend-long exhibition of student academic and co-curricular talent is held every spring and showcases submissions from freshman through seniors in many different categories.

Conclusion

Looking forward to the 2013 Winter intersession and 2013 Spring semester, we plan on 3D printing our prototype, establishing our final specifications, finalizing our cradle design, performing structural analysis on the model, and effectively communicating all of our findings to our client. As of current we believe that all of our specified goals will be met on time and within the budget allocated to us. Our main goal is to effectively complete our project to a degree in which we are providing the Herreshoff Museum with a perfected design and assurance that their construction of the model will stand as the premier attraction for years to come.

References

American Institute of Steel Construction, comp. Manual of Steel Construction. 7th ed. New York: American Institute of Steel Construction, 1970. Print.

Coutu. "R&D Technologies, Inc." R&D Technologies, Inc. N.p., 2012. Web. 14 Dec. 2012.

Elco. "Metals Depot." Metals Depot. N.p., 2012. Web. 14 Dec. 2012.

"Herreshoff Marine Museum & America's Cup Hall of Fame." Herreshoff Marine Museum & America's Cup Hall of Fame. N.p., 2012. Web. 14 Dec. 2012.

Hibbeler, R. C. Mechanics of Materials. Upper Saddle River, NJ: Pearson/Prentice Hall, 2008. Print.

Hibbeler, R. C. Structural Analysis. England: PRENTICE-HALL INC (NJ), 2008. Print.

Martin, Roger. "Americas Cup Yacht Sculpture." Americas Cup Yacht Sculpture. Rodger Martin Yacht Design, 2012. Web. 14 Dec. 2012. <http://www.rodgermartindesign.com/portfolio/mfa-sculpture/>.

Appendices

Appendix A: Calculations

Figure 13: calculations of centroids and surface areas per hull section

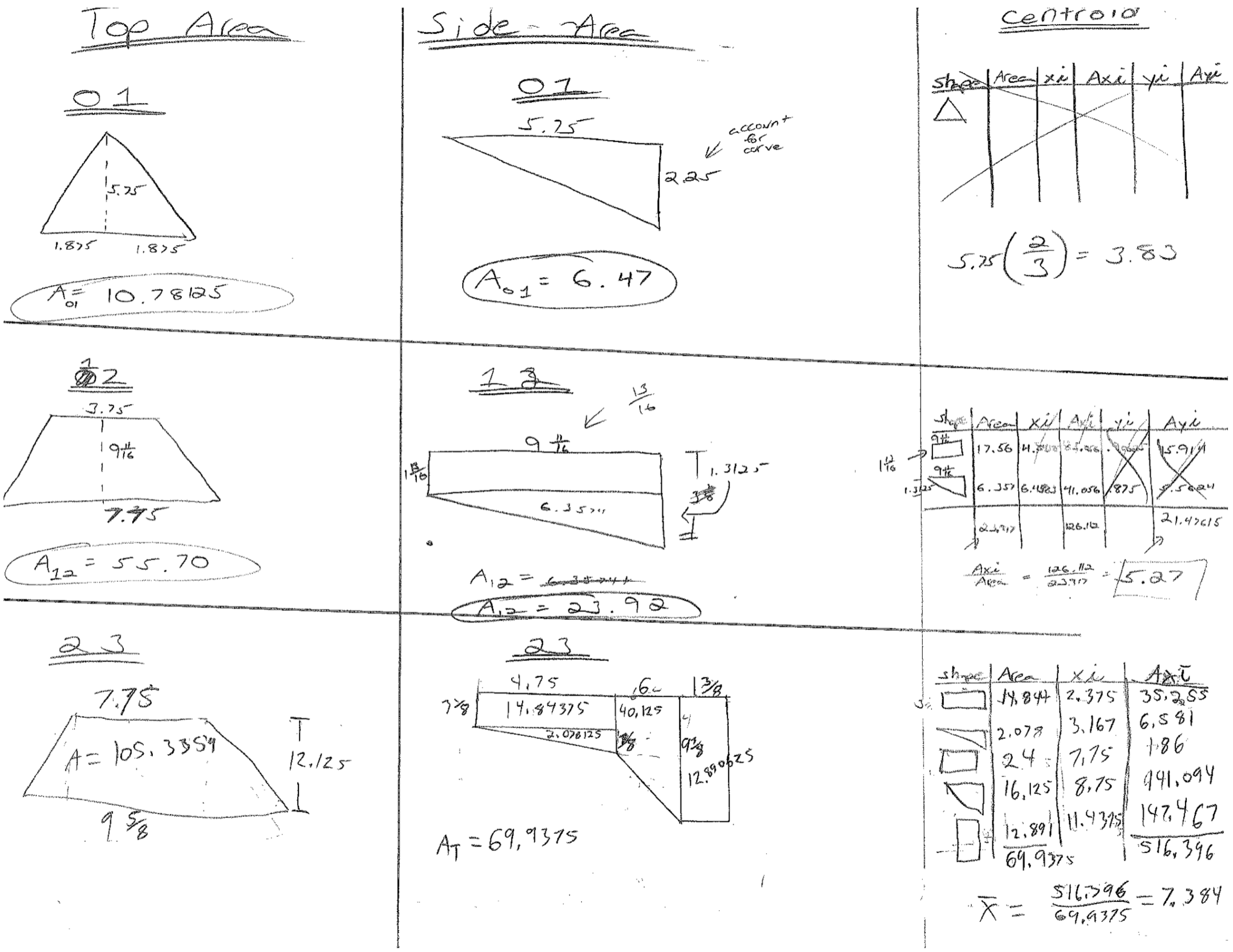


Figure 14: calculations of centroids and surface areas per hull section continued

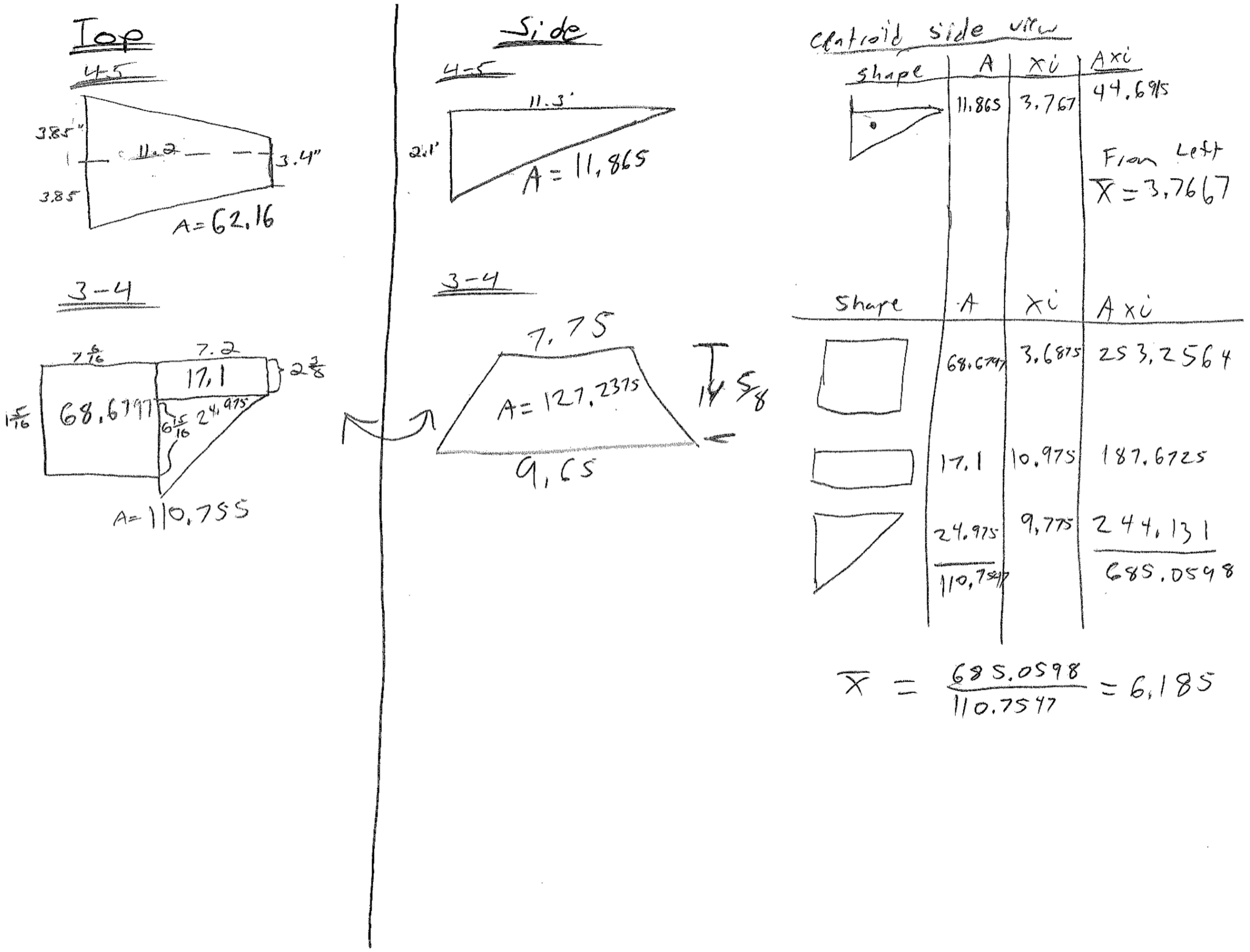
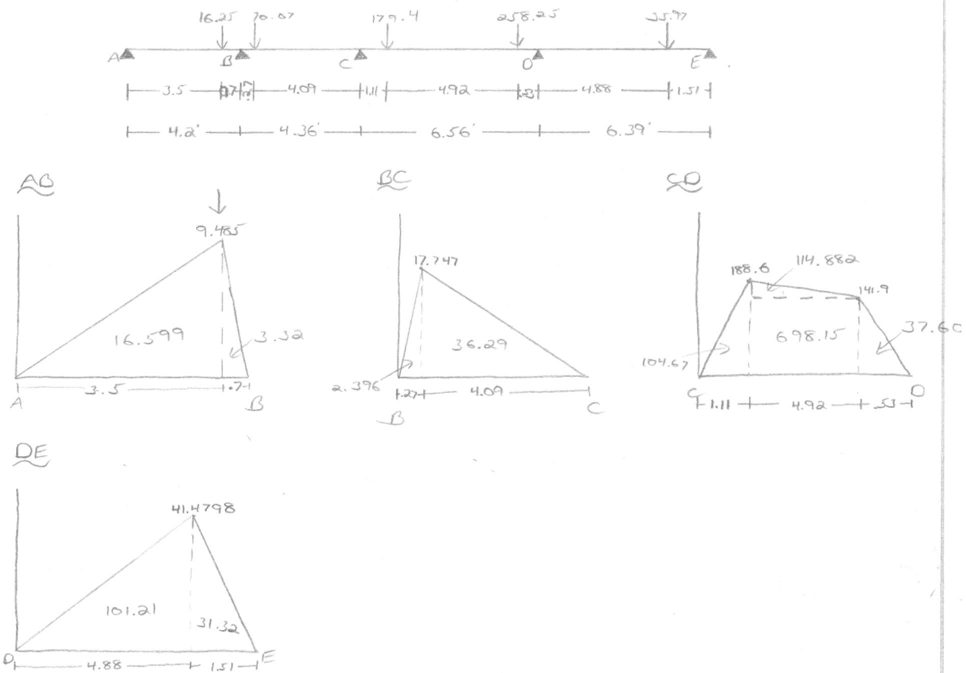


Figure 15: calculation of reaction forces
on hull using three moment method



Basic Equation

$$M_1(L_1)+2M_2(L_1+L_2)+M_3(L_2)+\frac{6A_1a_1}{L_1}+\frac{6A_2b_2}{L_2}=0$$

① $$M_A(4.2)+2M_B(4.2+4.36)+M_C(4.36)+\frac{6(16.599)(\frac{2}{3}3.5)}{4.2}+\frac{6(3.32)(3.74)}{4.2}+\frac{6(2.396)(4.18)}{4.36}+\frac{6(36.29)(24.19)}{4.36}$$

② $$M_B(4.36)+2M_C(4.36+6.56)+M_D(6.56)+\frac{6(.18)(2.39)}{4.36}+\frac{6(36.29)(1.63)}{4.36}+\frac{6(104.67)(5.82)}{6.56}+\frac{6(114.882)(3.81)}{6.56}+\frac{6(698.15)(2.99)}{6.56}+\frac{6(37.6)(.353)}{6.56}$$

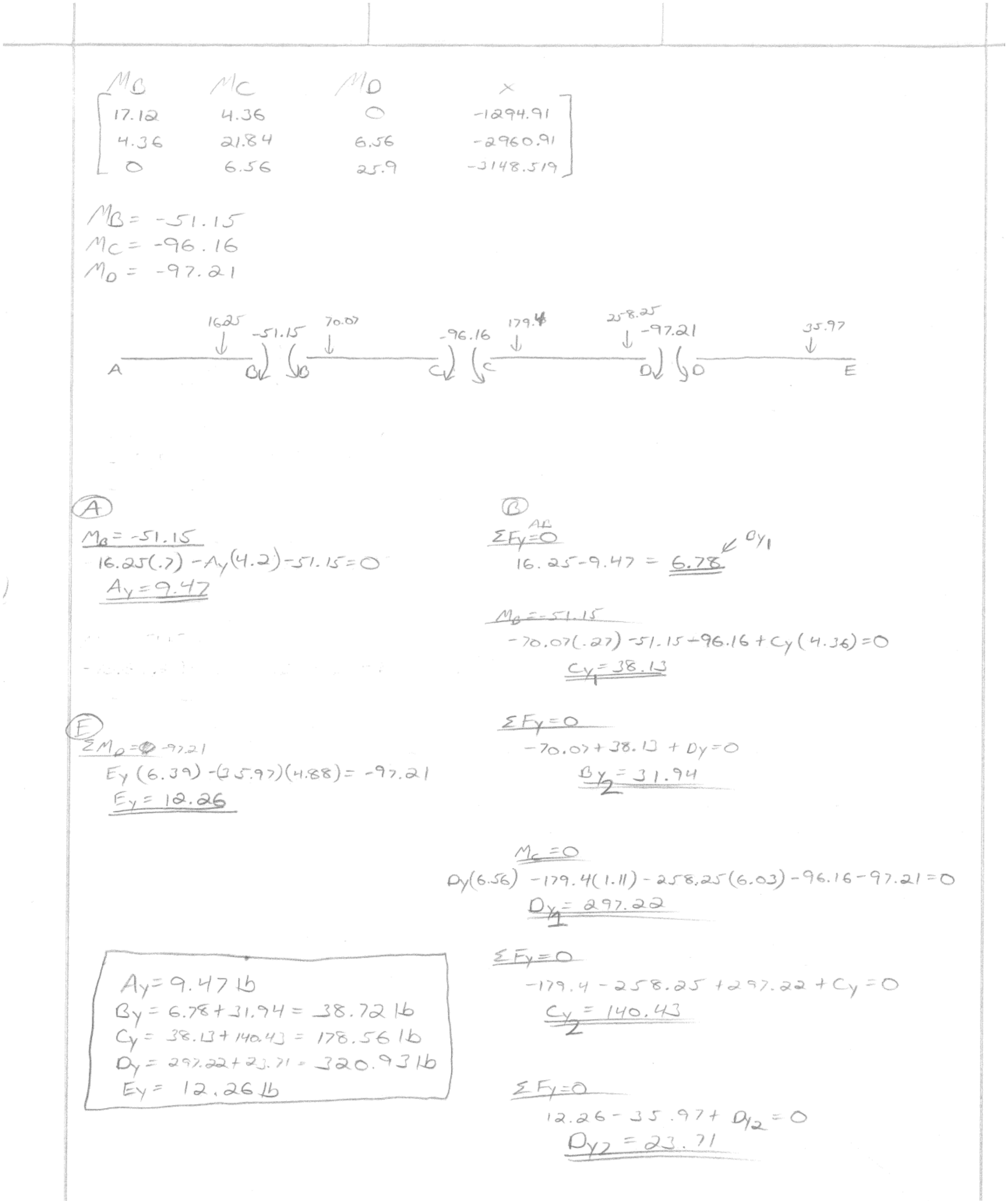
③ $$M_C(6.56)+2M_D(6.56+6.39)+M_E(6.39)+\frac{6(104.67)(.37)}{6.56}+\frac{6(114.882)(2.75)}{6.56}+\frac{6(698.15)(3.57)}{6.56}+\frac{6(37.6)(6.}{6.56}+\frac{6(101.21)(3.17)}{6.39}+\frac{6(31.32)(1.01)}{6.39}$$

① $4.2M_A+17.12M_B+4.36M_C+55.33+17.738+13.782+1208.057=0$
$=\cancel{4.2M_A}+17.12M_B+4.36M_C=-1294.91$

② $4.36M_B+21.84M_C+6.56M_D+.592+81.4+557.176+400.336+1909.27+12.14$
$4.36M_B+21.84M_C+6.56M_D=-2960.91$

③ $6.56M_C+25.9M_D+6.39M_E+35.42+288.956+2279.63+213.56+301.25+29.70$
$6.56M_C+25.9M_D+\cancel{6.39M_E}=-3148.519$

Figure 16: calculation of reaction forces on hull using three moment method continues



$$\begin{array}{cccc} M_B & M_C & M_D & x \\ \left[\begin{array}{c} 17.12 \\ 4.36 \\ 0 \end{array}\right. & \begin{array}{c} 4.36 \\ 21.84 \\ 6.56 \end{array} & \begin{array}{c} 0 \\ 6.56 \\ 25.9 \end{array} & \left.\begin{array}{c} -1294.91 \\ -2960.91 \\ -3148.519 \end{array}\right] \end{array}$$

$M_B = -51.15$
$M_C = -96.16$
$M_D = -97.21$

Ⓐ

$\underline{M_B = -51.15}$
$16.25(.7) - A_y(4.2) - 51.15 = 0$
$\underline{\underline{A_y = 9.47}}$

Ⓔ

$\underline{\Sigma M_D = -97.21}$
$E_y(6.39) - (35.97)(4.88) = -97.21$
$\underline{\underline{E_y = 12.26}}$

$A_y = 9.47 \text{ lb}$
$B_y = 6.78 + 31.94 = 38.72 \text{ lb}$
$C_y = 38.13 + 140.43 = 178.56 \text{ lb}$
$D_y = 297.22 + 23.71 = 320.93 \text{ lb}$
$E_y = 12.26 \text{ lb}$

Ⓑ

$\underline{\Sigma F_y \overset{AB}{=} 0}$
$16.25 - 9.47 = \underline{\underline{6.78}} \swarrow B_{y_1}$

$\underline{M_B = -51.15}$
$-70.07(.27) - 51.15 - 96.16 + C_y(4.36) = 0$
$\underline{\underline{C_{y_1} = 38.13}}$

$\underline{\Sigma F_y = 0}$
$-70.07 + 38.13 + D_y = 0$
$\underline{\underline{B_{y_2} = 31.94}}$

$\underline{M_C = 0}$
$D_y(6.56) - 179.4(1.11) - 258.25(6.03) - 96.16 - 97.21 = 0$
$\underline{\underline{D_{y_1} = 297.22}}$

$\underline{\Sigma F_y = 0}$
$-179.4 - 258.25 + 297.22 + C_y = 0$
$\underline{\underline{C_{y_2} = 140.43}}$

$\underline{\Sigma F_y = 0}$
$12.26 - 35.97 + D_{y_2} = 0$
$\underline{\underline{D_{y_2} = 23.71}}$

Figure 17: visual reference used to determine torque applied to outriggers and center spine

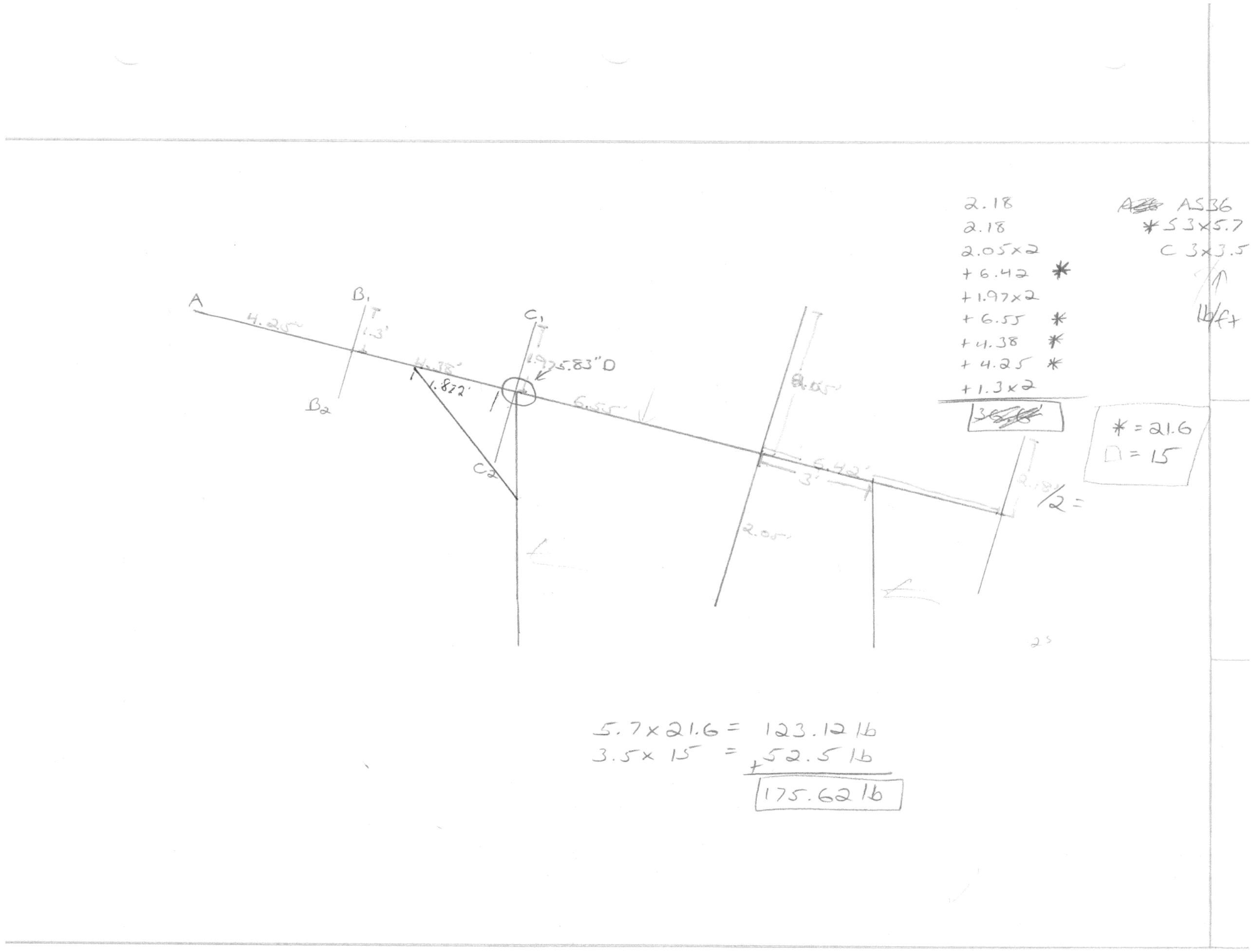
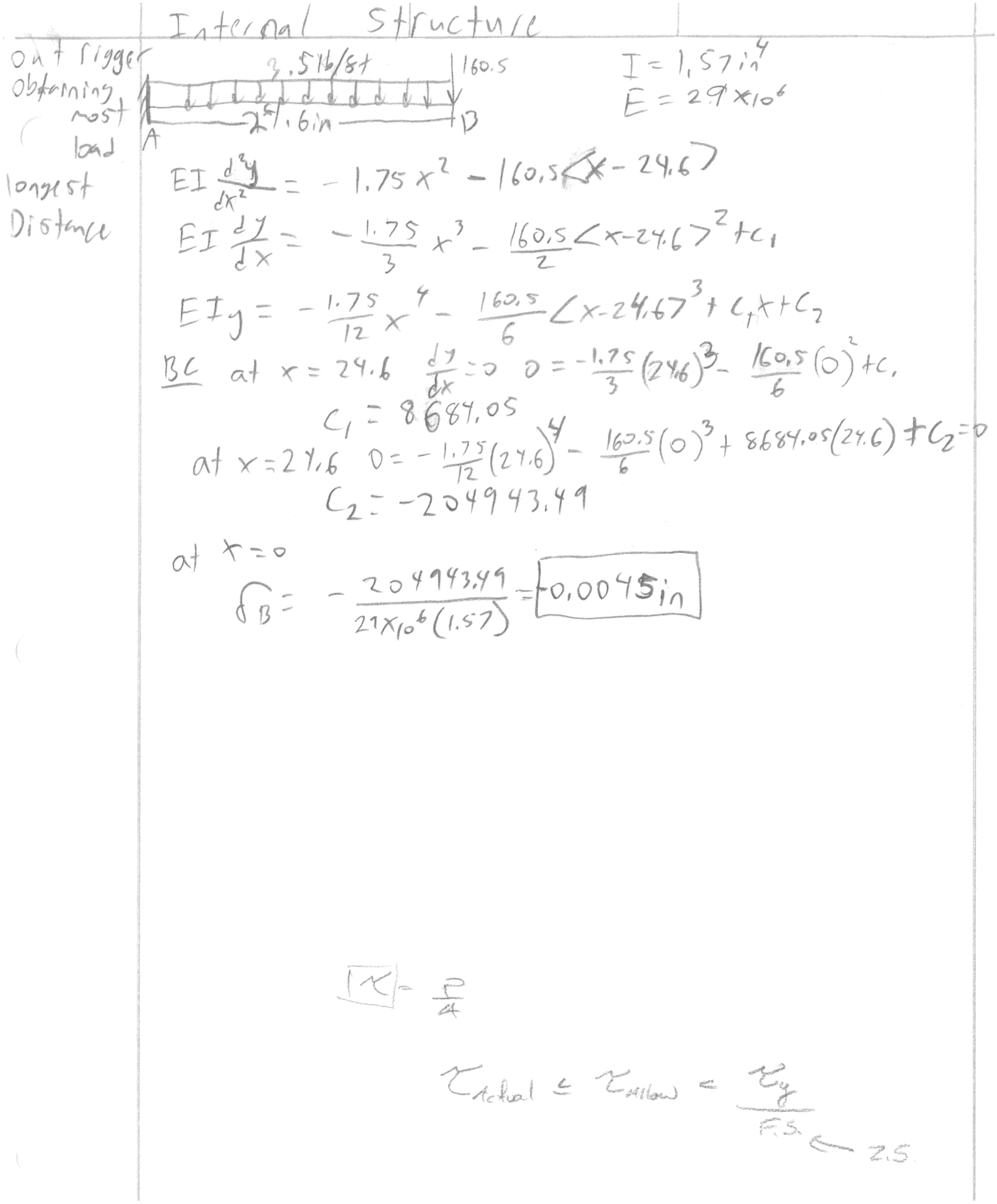


Figure 18: calculation of deflection of
outrigger undergoing largest moment



Internal Structure

outrigger obtaining most load longest Distance

3.5lb/ft 160.5

A 24.6in B

$I = 1.57 in^4$

$E = 29 \times 10^6$

$$EI\frac{d^2y}{dx^2} = -1.75x^2 - 160.5\langle x - 24.6\rangle$$

$$EI\frac{dy}{dx} = -\frac{1.75}{3}x^3 - \frac{160.5}{2}\langle x - 24.6\rangle^2 + c_1$$

$$EIy = -\frac{1.75}{12}x^4 - \frac{160.5}{6}\langle x - 24.6\rangle^3 + c_1x + c_2$$

BC at $x = 24.6$ $\frac{dy}{dx} = 0$ $0 = -\frac{1.75}{3}(24.6)^3 - \frac{160.5}{6}(0)^2 + c_1$

$c_1 = 8684.05$

at $x = 24.6$ $0 = -\frac{1.75}{12}(24.6)^4 - \frac{160.5}{6}(0)^3 + 8684.05(24.6) + c_2 = 0$

$c_2 = -204943.49$

at $x = 0$

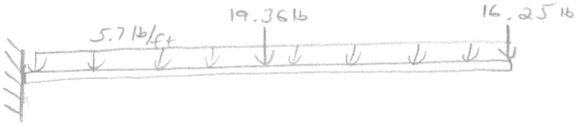
$$\delta_B = -\frac{204943.49}{29 \times 10^6(1.57)} = \boxed{-0.0045 in}$$

$\boxed{|\tau|} = \frac{P}{A}$

$\tau_{Actual} \le \tau_{allow} < \frac{\tau_y}{F.S.} \leftarrow 2.5$

Figure 19: calculation of deflection of front cantilever excluding support arm

Front Cantilever



$I = 2.52\,\text{in}^4$

$E = 29 \times 10^6$

$$EI\frac{d^2y}{dx^2} = -2.85x^2 - 19.36\langle x-4.38\rangle - 16.25\langle x-8.63\rangle$$

$$EI\frac{dy}{dx} = \frac{-285x^3}{3} - \frac{19.36}{2}\langle x-4.38\rangle^2 - \frac{16.25}{2}\langle x-8.63\rangle^2 + C_1$$

$$EI\,y = \frac{-.95x^4}{4} - \frac{9.68}{3}\langle x-4.38\rangle^3 - \frac{8.125}{3}\langle x-8.63\rangle^3 + C_1x + C_2$$

$$= -.2375x^4 - 3.23\langle x-4.38\rangle^3 - 2.71\langle x-8.63\rangle^3 + C_1x + C_2$$

Boundary

$$x = 8.63 \qquad \frac{dy}{dx} = 0 \Rightarrow \frac{-2.85(8.63)^3}{3} - \cancel{\frac{19.36}{2}\langle 2.85-4.38\rangle^2} - \cancel{\frac{16.25}{2}\langle 2.85-8.63\rangle^2} + C_1$$

$$0 = -610.599 + C_1$$

$$\boxed{C_1 = 610.599}$$

$$@\,x = 8.63\ \ y = 0 \Rightarrow 0 = -.2375(8.63)^4 - 3.23\langle 8.63-4.38\rangle^3 - \cancel{2.71\langle 8.63-8.63\rangle^3} + C_2$$

$$0 = -1317.367 - 247.95 + 610.599(8.63) + C_2$$

$$= -1565.317 + 5269.47 + C_2$$

$$3704.15$$

$y =$

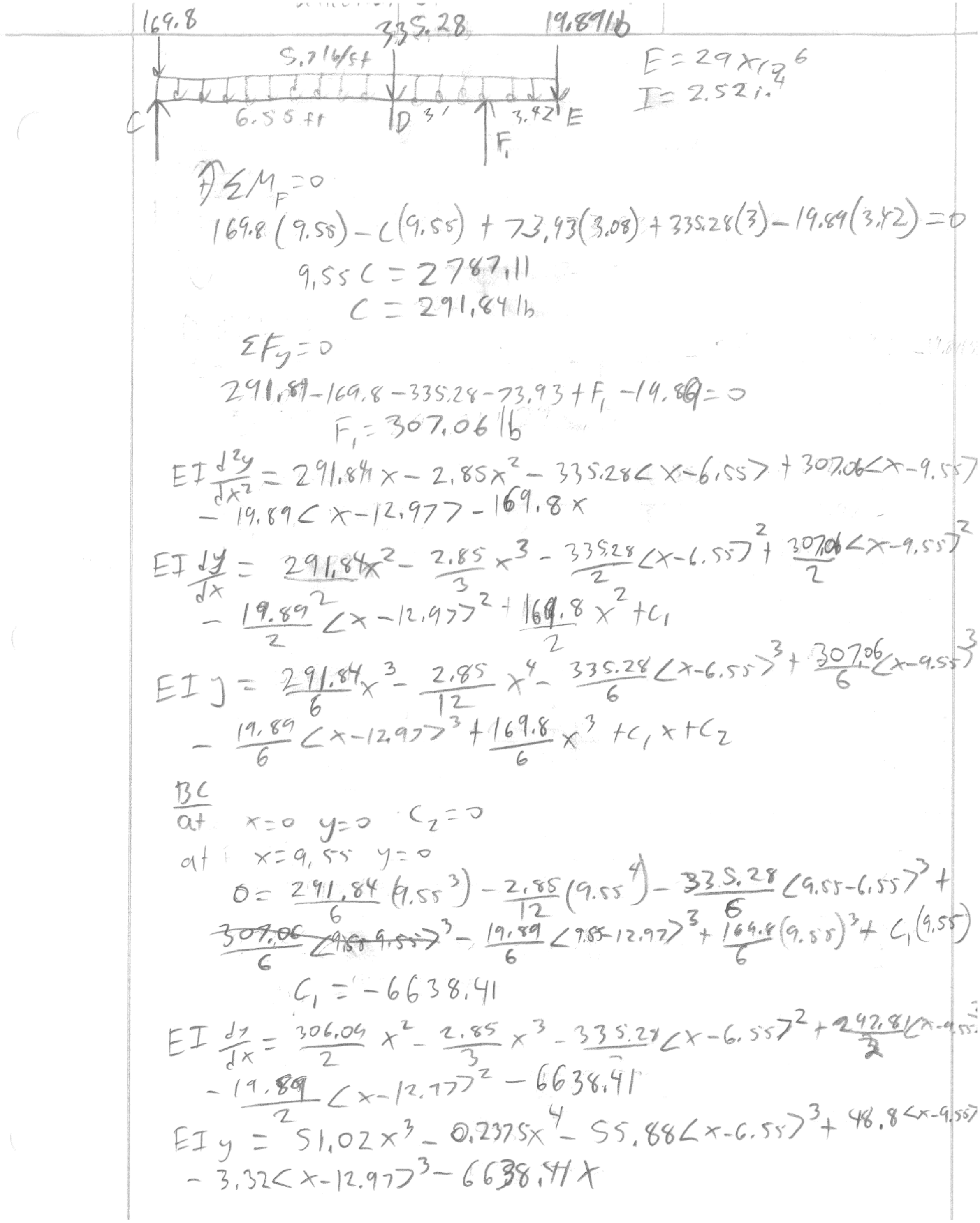
@ x = 0

$$y = \frac{3704 \times 12^3}{(29 \times 10^6)\,2.52} = -0.0876\ \text{in}\ ✓$$

+ cross member

good

Figure 20: calculation of deflection on S-beam spine



169.8

335.28

19.89 lb

5.71 lb/ft

C

6.55 ft

D

3'

3.42'

E

F_1

$E = 29 \times 10^6$

$I = 2.52\ in^4$

$$\circlearrowleft + \Sigma M_F = 0$$

$$169.8(9.55) - C(9.55) + 73.93(3.08) + 335.28(3) - 19.89(3.42) = 0$$

$$9.55C = 2787.11$$

$$C = 291.84\ lb$$

$$\Sigma F_y = 0$$

$$291.84 - 169.8 - 335.28 - 73.93 + F_1 - 14.89 = 0$$

$$F_1 = 307.06\ lb$$

$$EI\frac{d^2y}{dx^2} = 291.84x - 2.85x^2 - 335.28\langle x-6.55\rangle + 307.06\langle x-9.55\rangle - 19.89\langle x-12.97\rangle - 169.8x$$

$$EI\frac{dy}{dx} = \frac{291.84}{2}x^2 - \frac{2.85}{3}x^3 - \frac{335.28}{2}\langle x-6.55\rangle^2 + \frac{307.06}{2}\langle x-9.55\rangle^2 - \frac{19.89}{2}\langle x-12.97\rangle^2 + \frac{169.8}{2}x^2 + C_1$$

$$EIy = \frac{291.84}{6}x^3 - \frac{2.85}{12}x^4 - \frac{335.28}{6}\langle x-6.55\rangle^3 + \frac{307.06}{6}\langle x-9.55\rangle^3 - \frac{19.89}{6}\langle x-12.97\rangle^3 + \frac{169.8}{6}x^3 + C_1x + C_2$$

BC

at $x=0$ $y=0$ $C_2=0$

at $x=9.55$ $y=0$

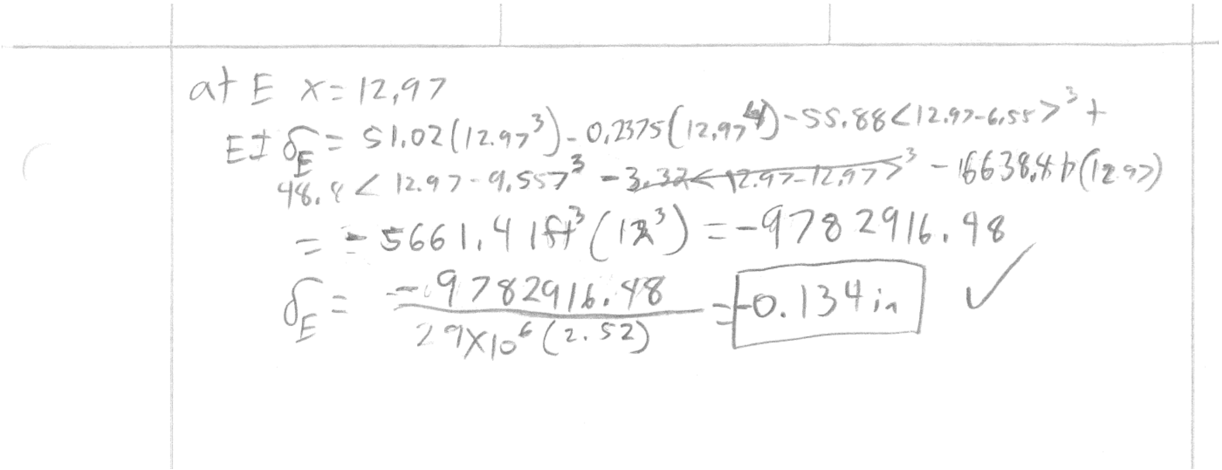
$$0 = \frac{291.84}{6}(9.55^3) - \frac{2.85}{12}(9.55^4) - \frac{335.28}{6}\langle 9.55-6.55\rangle^3 + \cancel{\frac{307.06}{6}\langle 9.55-9.55\rangle^3} - \frac{19.89}{6}\langle 9.55-12.97\rangle^3 + \frac{169.8}{6}(9.55)^3 + C_1(9.55)$$

$$C_1 = -6638.41$$

$$EI\frac{dy}{dx} = \frac{306.04}{2}x^2 - \frac{2.85}{3}x^3 - \frac{335.28}{2}\langle x-6.55\rangle^2 + \frac{242.81}{2}\langle x-9.55\rangle^2 - \frac{19.89}{2}\langle x-12.97\rangle^2 - 6638.41$$

$$EIy = 51.02x^3 - 0.2375x^4 - 55.88\langle x-6.55\rangle^3 + 48.8\langle x-9.55\rangle^3 - 3.32\langle x-12.97\rangle^3 - 6638.41x$$

Figure 21: calculation of deflection on S-beam spine continued



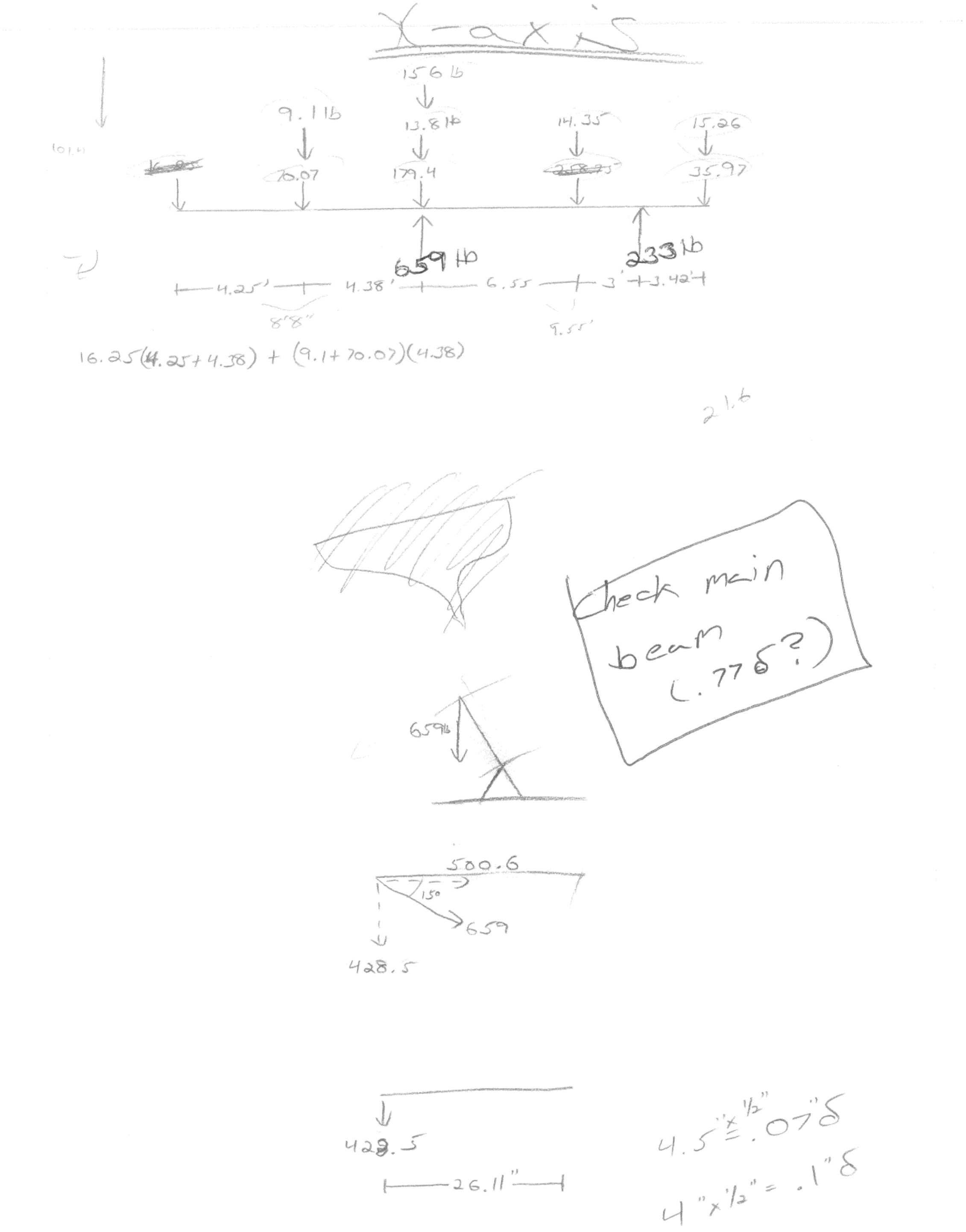
at E $x = 12{,}97$

$$EI\,\delta_E = 51.02(12.97^3) - 0.2375(12.97^4) - 55.88\langle 12.97-6.55\rangle^3 + 48.8\langle 12.97-9.55\rangle^3 - \cancel{3.32\langle 12.97-12.97\rangle^3} - 16638.46(12.97)$$

$$= -5661.41\ \text{ft}^3(12^3) = -9782916.48$$

$$\delta_E = \frac{-9782916.48}{29\times10^6(2.52)} = \boxed{-0.134\ \text{in}}\ \checkmark$$

Figure 22: determination of largest moment applied to support column



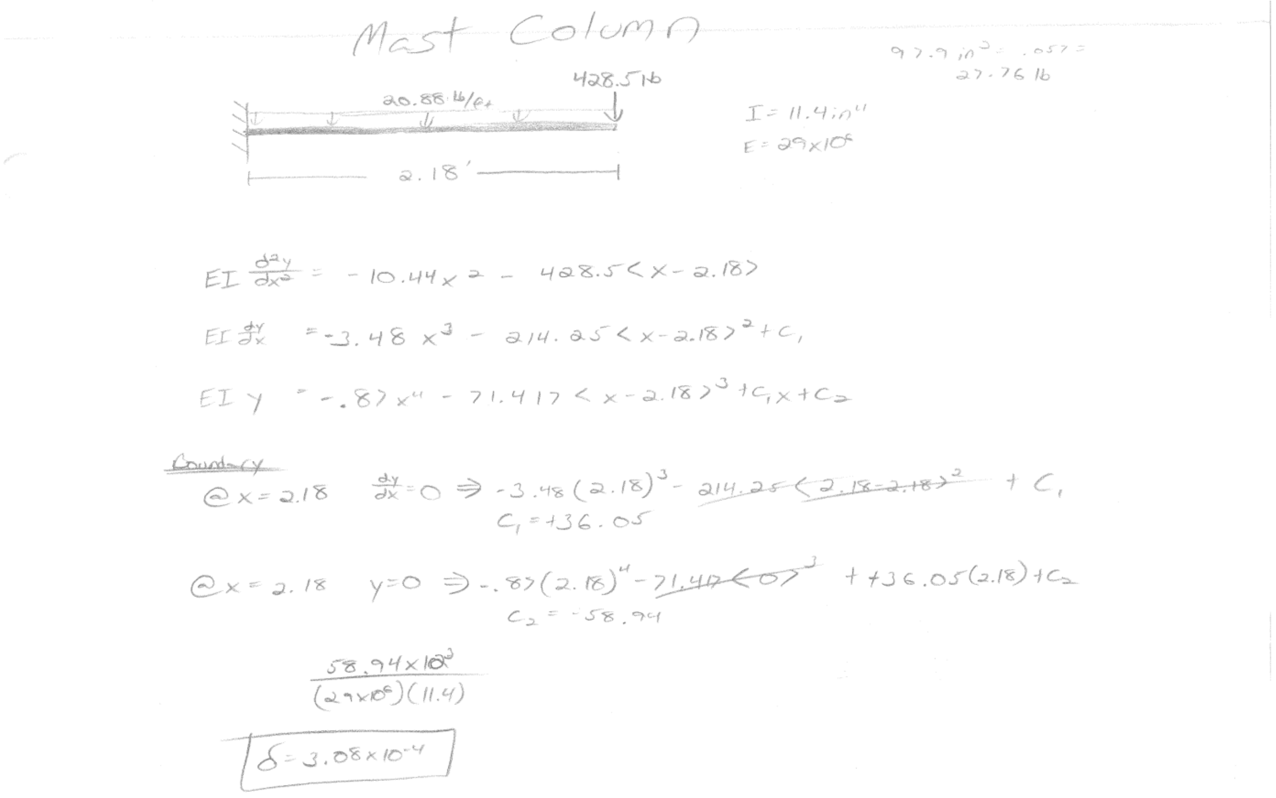


Figure 23: deflection of support column supporting highest load

Mast Column

97.9 in³ = .057 =
27.76 lb

$I = 11.4 in^4$

$E = 29 \times 10^6$

$$EI \frac{d^2y}{dx^2} = -10.44x^2 - 428.5\langle x - 2.18\rangle$$

$$EI \frac{dy}{dx} = -3.48x^3 - 214.25\langle x - 2.18\rangle^2 + C_1$$

$$EI\,y = -.87x^4 - 71.417\langle x - 2.18\rangle^3 + C_1x + C_2$$

Boundary

$$@x = 2.18 \quad \frac{dy}{dx} = 0 \Rightarrow -3.48(2.18)^3 - \cancel{214.25\langle 2.18 - 2.18\rangle^2} + C_1$$

$$C_1 = +36.05$$

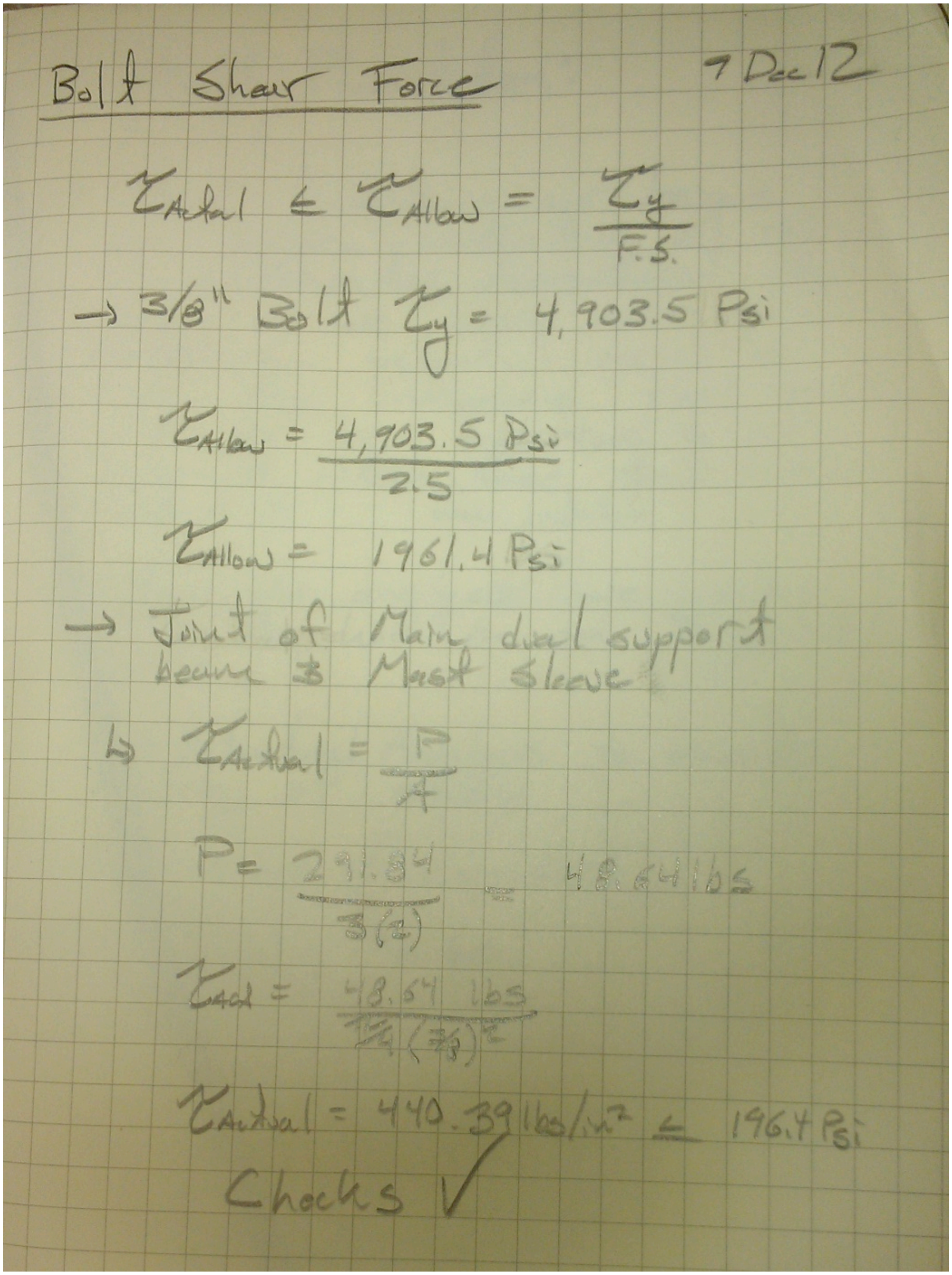
$$@x = 2.18 \quad y = 0 \Rightarrow -.87(2.18)^4 - \cancel{71.417\langle 0\rangle^3} + +36.05(2.18) + C_2$$

$$C_2 = -58.94$$

$$\frac{58.94 \times 12^3}{(29 \times 10^6)(11.4)}$$

$$\boxed{\delta = 3.08 \times 10^{-4}}$$

Figure 24: Determination of shear force acting on bolt



Bolt Shear Force

7 Dec 12

$$\tau_{Actual} \leq \tau_{Allow} = \frac{\tau_y}{F.S.}$$

→ 3/8" Bolt $\tau_y = 4,903.5$ Psi

$$\tau_{Allow} = \frac{4,903.5 \text{ Psi}}{2.5}$$

$$\tau_{Allow} = 1961.4 \text{ Psi}$$

→ Joint of Main dual support beam & Mast sleeve

↳ $\tau_{Actual} = \frac{P}{A}$

$$P = \frac{291.84}{3(2)} = 48.64 \text{ lbs}$$

$$\tau_{Act} = \frac{48.64 \text{ lbs}}{\frac{\pi}{4}\left(\frac{3}{8}\right)^2}$$

$$\tau_{Actual} = 440.39 \text{ lbs/in}^2 \leq 196.4 \text{ Psi}$$

Checks ✓

cpc
Community Partnerships Center
at Roger Williams University

Roger Williams University
One Old Ferry Road
Bristol, Rhode Island 02809

Phone: (401) 254-3307
Fax: (401) 254-3565

cpc@rwu.edu
http://cpc.rwu.edu