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A Discussion of Structural Analysis Techniques for Western Kentucky University's Concrete Canoe, "Courageous"

Aaron J. Daley
Western Kentucky University, Aaron.Daley433@topper.wku.edu

A DISCUSSION OF STRUCTURAL ANALYSIS TECHNIQUES FOR WESTERN KENTUCKY UNIVERSITY'S 2013 CONCRETE CANOE, "COURAGEOUS"

A Capstone Experience/Thesis Project

Presented in Partial Fulfillment of the Requirements for

the Degree Bachelors of Science with

Honors College Graduate Distinction at Western Kentucky University

By

Aaron J. Daley

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Western Kentucky University

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CE/T Committee:

Professor Matthew Dettman, P.E., Advisor

Dr. Shane Palmquist, P.E.

Ms. Cheryl Kirby-Stokes

Approved by

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Advisor
Department of Engineering

ABSTRACT

One of the most famous aspects of the WKU Civil Engineering department is the annual student participation in the Concrete Canoe Competition. This year-long project requires seniors to design, manage construction for, and compete with a twenty-foot long boat made out of concrete and reinforcement. It is important to know the loads that the canoe will experience during its use in paddling races. The process for determining these internal forces is called structural analysis. For my project I will be discussing the analysis process employed for the 2013 concrete canoe, exploring accuracy, technical knowledge required, and the practical application of all computations.

Keywords: Concrete Canoe, Structural Analysis, Two-Dimensional Analysis

Dedicated to my family, friends, and

classmates whose encouragement has

been invaluable in completing this project

ACKNOWLEDGEMENTS

This project would not have been possible without the help of the Civil Engineering staff at WKU, as well as the group of “Team Courageous” seniors who put forth so much effort into the concrete canoe this year.

Special thanks to Professor Matthew Dettman, who advised the entire concrete canoe team from the start of the project to its completion. Professor Dettman’s experience with concrete canoes and engineering projects in general was very helpful to a student who was working on his first large-scale engineering endeavor.

I would also like to thank Dr. Shane Palmquist, Civil Engineering professor, for his role as a technical reference with regards to structural analysis. Dr. Palmquist worked with me to develop accurate models and analysis techniques that I will be able to apply in my future structural engineering career.

Finally, the senior students who helped to design and build *Courageous* were a huge help. There was a great group dynamic this year, and someone was always willing to lend a hand with the calculations, data acquisition, and materials testing needed for my analysis.

VITA

August 12, 1991..Born – Louisville, Kentucky

2009…………………………………………….....duPont Manual High School,
Louisville, Kentucky

2011……………………………………………...…Intern, St. Anthony Falls Stream
Laboratory, Minneapolis, Minnesota

2011……………………………………………..….Treasurer, WKU American
Society of Civil Engineers

2012……………………………………………..….Intern, Qk4 Engineering,
Louisville, Kentucky

2012……………………………………………......President, WKU American
Society of Civil Engineers

FIELDS OF STUDY

Major Field: Civil Engineering

Concentration: Structural Engineering

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CHAPTER 1

AN INTRODUCTION TO CIVIL ENGINEERING

Italicized words are defined in the Glossary

Look around you. Are you indoors or outdoors? Are you at ground level, on an elevated floor, or below the earth's surface? Chances are, you are probably in contact with something that has been designed by a Civil Engineer. The profession of Civil Engineering deals with designing and maintaining our nation's infrastructure – from the roads and bridges on which people travel to the systems that provide them with clean drinking water and reliable waste disposal. There are many facets of this diverse career, and they are all very important to the American way of life.

The main sectors of Civil Engineering are *Construction, Environmental Engineering, Structural Engineering, Transportation Engineering, Geotechnical Engineering*, and *Materials Science*. The detailed responsibilities of each type are outlined in the Glossary in the back of this book. As one can conclude from this list, Civil Engineers have a large amount of responsibility to design safe and effective projects due to their large effect on public safety and welfare. An error in this field produces a much bigger problem than a simple product recall – it can result in millions of dollars in damage as well as human injury or death.

Because of this responsibility, Civil Engineering is treated like other professional careers such as Law, Medicine, and Dentistry. In order to fully practice civil engineering one must obtain at least a Bachelor's of Science degree from an accredited institution, as well as pass professional licensure tests. This testing process consists of a Fundamentals of Engineering (FE) Exam, after which an engineer must practice engineering with an Engineer-in-Training (EIT) license for four years. At the end of four years, an engineer may take the Professional Engineering (PE) Exam in a specific civil engineering subject area. These degree and license requirements are in place to ensure that today's civil engineers are competent enough to be responsible for our nation's infrastructure.

The field of structural engineering has two tracks: design and analysis. The design track involves researching the *loads* a structure will experience in its lifetime and determining a safe plan for the *members* and connections to effectively transfer these loads from their point of application into the structure's *foundation*. One of the main principles of design is that all loads are *factored* in order to over-design the structure and provide additional safety measures. The analysis track, on the other hand, examines an existing structure or completed design plan and reveals the actual, *unfactored* forces that the structure will experience.

In today's technology-laden society, structural engineering is becoming increasingly computer-based. *Finite element analysis* programs are able to analyze a structure in three dimensions at once by virtually breaking the structure into thousands of tiny square-shaped plates. Deflection and rotation calculations are performed on each of the plates, which are then added together to obtain a force analysis of the entire structure. This method will yield more accurate values, due to the fact that it performs its analysis of all the forces acting on the entire structure at the same time. A *two-dimensional analysis*, on the other hand, requires the structure to be converted into several equivalent two-dimensional models. Each applied load is then added separately, and all scenarios are added together to get an estimation of the total internal force.

Each year, senior Civil Engineering students at Western Kentucky University take a senior project class. This class centers on the design, construction, and competition of a canoe made out of concrete. The purpose of the competition is to give students experience managing a civil engineering project, and the engagement results in competency with task delegation, project scheduling, and personal responsibility. The project is divided into task-based action items, each with a senior in charge of their completion. This report details the process of the structural analysis of the 2013 concrete canoe, managed by civil engineering student Aaron Daley.

CHAPTER 2

THE 2013 CONCRETE CANOE

Each canoe starts with the selection of a theme. In past years, WKU has used the names *XX Legacy* (for the school's 20^{th} anniversary in the competition), *Aftershock* (an earthquake-themed boat), and *The Phoenix* (a canoe that was to "rise from the ashes of past competitions" as a new and improved boat), along with many others. This year, the theme was based on cancer awareness and the boat was named *Courageous.* This theme was chosen because a senior Civil Engineering student was diagnosed with stage IV cancer at the beginning of the Fall 2012 semester. He was so determined to continue his goal of becoming a civil engineer that he continued to attend class even through his chemotherapy and radiation treatments. The other seniors were so impressed by his dedication that they decided the project would be completed in celebration of his fight.

The largest challenge facing Team Courageous was the need for a new canoe hull. In the 2012 competition, *XX Legacy* did not perform well in the races due to its excessive weight, flat bottom, and wide cross section. A hull was developed using Prolines 7 © software. This program generated optimal values for length, cross section, width, side slopes, and other measurements that allowed the canoe team to create a drawing in *AutoCAD*. This drawing was then sent to the WKU Architectural and Manufacturing Sciences department, where a high-pressure water jet was able to cut a mold out of styrofoam. This foam was covered with drywall putty and shrink wrap, which would allow the concrete to be applied without bonding to the form.

Once the hull was finalized, the canoe ingredients had to be decided upon. In addition to concrete, WKU canoe teams use various types of mesh, wire, and other reinforcement in their boats. This is because concrete can resist a very high *compressive* load but not a high *tensile* load. To prevent the canoe from cracking in areas where it is being pulled, materials must be added to handle this tension. In *Courageous,* the tensile materials were fiberglass mesh, carbon fiber mesh, and braided steel wire. Materials such as Nitinol memory wire have been used in the past, but the 2013 budget did not allow for these much more expensive additions.

Construction began when designs were complete and all materials had arrived. Team Courageous poured a practice canoe that served a dual purpose – it allowed the project manager to find any difficulties in the construction process and develop solutions, and it also provided a boat with the correct dimensions to the paddling team for practice. This was important because the new hull was so unstable in the water that paddlers had to take extra time learning how to balance it for the races. After the practice canoe had been studied for any problems, a final canoe was made. This final draft had three layers of concrete covering two layers of fiberglass mesh, a layer of carbon fiber mesh, and ten braided steel cables running longitudinally along the canoe's side walls. The concrete was allowed to cure for 14 days, and then was taken off the foam mold and the finishing process (sanding, *grouting*, decorating, and *sealing*) began.

The boat's completion did not signify the end of the project. Team Courageous had to prepare the structural analysis, technical design paper, oral presentation, and a display table on which all materials used were available for the conference judges to view. The organization and planning of the competition itself was a learning experience. *Courageous* won the third place overall award at the Ohio Valley Student Conference, following Youngstown State University's and The University of Akron's boats.

CHAPTER 3

DEVELOPING AN ANALYSIS PLAN

The judges who develop the National Concrete Canoe Competition (NCCC) rules introduce differences in design requirements every year to keep competition alive and prevent schools from reusing canoes from previous years. For the 2012-2013 competition, one of the new regulations was that the structural analysis had to be two-dimensional. In the past, a three-dimensional analysis rule allowed teams to input the canoe's shape into a finite element analysis program and obtain very accurate values for internal forces during different paddling and transportation models or *loading scenarios.* Finite element program classes are not a required part of the undergraduate civil engineering curriculum, and judges believed that schools with graduate programs were at an unfair advantage due to the presence of students and faculty who were familiar with advanced structural engineering computer knowledge. The requirement of a two-dimensional canoe analysis meant that every undergraduate senior civil engineering student had been exposed to classes that would qualify him or her to perform a complete calculation of the boat's internal forces.

Generally, the analysis of a structure can begin as soon as the structure in question has a complete design. It is sometimes more appropriate to wait until construction has finished in order to include any changes that may be made during the construction process, but the creation of the practice boat minimized the risk of unforeseen problems that would require a last-minute change. Therefore, the structural analysis of *Courageous* was started when the hull design was finalized and material decisions were made.

To begin the analysis, Daley discussed with Civil Engineering professor Matthew Dettman which loading scenarios would be appropriate to consider for the canoe. Dettman informed him that past teams had done an analysis of the boat with a *point load* near each end to represent the two paddler races, one with four point loads evenly spaced to represent the four paddler races, and one with eight point loads along the side walls while the canoe was inverted to represent team members carrying the boat on the day of the competition. Teams also studied the forces on the side walls of the canoe due to the water pressure acting inward during paddling and performed an estimation of this for both the two person and four person races. Considering all of these cases, five loading scenarios were to be used.

The next step was for Daley to meet with Dr. Shane Palmquist, a Civil Engineering professor at WKU, who specializes in structural engineering. The two developed several two-dimensional models that would allow for the most accurate internal force calculations. A challenge presented by analyzing a canoe-like shape is that the object is *non-prismatic,* meaning that it does not have a uniform cross-section along its length. Even if the external applied load is the exact same over the entire canoe, the internal forces will still vary at different points on the boat.

Professor Dettman offered help on this issue by referencing the process used on the 2003 WKU concrete canoe *Illusion,* which was also analyzed two-dimensionally. The *Illusion* team created an estimation of the canoe's surface area in contact with the water by converting the boat's dimensions into rectangular sections. A similar process was used for *Courageous;* however, since its widest point was not at mid-length, it was determined that there should be more rectangular sections and that each one should be shorter in order to increase the accuracy of the analysis. These rectangular sections would be separated and analyzed as prismatic members, then superimposed back together to retain a shape close to that of the original boat.

A cross section is another essential model for the structural analysis process. The canoe's non-prismatic quality presented problems here, and it was decided that an "equivalent" cross section would be used for analysis purposes. This section, oriented as if observing the canoe while facing one of the end points, resembled an inverted T and accounted for the fact that the boat resembled a V at each end and a U at mid-length. With the T shape, a middle ground was found between the two cross section extremes. Cross sections for the side walls were simple and could be represented accurately by rectangles.

The idea behind a structural analysis is to compute as accurately as possible the internal loads that an object will experience during its intended use. These loads are then compared to the strength of the materials in the structure to obtain a *safety factor*. This safety factor is an indication of how strong a structure is relative to its minimum required strength. The types of forces that were analyzed in *Courageous* were *flexure,* compression, and tension. Another common type of force, *torsion,* was not present enough in the canoe to merit its own analysis.

CHAPTER 4

PERFORMING THE ANALYSIS

Once a plan had been developed with the professors, Daley could perform the analysis itself fairly easily. The analysis process for *Courageous* follows in a step-by-step format. Most of the uncommon technical terms can be found in the Glossary in the back of this book.

Calculating the Buoyant Force under each Paddling Scenario

In order for the canoe to stay afloat, the buoyant force of the water pushing upward on the bottom of the boat must be equal to the sum of the weight of the boat and the weight of the paddlers. In the analysis, each paddler had a weight of 165 pounds (lb) and the canoe's weight was 200 lb.

$$\boldsymbol{F_B = 200 + (165 * N_P)}$$

Where:

$F_B = Total\ Buoyant\ Force, lb$

$N_P = Number\ of\ Paddlers$

This formula resulted in a buoyant force of 530 lb for the two person scenario and 860 lb for the four person scenario.

Calculating the Pressure on the Bottom of the Canoe

The buoyant force values were then divided by the total canoe surface area as found from the sum of the areas of rectangular sections, generating a pressure value in pounds per square inch (psi) distributed over the bottom of the boat. This pressure allowed the load on each individual section to be calculated.

Refer to Figure 1 in Appendix for Rectangular Section Diagram

Creating a Two-Dimensional Beam Representation

The boat was then represented as a two-dimensional beam with point loads pushing upward acting in the middle of each rectangular cross section, while point loads pushing downward acted at the location of each paddler. From this representation, the *moment diagram* can be produced, which shows how the internal *moment* varies along the length of the boat. The maximum moment magnitude is the most important value for analysis purposes, and it occurred at the boat's mid-length. The moment has a negative value, meaning the boat is experiencing a force that is trying to bend it into a rainbow shape.

$$\mathbf{M} = \boldsymbol{F} * \boldsymbol{D}$$

Where:

$M = Moment, lb * ft$

$F = Applied\ Force, lb$

$D = Distance\ to\ Applied\ Force, ft$

Since the moment is found by multiplying the applied force by the distance to the point in question, the two paddler scenario results in a higher internal moment value due to the larger distance between paddlers.

Refer to Figure 2 in Appendix for Beam Representation Diagrams

<u>Using the Cross Section to Calculate Compression and Tension</u>

The equivalent cross section now comes into play to determine the compressive loads in the concrete and the tensile loads in the steel and mesh. First, the location of the *neutral axis* must be found. This can be done using the equation

$$\boldsymbol{\bar{Y}} = \frac{\sum(\boldsymbol{\bar{y}} * \boldsymbol{A})}{\sum \boldsymbol{A}}$$

Where:

$\bar{Y} = Location\ of\ neutral\ axis\ measured\ from\ the\ bottom\ of\ the\ shape, in$

$\bar{y} = Distance\ from\ the\ bottom\ of\ the\ shape\ to\ the\ center\ of\ a\ section, in$

$A = Area\ of\ a\ section, in^2$

The inverted T shape was split into two rectangular sections for this equation – a 3/8" x 18 1/2" horizontal rectangle and a 6/8" x 20" vertical rectangle. Using these values and their centroids in the neutral axis equation revealed that the neutral axis was 5 1/2" above the bottom of the canoe.

The canoe's negative moment value at mid-length indicates that the material above the neutral axis is in tension, and the material below the neutral axis is in compression. The moment found in the beam representation is divided by two and then divided by the distance from the centroid of the compression area to the neutral axis. This gives the total force in the compression section and, therefore, the total compressive force for the concrete. The necessary concrete compressive strength for *Courageous* was found to be 890 psi. The same process was used to determine the tensile load in the steel and mesh. Since three different types of materials were used to resist the tensile load, it is impossible to determine the exact load within each material on an individual basis without highly sophisticated material testing equipment. Compatibility equations would have to be developed to relate the three materials' deformation and elasticity properties. However, the total tensile load for all three materials was found to be 500 lb.

Refer to Figure 3 in Appendix for Cross Section Diagram

<u>Calculating Side Wall Flexure Loads</u>

The depth of the canoe in the water under each paddling scenario has to be calculated in order to start side wall pressure equations. To find the depth, the following equation is used:

$$\boldsymbol{D = \frac{62.4}{W_C + \sum W_P} * \frac{1728}{A}}$$

Where:

$D = Depth\ of\ canoe\ in\ water, in$

$A = Surface\ area\ of\ canoe, in^2$

$W_C = Weight\ of\ canoe, lb$

$W_P = Weight\ of\ paddlers, lb$

After depth is found, it is quite simple to find the water pressure on each wall. The density of water, .0361 pounds per cubic inch, is multiplied by the depth of the water in inches for each load case to find the pressure at the base of the cross section. It is known that water pressure increases linearly with depth, so a triangle was drawn on the side of the cross section representing a pressure of zero at the water's surface. Calculating the area of this triangle gives the total force, and multiplying by one-third of its height results in the internal moment at the base of the cross section. This minimum flexural strength value for *Courageous* was 16 lb*ft.

Refer to Figure 4 in Appendix for Side Wall Pressure Diagram

CHAPTER 5

DISCUSSION OF ANALYSIS

When the compressive, tensile, and flexural strengths for *Courageous* were found (see Tables 1A and 1B in Appendix), the numbers were compared to data collected by Joshua Amos, the senior in charge of mix design. Through material testing and research, Amos was able to find the actual strength values for the canoe's ingredients. Table 2 in the Appendix illustrates the safety factors generated by dividing the material strengths by their minimum requirements.

Whether a safety factor is adequate is up to the engineer to decide. Regarding very common situations incorporating a well-known design, the safety factor can be in the range of 2 or 3. However, since the concrete canoe does not have a specific set of design guidelines or safety codes, Team Courageous did not feel that a safety factor of 2 would provide the necessary confidence, especially when the boat was needed to keep paddlers warm and dry while on the Cleveland pond. Fortunately, the materials were strong enough to provide safety factors of 4 or greater for each of the forces measured.

Although Daley and his advisors felt that the analysis techniques used on *Courageous* were accurate, there are always improvements that can be made. One opportunity to check the accuracy of the numbers generated would be to attach strain gauges to the canoe and measure the internal strain in the canoe as a known stress of the paddlers sit in it on the water. Another measurement that could be analyzed is *deflection*

– a common value in analysis but one not considered this year. Accuracy could also be increased by using shorter rectangular sections, or by attempting to fit the curve of the boat’s side walls to an equation and then integrating the equation to find a more accurate surface area value.

The two-dimensional analysis provided a huge learning opportunity for the senior Civil Engineering students who participated in the concrete canoe project. The practice of adapting previous knowledge to a new set of circumstances is one that will follow the students throughout their careers. The project has been continued and repeated for 21 years, and the annual improvements on past experiences are the epitome of what engineering is all about. Witnessing accomplishments such as this can cause one to think that the abilities of WKU engineers are almost limitless.

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APPENDIX

The Appendix contains figures and tables referenced throughout this document.

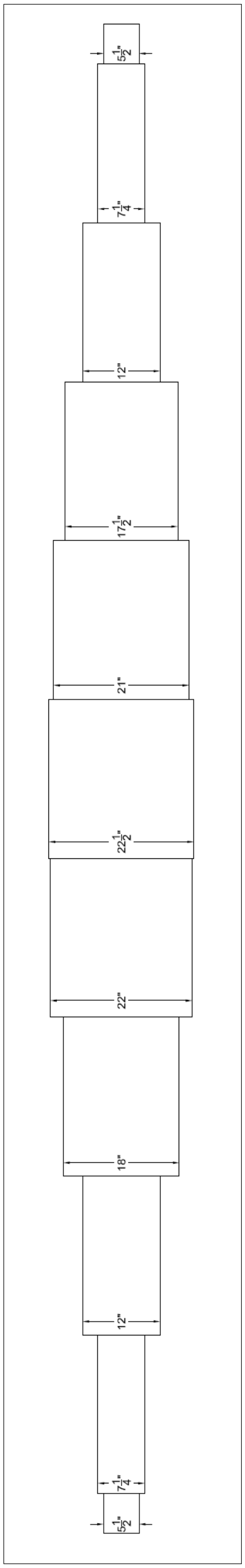

Figure 1 – Rectangular Section Model used for Two-Dimensional Canoe Area Estimation

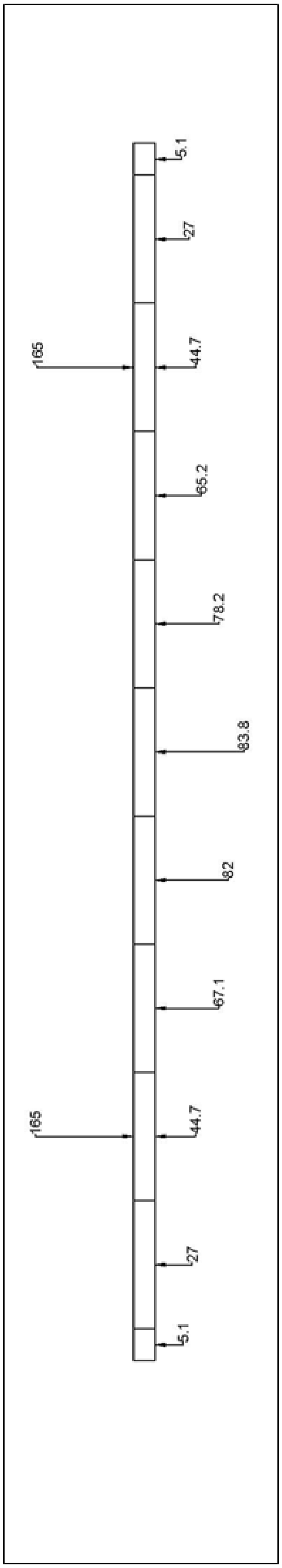

Figure 2A - Beam Representation of Canoe

Experiencing Two-Paddler Loading

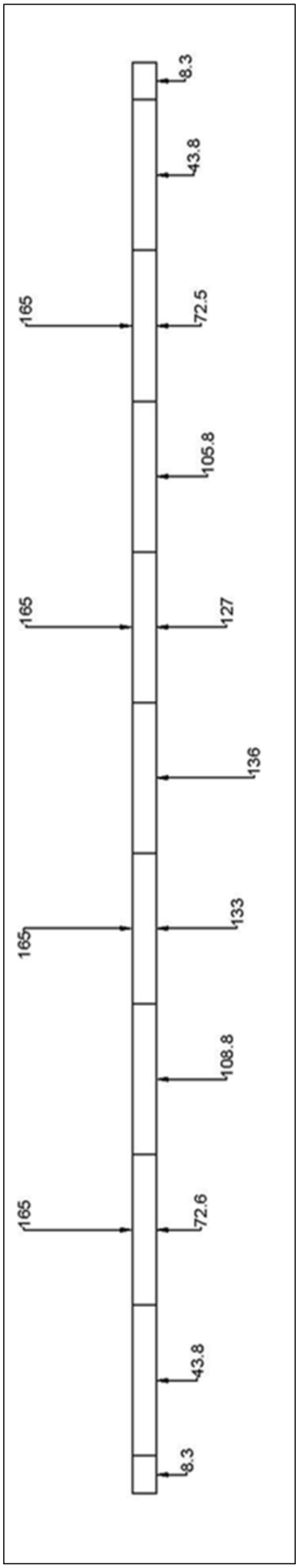

Figure 2B – Beam Representation of Canoe

Experiencing Four-Paddler Loading

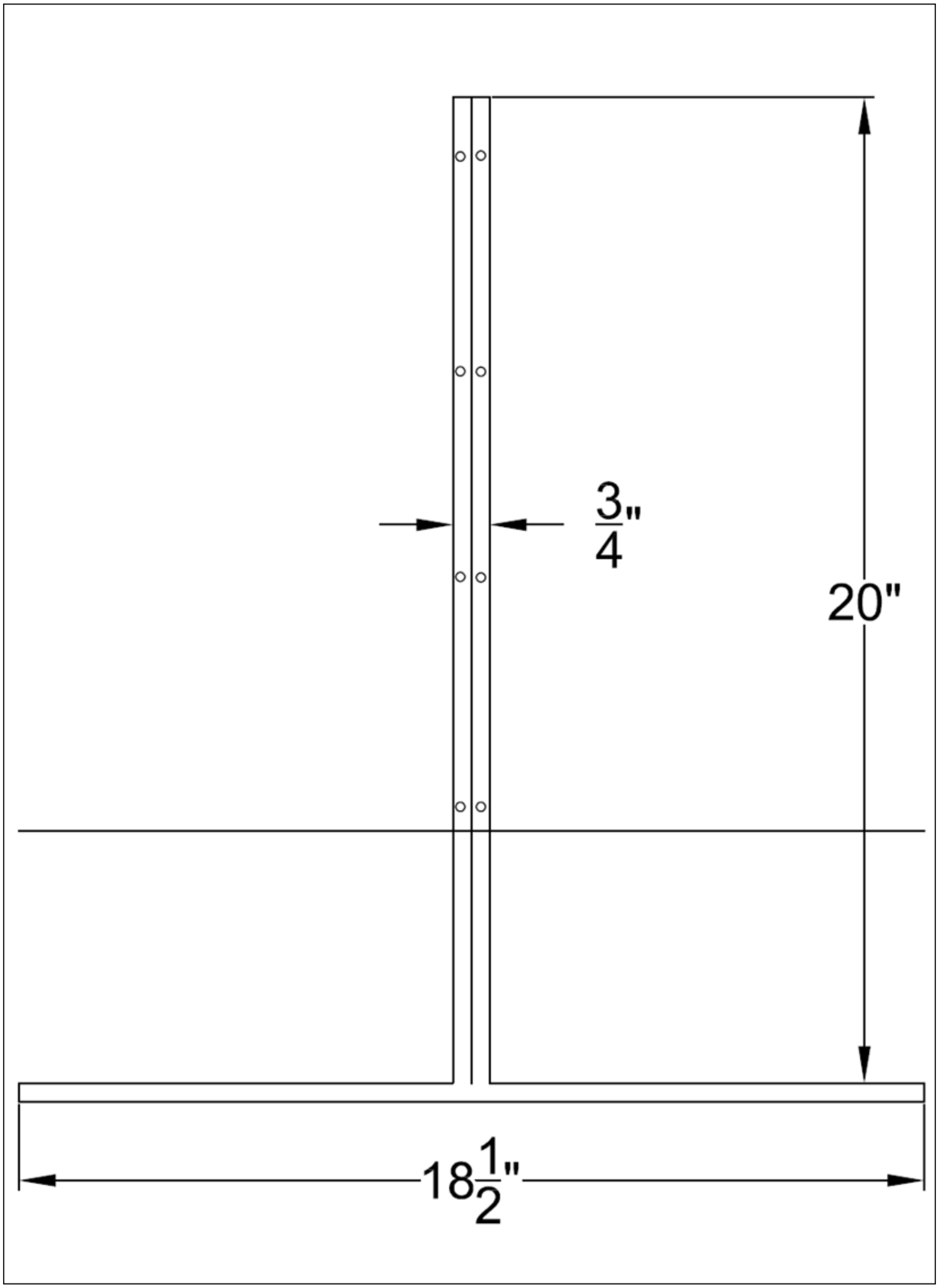

Figure 3 – Equivalent Cross Section Used for Internal Moment Analysis

Showing Neutral Axis 5.5” from Bottom

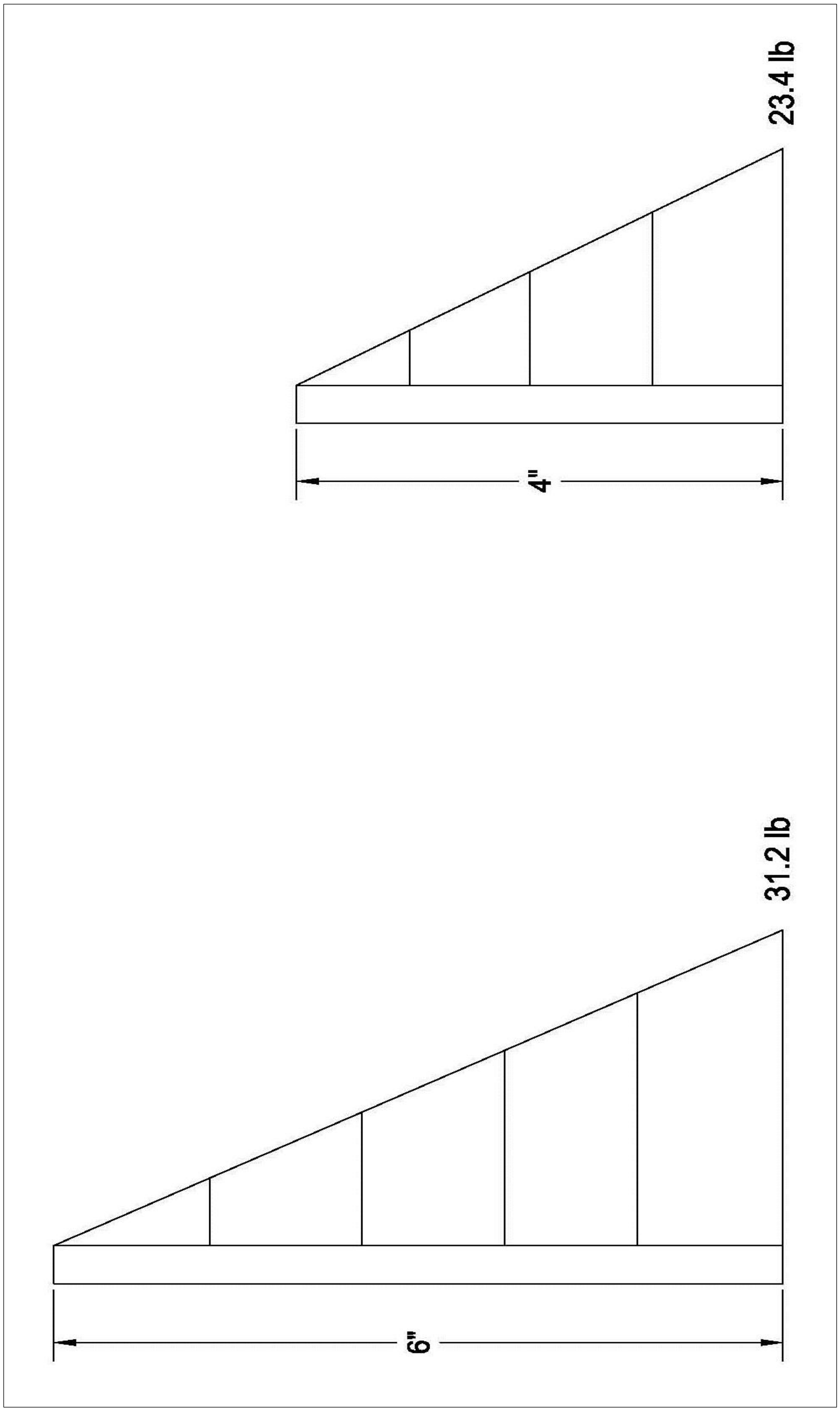

Figure 4 – Side Wall Cross Section Showing Pressure Triangle Created by Water During each Load Case

	Four-Person	Two-Person
Moment (lb-ft)	750	1000
Shear (lb)	70	100

Table 1A – Maximum Values Found During Analysis

	Four-Person	Two-Person
Concrete Compressive Load (psi)	76	890
Steel/Mesh Tensile Load (lb)	375	500

Table 1B – Maximum Values Found During Analysis

	Design Specification (unfactored)	Test Result	Safety Factor
Tension	500 lb	4375 lb	9.5
Compression	890 psi	3500 psi	4
Flexure	16 lb-ft	115 lb-ft	7

Table 2 – Safety Factors Found by Comparison of Analysis Values to Material Test Values

GLOSSARY

Compressive Load – A load on a structure or piece of a structure that pushes material together and will cause a negative deformation in the direction of the force

Construction Engineering – A type of Civil Engineering that studies construction inspection, management, optimization, and safety

Deflection – Deformation of a structure or part of a structure due to its self weight or an applied external load

Environmental Engineering – A type of Civil Engineering that studies fluid mechanics, drinking water purification, wastewater treatment, and environmental chemistry

Factored Load – A load used when designing a structure that includes a safety factor and is therefore exaggerated from the probable actual load the structure will experience

Finite Element Analysis – A method of analyzing a structure three-dimensionally which involves virtually breaking the structure into many small pieces, analyzing the pieces, and summing their effects

Flexure – The bending property of a material

Foundation – A structure's subsurface support system

Geotechnical Engineering – A type of Civil Engineering that studies soil mechanics and foundation design

Grouting – A process of placing a watery cementitious material on a concrete object in order to fill voids in the outside of the concrete

Loads – A weight or force on a structure due to a process the structure will experience during its intended use

Loading Scenarios – The sum of all loads acting on a structure during a certain type of use

Materials Science – A type of Civil Engineering that studies material strength and failure properties

Members – Parts of a structure that reach between connections and transfer loads from their point of application to another place on the structure or the structure's foundation

Moment – A term used to refer to the internal bending force or tendency to rotate felt by a structure

Moment Diagram – A visual representation of the internal moment values at each point along an object's length

Neutral Axis – An imaginary line on an object which indicates the location where the object changes from feeling a compressive load to feeling a tensile load

Non-Prismatic – Refers to an object whose cross section is not uniform along its length

Point Load – A load that acts at a single, infinitesimally small point on a structure

Safety Factor – A measure of how many times stronger an object is than its minimum strength to perform its intended task.

Sealing – The process of applying a clear protective coat over concrete so that any dye or surface material is not damaged

Structural Engineering – A type of Civil Engineering that studies the support systems of structures

Tensile Load – A load on a structure or piece of a structure that pulls material apart and will cause a positive deformation in the direction of the force

Torsion – A twisting force not considered in the 2013 canoe analysis

Transportation Engineering – A type of Civil Engineering that studies traffic control, roadway design, and pavement composition.

Two-Dimensional Analysis – An analysis method where a three-dimensional object is converted to two-dimensional models and then analyzed

Unfactored Load – A load on a structure that does not include a safety factor and is very close to the actual load a structure will experience during its intended use