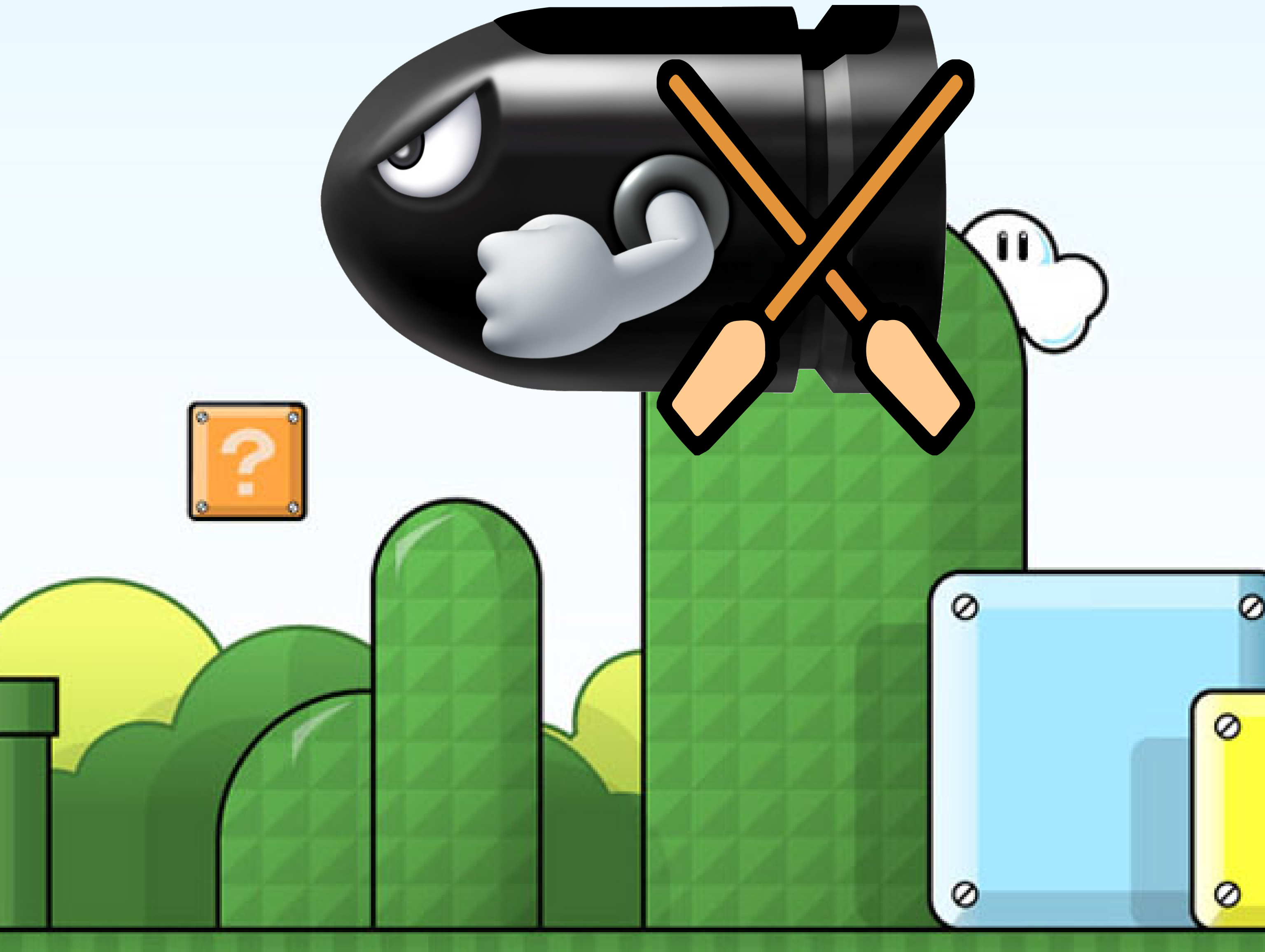
BULLET BILL

2018

CONCRETE CANOE DESIGN REPORT



ARIZONA STATE UNIVERSITY

TEMPE, AZ

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Bullet Bill is one of the many enemies that Mario faces throughout the saga of countless *Super Mario* adventures. As Mario attempts to make his way through the every-changing levels and worlds of *Super Mario*, one thing can be counted on: Bullet Bill's relentless, untiring chase of Mario. Wherever Mario runs, Bullet Bill is biting at his heels. Bill has been an important character of the series since its inception in 1987 and will continue to be into the future. Just like throughout the *Super Mario* series, *Bullet Bill* will be in pursuit of a single object: Victory (Bullet Bill).

Table 1: Structural Mix Properties

Mix Properties	
Wet Density	69.7 pcf
Dry Density	60.50 pcf
28-Day Compressive Strength	1914.6 psi
14-Day Tensile Strength	588 psi
14-Day Composite Flexural Strength	1770 psi
Air Content	0.61%

Arizona State University is located in Tempe, Arizona and was originally entitled the Territorial Normal School. It was founded in 1885 and had a total enrollment of 33 students. Since then, Arizona State University has grown to be the largest public university in the United States with over 98,000 students enrolled today ("Arizona State University"). The Ira A. Fulton Schools of Engineering unit within ASU enrolled almost 21,200 students this year (Ira A Fulton). Approximately 1,400 are enrolled in the School of Sustainable Engineering and the Built Environment as civil, environmental, and sustainable or construction engineering majors (School of Sustainable Engineering and the Built Environment).

The ASU Concrete Canoe team is a competitive team within the American Society of Civil Engineers club on campus. ASCE ASU participates in the Pacific Southwest Conference each year. ASCE ASU Concrete Canoe has placed eleventh with *Mandjet* (2015), third with *Pondicherry* (2016), and ninth with *Firebolt* (2017). The 2018 team hopes to improve upon these scores and rank as the best team from Arizona. This improvement hopes to come from this year's experienced leadership, increased funding, and innovations in the construction and curing processes.

Table 2: Canoe Physical Properties

Canoe Properties	
Name	Bullet Bill
Length	20 ft
Width	28 in
Depth	14 in
Avg. Thickness	0.75 in
Estimated Weight	230 lbs
Colors	Dark Gray, White, Black
Primary Reinforcmenet	Fiberglass Mesh
Secondary Reinforcment	Glass Fibers

With the help of alumni, a MATLAB code was written to perform all structural analysis calculations instantaneously to drastically speed up the hull design and analysis portion of the project. A few hull designs were created using the program, and the analysis results were immediately studied to determine the optimal design. The mix design team promoted sustainability techniques by incorporating recycled materials such as Class F Fly Ash and recycled glass Poraver. In addition, the final mix design for *Bullet Bill* significantly reduced the amount of Ordinary Portland Cement and replaced it with more sustainable cementitious materials, resulting in significantly reduced CO_2 emissions associated with the life cycle of cementitious material.

The construction team saw improvements and innovation in several aspects of the process. The construction team was able to turn the semi-permanent curing chamber into an autonomous, permanent curing chamber that can be utilized for years to come. This curing chamber allowed the team to focus on other aspects of the project, ensuring the construction of *Bullet Bill* will be as efficient as possible.

Project management is one of the most vital aspects of a project to ensure its successful completion. Project managers are key to leading a team in all aspects, including scheduling, finances, and engineering. In the creation of *Bullet Bill*, we elected two Project Managers to lead the team. Our overall objective was to create a lightweight canoe with a great enough strength to withstand the stress of racing conditions. With the help from a strong group of captains, hand selected from the 2016-2017 *Firebolt* team and from other exemplary peers within ASCE, we felt confident in our ability to create an extraordinary canoe. We assigned captain positions and met immediately following the 2017 Pacific Southwest Conference to begin planning for *Bullet Bill.*

The majority of our funds for *Bullet Bill* were acquired from donations made by local engineering and construction material companies. In addition, we received cement, aggregate, and display donations which helped significantly with our budgeting. While the final cost of *Bullet Bill* was $2,640, we were able to put the new funds into a self-sustaining curing chamber. We created a detailed account ledger from the beginning of the project to ensure that all funds were tracked and allocated properly.

We created the schedule for *Bullet Bill* at the end of the 2017 spring semester to maximize the time for research prior to the 2017 fall semester. The schedule was distributed to all captains and was referred to weekly to ensure we were on track throughout the process. The major milestones were hull design selection, cutting the foam using CNC, finalizing the mix design, and casting the canoe, the critical path can be seen on page 11. These milestones are outlined in Table 3. With the creation of a MATLAB program that performs hull design and structural analysis in one program, were able to significantly reduce the hull design person hours. We encountered problems allocating a TechShop to access a CNC machine that as the one previously used closed down unexpectedly. With the lack of manpower throughout winter break, we saw a delay in the mold construction time, thus setting the cast day one week later than expected. Despite the cast day setback, the canoe construction stayed on task and followed closely to path.

Table 3: Major Project Milestones

Milestone	Delay	Cause
Hull Design Selection	none	MATAB program creation
CNC the Foam	3 weeks	Techshop closure, new location
Finalze Mix Design	2 weeks	Lack of manpower
Casting the canoe	1 week	Material procurement

The utmost attention was paid to the safety for each team member throughout the design and construction of *Bullet Bill*. During the mix design and construction phases, all members were required to wear gloves and respirators. Safety data sheets were readily available at all times as well. We made an extreme effort to practice sustainability throughout the project. An effort was made to include sustainable materials in our concrete mixture, such as Poraver and Fly Ash. We used 2"x4" cylinders to test our mix designs so as not to waste expensive materials and discard excess concrete. We also were able to use the excess concrete to from mix design to create a miniature concrete canoe for displays and events.

The total man hours spent creating *Bullet Bill* was approximately 1,270 hours, 450 of which are from paddling practice. The allocation of man hours can be seen in Figures 1 and 2 on page 2.

The allocation of man hours with paddling and without paddling are represented in the figures below. As the mix design team used last year's canoe, *Firebolt*, as a base for this year's mix design, the total man hour spent on mix design was significantly less. The construction team used a similar mold design as *Firebolt* and with the additional time, the team built a self-sustaining curing chamber. The new additions to the curing chamber include rainfall catchers, gutter drainage system, and a self-timer draining pump. Altogether, *Bullet Bill* took approximately 1,270 hours to create, 450 hours spent paddling.

Throughout the duration of the *Bullet Bill* project, the utmost attention was paid to the quality control and quality assurance of multiple project aspects. Quality control and assurance measures were put into place during all aspects of the project including: hull design and structural analysis, mix design, mold construction, canoe casting, and canoe finishing. Peer review was incorporated to ensure the accuracy and quality of calculations and written work such as the design report.

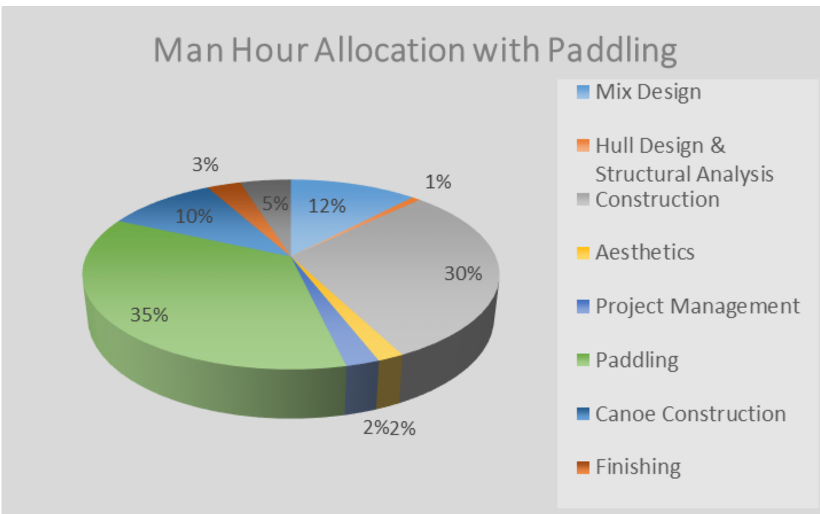


Figure 1: Man Hour Allocation with Paddling. Figure 1 shows the man hour allocation of the approximately 1,270 hours put into the project, including paddling practice. As is evident from this figure, paddling took up more than one-third of the time allocation.

Note: Some of the hours have been estimated as they are ongoing.

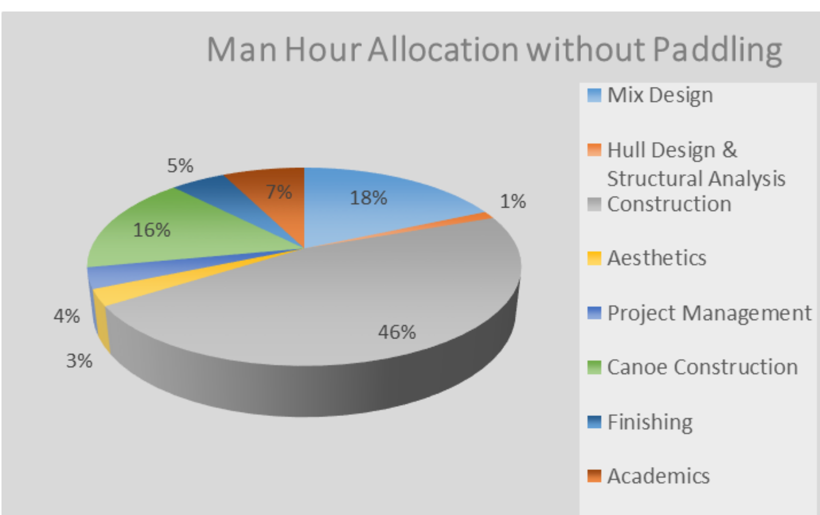


Figure 2: Man Hour Allocation without Paddling. Figure 2 shows the man hour allocation of the approximately 1,270 hours out into the project, not including paddling practice. Construction (46%) and mix design (18%) took up more than half of the total time for the project.

Note: Some of the hours have been estimated as they are ongoing.

ORGANIZATION CHART

WORLD OF PROJECT MANAGERS

Natalie Miller, Jr.

Ian Contreras, Sr.

Created and maintained project schedule and budgets	Ensured compliance with competition rules	Ordered materials and managed finances	Delegated tasks and coordinated teams

WORLD OF AESTHETICS

Ana Repta, Sr.

Allison Charles, Jr.

Joseph Garcia, Sr.

- Developed and designed theme of canoe
- Designed and produced canoe display
- Oversaw development of final product

WORLD OF MIX DESIGN

Ian Contreras, Sr.

Nathan Reisenauer, Sr.

- Conducted concrete research and development
- Developed concrete mix design
- Performed laboratory testing

WORLD OF CONSTRUCTION

Natalie Miller, Jr.

Connor Fegard, Jr.

- Organized and carried out mold construction and concrete casting and finishing
- Coordinated quality control and safety
- Oversaw curing chamber construction

WORLD OF SAFETY

Joseph Garcia, Sr.

- Ensured all facilities were properly cleaned
- Monitored PPE usage by all team members

WORLD OF PADDLING

Connor Fegard, Jr.

- Coordinated paddling practices
- Conducted tryouts and organized paddling
- Researched and taught paddling techniques to team

WORLD OF HULL DESIGN & ANALYSIS

Natalie Miller, Jr.

- Performed design and analysis of hull using MATLAB and AutoCAD
- Determined strength requirements of concrete mix team
- Conducted file conversion from AutoCAD to Vcarve Pro

HULL DESIGN AND STRUCTURAL ANALYSIS

Bullet Bill's hull design team began working early in the summer to utilize the hull design program created in MATLAB (MathWorks, 2014b). The completed program requires several user specified points to form the bow, stern, keel, and widest cross-section, then uses quadratic splines to connect these points, and finally offsets the splines to create the inner and outer surfaces of the hull. Figure 3 demonstrates the programs modeling capability; key points are shown as black dots and splines are shown as the blue and green lines.

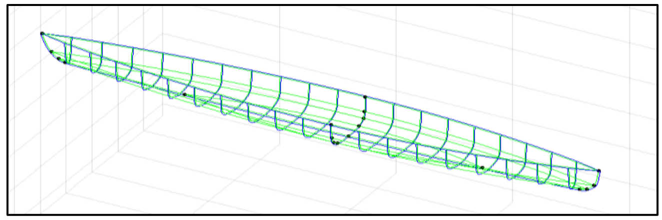


Figure 3 - MATLAB Canoe Model

Firebolt's hull design was utilized as the baseline for *Bullet Bill's* design. Last year's canoe design was chosen as the baseline due to its fast-straight line speed and ease of paddling. The team aimed to ensure maneuverability and initial stability by keeping the stern rocker at 4" and the bow rocker at 4". This lifts the ends up, which forces the center of the canoe to bear more weight, making the canoe easier to turn at its midpoint (EoHD). However, an increased rocker decreases tracking. To offset the lost tracking, the widest point was moved 1' aft of midship. This elongated the streamlined bow allowing the canoe to track better and travel faster due to the sharper entry line.

The team addressed initial stability by giving the profile a rounder transition between the bottom and walls of the hull (Figure 4). This helped widen the hull at higher waterline levels, which increased the transverse metacentric height (GM_T) to 1.10 (Table 4). As transverse metacentric height provides a measure of the initial stability and resistance to overturning where a larger value implies greater stability and resistance, *Bullet Bill* will have a very similar performance to *Firebolt* as the wetted surface area and prismatic coefficient were not changed to due sufficient initial stability.

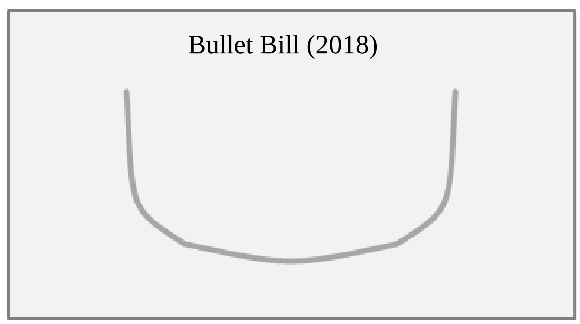


Figure 4 – Hull Profile

Bullet Bill's final hull design is asymmetric with a shallow arc bottom and slightly flared walls. With an overall length of 20', a beam width of 28", a depth of 15" at widest section, a bow and stern depth of 16", and a ¾" thickness throughout

Upon completing the hull design, the team performed a two-dimensional longitudinal and lateral analysis to ensure *Bullet Bill* would endure all loading conditions. MATLAB was used in combination with Excel to compute cross-sectional properties and perform each analysis. Five loading cases were taken into account: (1) display, (2) carrying, (3) two female paddlers, (4) two male paddlers, and (5) coed.

Table 4: Performance Comparison (2 Male Race)

Canoe Name	Wetted Surface Area	Prismitic Coefficient	GM_T
***Firebolt* (2017)**	37.0 ft²	0.59	1.10
***Bullet Bill* (2018)**	37.0 ft²	0.59	1.10

For the longitudinal analysis, the canoe was modeled as a simply supported beam with self-weight and paddler weight acting in the negative gravity direction and the buoyant force acting in the positive gravity direction (Figure 5). Cuts were taken at 1” intervals to compute the internal forces and moments. Concrete unit weight was conservatively estimated as 62 pcf for the analysis resulting in a conservative weight of 260 lbs. Male and female paddlers were modeled as 190 lbs and 130 lbs point loads, respectively. For paddling load cases, static equilibrium was maintained by balancing the net downward forces with the resultant buoyant force to eliminate the simple support reaction; the centroids of the upward and downward forces aligned in order to eliminate residual moments. For the display case, supports were located 4’ inward from the bow and stern. For the carrying case, supports were located at each end. Bending stresses were determined using the theory of simple bending: $\sigma = M/S_x$. Where, M is the bending moment, c is the distance from the neutral axis to the outer most fiber, and S_x is the section modulus.

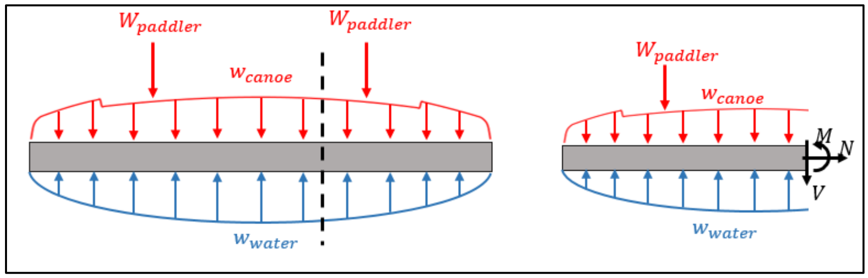


Figure 5 – Longitudinal Analysis FBD

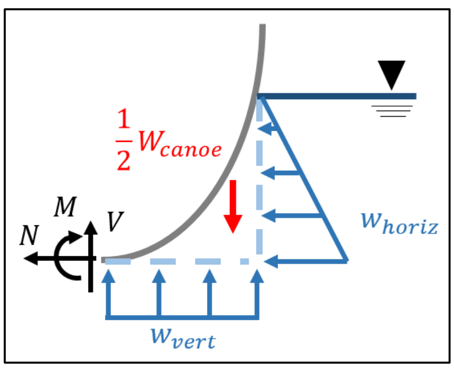


Figure 6 – Lateral Analysis FBD

The transverse analysis was only performed for the paddling load cases where the canoe was modeled as a curbed cantilever beam with the same loading as the longitudinal analysis. Moments and forces were determined using the free body diagram in Figure 6. Stress was then determined using the curved beam equation: $\sigma_{\theta\theta} = \frac{N}{wt} + \frac{M\left(wt - rw\ln\left(\frac{r_o}{r_i}\right)\right)}{wtr\left(Rw\ln\left(\frac{r_o}{r_i}\right) - wt\right)}$, where N is the axial force, M is the moment, w is the width, t is the thickness, r_o is the outer radius, r_i is the inner radius, R is the radius to centroid (Bending of Curved Beams). The coed race lateral analysis controls the concrete strength where the maximum stress occurs at the widest hull section (Table 5).

The team decided to add a 2” diameter semi-circular gunnel rail to mitigate cracks that would develop throughout stresses of carrying and paddling. Three feet of bulkhead was added at the bow and stern to improve floatation. Bulkheads were made from EPS foam encased in a layer of concrete.

Table 5: Maximum Stress

Load Case	Compressive (psi)	Tensile (psi)
2 Male**	160	155
2 Female**	127	123
Coed**	231	224
Carrying*	131	110
Display*	16	31

**Lateral Analysis Governs *Longitudinal Analysis Governs

The overarching goal for the 2017-2018 mix design team was to create a concrete mix that was suitable for the paddlers, and their races. In the past, the mix design team had made it their goal to make the canoe as strong and lightweight as possible, but this led the canoes to be overly buoyant. Therefore, using last year's mix design as a baseline, the design team set out to make a mix design that would create a stable canoe for the paddlers. As well as the refinement in the stabilization of the concrete in the water, admixture dosing was evaluated further from the previous year's mix design.

Last year's rule change required 25% of the total aggregate volume to be composed of non-glass aggregate. For this reason, last year's mix, *Firebolt*, served as a baseline for *Bullet Bill*. *Firebolt* consisted of Type I White Portland Cement, Class F Fly Ash, Metakaolin, VCAS-8, UTElite Clay Shales with size variations, 3M Glass Bubbles, Poraver (0.1-2.0 mm), GRACE short glass fibers, Acryl-60 (latex), AEA-92 (air entrainer), and ADVA Cast 575 (high range water reducer). *Firebolt* possessed a wet unit weight of 61.29 pcf, a dry unit weight of 47.2 pcf, a 28-day compressive strength of 1877 psi, and a tensile strength of 560 psi. Focus was placed on decreasing buoyancy without compromising strength in order to aid paddlers, and prevent the formation of distributed cracking during the swamp test.

The design process began by formulating a plan with numerous options on how to improve the canoe's stability in the water. The first option was to decrease the buoyancy of the concrete being tested by increasing the overall weight of the concrete. This was evaluated by proportionally increasing the amount of each aggregate type and cementitious material that was used in the mix. This ensured that the gradation of *Firebolt's* mix was left intact, and that the sole effect of increasing the weight of the concrete could be examined. Initial mix designs with increases in aggregates and cementitious materials of 5% and 10% were conducted. Testing the two mix designs for their compressive strength, it was found that the 5% mix design (1800.04 psi) outperformed the 10% mix design (1709.32 psi). Although the 5% concrete mix outperformed the 10% mix design, its design unit weight was dangerously close to that of water at 62.14 pcf. The mix design team was not quite satisfied having their unit weight of concrete so close to that of water, so the 5% mix design was set as the upper limit in terms of allowable design unit weight. The amount of each component was then scaled down, from the 5% mix design, by increments of 1% until the amount of aggregate and cementitious material was similar to *Firebolt's*. From the results, changing the weight by increasing the amount of aggregates and cementitious materials was not a good approach to decrease the buoyancy of the canoe because the concrete easily became too close to the unit weight of water.

The next option was to analyze the proportioning of the admixtures that were added to each mix design (Table 6). Overall, the three admixtures added to the mix were ADVA Cast 575 (high range water reducer), AEA-92 (air entrainer), and Acryl-60 (latex). It was found that, for ADVA Cast 575 and AEA-92, the amounts of the two admixtures could be reduced by 4% and 3% respectively from *Firebolt's* mix without compromising the strength of the concrete. Latex had a large effect on the buoyancy and unit weight of the canoe, so it was with this

Table 6: Admixtures

Admixture	Type	Recommended Dosage	Structural Mix
AEA-92	AEA	0.1-7 fl oz/cwt.	10 fl oz/cwt.
ADVA Cast 575	HRWR	2-10 fl oz/cwt.	5 fl oz/cwt.
ACRYL 60	Latex	-	10 fl oz/cwt.

admixture that the mix design team chose next to create a less buoyant mix. Therefore, it was found that the latex could be significantly reduced from 50 mL (in *Firebolt's* mix design) to 9 mL while preserving the strength of the concrete. By reducing the amount of latex in the mix design, the unit weight of the concrete had been increased by a desired amount. This also improved the workability of the concrete, effectively aiding the construction process.

As determined last year by the mix design team, Clay Shales served as the optimum glass-aggregate substitute since it didn't heavily impact the weight of the concrete, and it increased the overall strength of the mix. *Firebolt's* mix had a minimal amount of air voids and was devoid of an excess of grains, making casting simple without affecting the quality of the finish. The gradation of the mix for *Bullet Bill* was thus mirrored from the gradation used for *Firebolt*. The initial gradation was performed digitally rather than through trial mixes, thus reducing man-hours and material wastes. This theoretical approach was executed by creating a 0.45 power chart in Excel which was used to analyze a wide distribution of possible volume fractions. A nearly linear 0.45 power chart distribution was achieved using 11.1% of Crushed Fine Clay Shale, 14.6% 10 Mesh Clay Shale, 26.8% 3M Glass Bubbles, 8.9% Poraver (0.1-0.3), 7.9% Poraver (0.25-0.5), 28.5% Poraver (0.5- 1.0), and 2.0% Poraver (1.0-2.0) by volume. Trial cylinders cast with this distribution had an average compressive strength of 1007 psi and a wet unit weight of 62.43 pcf. Subsequent gradations were achieved experimentally, and aimed at increasing compressive strength while reducing wet unit weight. After various iterations in the design process, the final distribution consisted of 12.82% Fine Clay Shale, 8.97% Crushed Fine Clay Shale, 3.85% 10 Mesh Clay Shale, 16.67% 3M Glass Bubbles, 10.26% Poraver (0.1-0.3 mm), 5.13% Poraver (0.25-0.5 mm), 30.76% Poraver (0.5- 1.0 mm), and 11.54% Poraver (1.0-2.0 mm) by volume, (Figure 6).

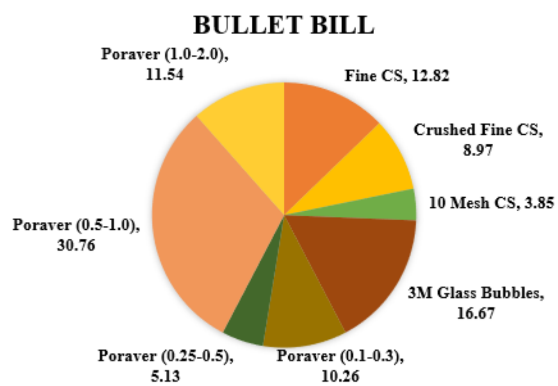


Figure 7 – Material Distribution Percent by Volume

Overall, a decrease in total amount of cementitious materials was achieved through the mix design process. The four cementitious materials that were used were Ordinary Portland Cement (OPC), VCAS-8, Fly Ash, and Metakaolin. The final weight distribution of these cementitious materials was found to be 49% OPC, 15% VCAS-8, 26% Fly Ash, and 10% Metakaolin. This distribution was similar to *Firebolt's* distribution of cementitious materials and was kept the same due to its continued excellent performance. Despite the similar ratio of cementitious materials, the mix design team was able to decrease the overall weight of cementitious materials used for *Bullet Bill's* mix design by 3%.

Implementing fiber reinforcement into the canoe was further examined to improve tensile strength because of concrete's known characteristic of being weak in tension. The canoe had two types of reinforcement: the primary reinforcement withstood stress from structural loads such as the paddlers, while a secondary reinforcement bridged and resisted possible fracturing and shrinkage.

For the primary reinforcement, this canoe had the same reinforcement as *Firebolt*, which was a dual layer white fiberglass mesh. The white mesh was placed with fiber orientation in the principle directions to acquire an equal fiber distribution, and improve tensile and flexural strength. To successfully implement this mesh, the mix needed to have the correct amount of workability and adhesiveness to allow a secure impregnation. This was tested by creating 14 inch by 4 inch by 0.75 inch beams, which resulted in a 300% increase in flexural strength compared to a beam with no primary reinforcement. In addition, the white mesh is finer compared to other tested mesh, meaning it had a higher volume fraction of textile that provided more bridging to minimize crack propagation through the matrix.

For the secondary reinforcement, the mix design team continued to incorporate GRACE short glass fibers. These fibers were ideal for this mix because of their light weight, and optimizing capabilities by better dispersing in the concrete due to their length. This effective fiber distribution was able to minimize the fractures, and allow the concrete to withstand higher stress values. Therefore, a similar fiber distribution from *Firebolt's* mix design was desired, but less overall fibers were used. The amount of fibers that were present in *Firebolt's* mix design caused many fibers to protrude along the surface of the canoe. Therefore, to increase the aesthetic appeal of the canoe, the fiber content was reduced by 25% (from 4 pcf to 3 pcf) to limit the amount of fibers sticking out of the canoe, but still have enough to increase the allowable stress of the canoe. In all, the implementation of both reinforcements was successful in improving the tensile and flexural strength of concrete without compromising weight.

The concept of sustainability was a goal in choosing the types of materials that were used. Therefore, the heavy use of supplementary cementitious materials contributed greatly to the sustainability of the mix. Ordinary Portland cement (OPC) is incredibly energy-intensive to manufacture, and the calcination reaction which is used to manufacture it from limestone has carbon dioxide as a 1:1 stoichiometric product. Any material which can offset the need for OPC therefore significantly offsets the carbon impact of the concrete mix. In addition to reducing OPC usage, Fly Ash and VCAS both have their own sustainability benefits. Fly ash is a waste product of coal-burning power plants, and it is far more environmentally friendly to use its low heat-of hydration pozzolanic reaction to bind concrete than it is to disperse it throughout the air or sequester it to landfills. VCAS is manufactured from industrial by-products, which helps to divert waste from landfills. The increased durability it adds to concrete reduces the future need for repairs and replacements.

Table 7: Final Testing Results

Property	Required Value	Actual Value
Compressive Strength	231 psi	1914.6 psi
Tensile Strength	224 psi	588 psi
Dry Unit Weight	<62.43 pcf	60.50 pcf

Finally, several additional measures were taken in order to minimize the quantity of waste generated by the mix design process. Before any trial designs were mixed and cast, they were subject to peer review to ensure that each mix was logically designed and had a clear investigatory purpose. In addition, the overall amount of admixtures that were necessary for the mix design were reduced. Additionally, whenever the effect of varying a single mix component was a desired quantity, the mixes were cast as 2"x 4" cylinders rather than 3"x 6". As a result, the design process reduced the total amount of concrete and preserved 7.5 ft^3 of concrete.

Overall, the mix design team's extensive research and testing led to a final mix that exceeded the set goals. The final design improved the compressive and tensile strength compared to the canoe's predecessors. This final mix led to the creation of *Bullet Bill*, with the following design properties.

After issuance of the rules and regulations, weekly meetings were held during the hull design phase to determine the most viable materials and methods for constructing *Bullet Bill*. The team decided to use a male mold made from 2 pcf expanded polystyrene (EPS) foam due to the ease of construction as well as the additional buoyancy provided when left in the bulkheads. The goal for construction was to improve upon last year's process by implementing new and sustainable construction techniques based on lessons learned from past years. The entire construction process was carried out over a five-month period, beginning with mold construction, followed by casting, and lastly, concrete finishing.

Figure 8 – Shopbot CNC

AutoCAD® was used to draft the finalized hull design in order to begin mold construction. Cross-section cuts were taken at two-inch intervals, generating a stair-step pattern when assembled. Due to cracking along the top edges of the canoe in past years, gunnel rails were added. Upon completion of drafting, cross sections were imported into VCarve Pro (Vectric 2017 V9), a tool pathing software that converts AutoCAD® cut files into files that a CNC (Computer Numeric Control) machine can read. The Innovation Hub at Arizona State University Polytechnic campus provided free access and training on the ShopBot CNC machine (Figure 8). The construction team operated the CNC machine, resulting in a cost savings of $3000 towards the construction budget compared to previous years.

Figure 9 – Assembling the Mold

After cutting was completed, the 120 cut-sections were adhered using waterproof carpet tape and fitted along a continuous steel bar for proper alignment of the mold (Figure 9). The stair-step pattern was sanded flush using 80-grit sand paper to create smooth transitions between adjacent sections. Any defects during initial sanding were fixed by applying 1/16" thick layers of Rosco Foamcoat™. This layer of Rosco Foamcoat™ was sanded using 120-grit sand paper until imperfections were minimized so that the mold met quality control specifications. To improve upon previous years releasing agent, two layers of Releasing Agent was applied to the canoe before cast day. Releasing agent was not applied to the bow and stern as 3 feet of foam was intended to be left in place to provide additional flotation.

Bullet Bill incorporates two layers of fiberglass mesh to resist tensile forces and protect against puncture. The mesh was draped along the length of the mold and contoured to fit the mold prior to casting. Additional mesh reinforcing was required along the walls since the mesh could not span the entire canoe. A two-inch overlap was provided between the two sheets of mesh to ensure the reinforcement acted as a continuous system.

The team constructed a self-sufficient curing chamber in addition to curing chamber used in previous years (Figure 11). To ensure a self-sustaining curing chamber, a rain fall system was constructed. Tarps were attached to the existing steel frame then connected to the guttering along the edge of the cast table. These gutters streamed the water to a large trough set to drain every 6 hours. The PVC pipe misting system was scheduled to run every 4 hours for 30 minutes. This created a controlled environment providing proper hydration and humidity for an efficient wet curing process, safe from the dry Arizona air. It is intended for this curing chamber to be permanent and self-sustaining for years to come, compared to last year in which the curing chamber required attention every 12 hours.


Figure 10 – Concrete Casting

Due to constraints on the use of stain and acrylic paint, pigment was added to a portion of the concrete. Because of the theme of the canoe was based on Super Mario Bros., it was decided that the canoe would be dark gray. *Bullet Bill* was casted in a six-step process (Figure 10). First, the gunnel rails were filled with a dark gray structural mix, extending ¼” from the main body of the canoe. Second, a ¼” layer of dark gray structural mix was applied by hand, excluding the gunnel rails and using tire tread gauges to regulate the thickness. Third, the pre-fitted fiberglass mesh was placed over this layer of concrete. Then a ¼” layer of dark gray structural mix was applied, followed by another fiberglass mesh layer. Finally, another ¼” layer of dark gray structural mix was applied and smoothed evenly using trowels. The tire gauges were used through the placement process to ensure uniform thickness. After the cast day was completed, the construction captains added aesthetic inlays to the front bulkhead. The canoe was covered in cheesecloth while curing to ensure the concrete remained moist (Figure 11).

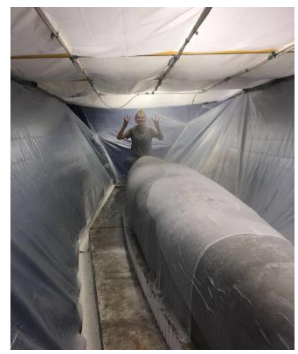


Figure 11 – Curing Chamber

The sanding process was initiated after a 21-day cure. The team performed a wet sand of the outside with 80-grit, 120-grit, 180-grit, and 220-grit sandpaper. A patching mix was applied to fill inconsistencies at 28-days. *Bullet Bill* was removed from the mold by hand after the 28-day curing period. The canoe was turned over so that the mold could be removed by carefully cutting the foam from the inside of the canoe, leaving 2 feet of foam in each bulkhead. The bulkheads and inside were patched and then the inside of the canoe was wet-sanded using various grits of sandpaper to create a smooth surface. Wet sanding was utilized to reduce exposure to dust particles containing calcium hydroxide and crystalline silica, providing a safer work environment. Adhesive appliques were applied to the canoe after sanding was completed. These appliques were applied by hand and additional detail was added to the bulkheads.

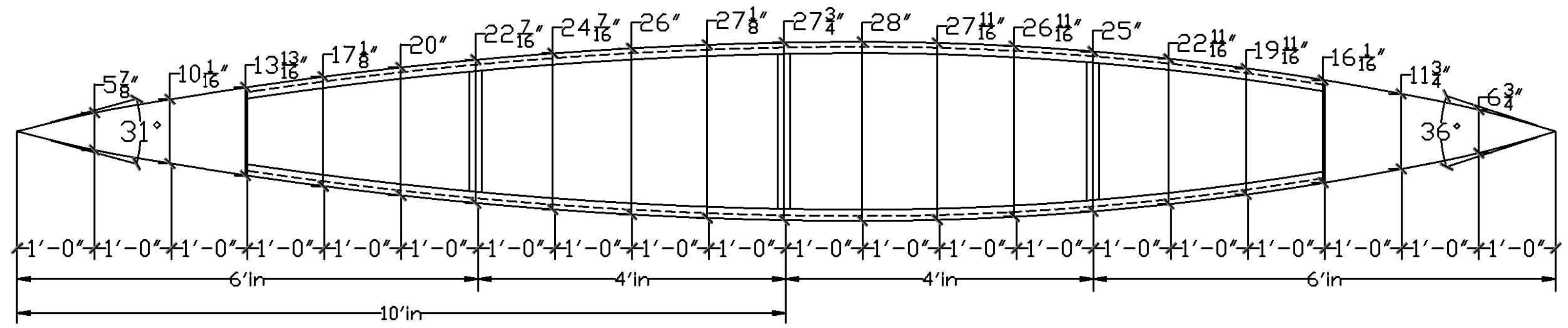
Sustainability was incorporated by efficiently utilizing resources to reduce waste. The team utilized VCarve’s optimization tool to fit as many section cuts as possible on one sheet of foam. This reduced the amount of foam needed by 6 sheets. The team also utilized Arizona State University’s hazardous waste disposal program to proper dispose of expired admixtures, old concrete specimens, and other waster from mold construction. A self-sustaining curing chamber was constructed using the pre-existing steel frames and misting system, saving time and materials for future years.

Overall, the team succeeded in improving upon last year’s construction techniques, saving time, materials, and cost, while improving upon quality. *Bullet Bill* will rocket past the competition on the road to victory.

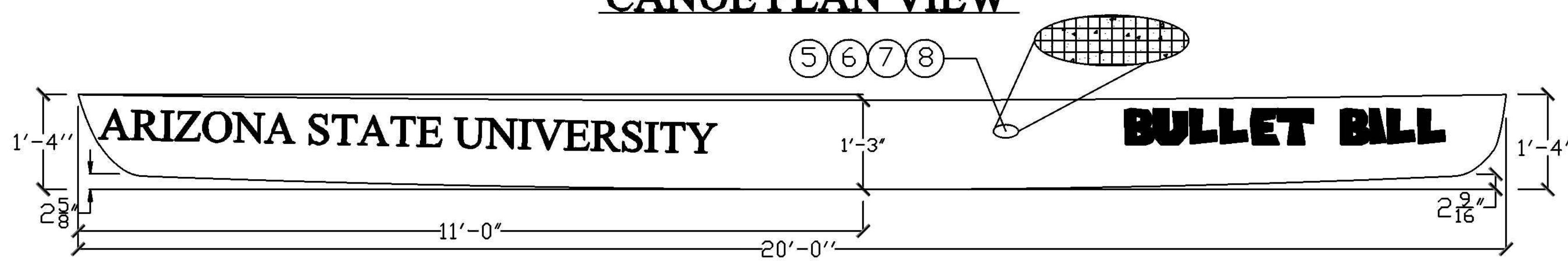
ID	Task Mode	Task Name	Duration	Start	Finish	Baseline Start	Baseline2 Finish
1		**Concrete Canoe 2018**	184 days	Mon 8/7/17	Sat 4/14/18	Mon 8/14/17	Sat 4/14/18
2		**Performance Review**	11 days	Mon 8/7/17	Mon 8/21/17	Mon 8/14/17	Mon 8/21/17
3		**Project Planning & Research**	122 days	Mon 8/7/17	Fri 1/19/18	Mon 8/14/17	Fri 1/26/18
4		**Mix Design**	**86 days**	**Tue 8/15/17**	**Fri 12/8/17**	**Tue 8/15/17**	**Wed 12/6/17**
5		Materials Procurement	57 days	Tue 8/15/17	Tue 10/31/17	Tue 8/15/17	Wed 12/13/17
6		Materials Testing	35 days	Mon 8/28/17	Fri 10/13/17	Mon 8/28/17	Fri 10/13/17
7		Baseline Mixes	32 days	Fri 9/1/17	Sun 10/15/17	Mon 9/4/17	Tue 10/17/17
8		Cementious Materials Testing	29 days	Fri 9/8/17	Wed 10/18/17	Fri 9/8/17	Wed 10/18/17
9		Aggregate Testing	31 days	Wed 9/6/17	Wed 10/18/17	Wed 9/6/17	Wed 10/18/17
10		Admixture Testing	41 days	Wed 9/6/17	Tue 10/31/17	Wed 9/6/17	Tue 10/31/17
11		Fiber & Mesh Testing	44 days	Sun 9/10/17	Tue 11/7/17	Sun 9/10/17	Thu 12/14/17
12		Final Mix Selection	23 days	Wed 11/8/17	Thu 12/7/17	Wed 11/8/17	Wed 12/6/17
13		**Hull Design**	**50 days**	**Thu 8/24/17**	**Tue 10/31/17**	**Thu 8/31/17**	**Tue 10/3/17**
14		Develop MATLAB Program	38 days	Thu 8/24/17	Sun 10/15/17	Thu 8/31/17	Sat 9/2/17
15		Drafting & Modeling	23 days	Sat 9/2/17	Tue 10/3/17	Fri 9/1/17	Fri 9/29/17
16		Finalize Design	11 days	Mon 10/16/17	Sun 10/29/17	Thu 9/28/17	Tue 10/3/17
17		CNC Drafting	1 day	Tue 10/31/17	Tue 10/31/17	Tue 10/3/17	Tue 10/3/17
18		**Structural Analysis**	**31 days**	**Wed 10/25/17**	**Mon 12/4/17**	**Wed 10/25/17**	**Tue 11/21/17**
19		Finalize Analysis	26 days	Tue 10/31/17	Mon 12/4/17	Tue 10/31/17	Tue 11/21/17
20		**Construction**	**157 days**	**Fri 8/25/17**	**Wed 3/28/18**	**Fri 8/25/17**	**Sat 4/7/18**
21		Small Scale Testing	14 days	Fri 9/15/17	Wed 10/4/17	Fri 9/15/17	Wed 10/4/17
22		Material Procurement	40 days	Fri 9/15/17	Wed 11/8/17	Fri 9/15/17	Fri 11/10/17
23		CNC Form	1 day	Fri 11/10/17	Fri 11/10/17	Fri 11/10/17	Fri 11/10/17
24		Mold Construction	42 days	Sat 11/11/17	Mon 1/8/18	Sat 11/11/17	Fri 1/12/18
25		Finish Mold	23 days	Sat 12/9/17	Tue 1/9/18	Sat 12/9/17	Fri 1/12/18
26		Prebatching for Cast Day	12 days	Fri 12/8/17	Mon 12/25/17	Fri 12/8/17	Tue 1/9/18
27		**Casting Concrete**	**49 days**	**Sat 1/20/18**	**Wed 3/28/18**	**Sat 1/20/18**	**Fri 4/6/18**
28		Cast Day	1 day	Sat 1/20/18	Sat 1/20/18	Sat 1/20/18	Sat 1/27/18
29		Curing	22 days	Sat 1/20/18	Sat 2/17/18	Sat 1/27/18	Sun 2/25/18
30		Form Removal	12 days	Mon 2/19/18	Tue 3/6/18	Mon 3/12/18	Sat 3/17/18
31		**Finishing**	**20 days**	**Thu 3/1/18**	**Wed 3/28/18**	**Thu 3/1/18**	**Sat 4/7/18**
32		Patching/Sanding Exterior	12 days	Thu 3/1/18	Fri 3/16/18	Mon 2/26/18	Sat 3/17/18
33		Patching/Sanding Interior	12 days	Thu 3/1/18	Fri 3/16/18	Thu 3/15/18	Sat 3/17/18
34		Sealing	2 days	Mon 3/19/18	Tue 3/20/18	Mon 3/19/18	Fri 3/23/18
35		Finished Product	28 days	Mon 2/19/18	Wed 3/28/18	Mon 2/19/18	Sat 4/7/18
36		**Aesthetics**	**145 days**	**Fri 8/25/17**	**Mon 3/12/18**	**Fri 8/25/17**	**Mon 4/2/18**
37		Theme Selection	40 days	Fri 8/25/17	Thu 10/19/17	Fri 8/25/17	Mon 10/9/17
38		Design Sketching & Planning	40 days	Fri 10/20/17	Tue 12/12/17	Fri 10/20/17	Sat 1/20/18
39		Pigment Testing	23 days	Wed 11/8/17	Thu 12/7/17	Wed 11/8/17	Thu 12/7/17
40		Finalize Theme Designs	7 days	Thu 12/14/17	Fri 12/22/17	Thu 12/14/17	Fri 12/22/17
41		**Conference Preperation**	**165 days**	**Fri 9/1/17**	**Sat 4/14/18**	**Fri 9/1/17**	**Wed 4/11/18**
42		**Paddling**	**164 days**	**Fri 9/1/17**	**Fri 4/13/18**	**Fri 9/1/17**	**Fri 4/13/18**
43		Information Sessions & Open Training	37 days	Sun 10/22/17	Thu 12/7/17	Sun 10/15/17	Thu 12/7/17
44		Tryouts	3 days	Fri 1/19/18	Sun 1/21/18	Sat 2/10/18	Sun 2/11/18
45		Team Selection	4 days	Mon 1/22/18	Thu 1/25/18	Sun 2/11/18	Mon 2/12/18
46		Practice	53 days	Fri 1/26/18	Tue 4/10/18	Sat 2/17/18	Sun 4/8/18
47		**Design Paper**	**89 days**	**Fri 12/8/17**	**Tue 4/10/18**	**Fri 12/8/17**	**Tue 4/10/18**
48		Rough Draft	50 days	Fri 12/8/17	Wed 2/14/18	Fri 12/8/17	Wed 2/28/18
49		Final Draft & Editing	17 days	Thu 2/15/18	Fri 3/9/18	Wed 2/28/18	Thu 3/15/18
50		Send Paper	2 days	Wed 3/14/18	Thu 3/15/18	Wed 3/14/18	Thu 3/15/18
51		Rehearse Technical Presentation	7 days	Mon 4/2/18	Tue 4/10/18	Sat 3/31/18	Tue 4/10/18
52		**Final Product Display**	**109 days**	**Sat 11/11/17**	**Tue 4/10/18**	**Sat 11/11/17**	**Tue 4/10/18**
53		Construct stand	79 days	Wed 12/20/17	Fri 4/6/18	Wed 12/20/17	Mon 4/9/18
54		Construct Table Display	35 days	Sat 2/10/18	Thu 3/29/18	Fri 3/16/18	Mon 4/9/18
55		Cutaway	7 days	Sun 2/18/18	Sat 2/24/18	Mon 3/26/18	Fri 3/30/18
56		Engineer's Notebook	91 days	Sat 11/11/17	Thu 3/15/18	Sat 11/11/17	Thu 3/15/18
57		Complete Display	7 days	Mon 4/2/18	Tue 4/10/18	Wed 4/4/18	Tue 4/10/18
58		**Attend PSWC at ASU**	4 days	Wed 4/11/18	Sat 4/14/18	Wed 4/11/18	Sat 4/14/18

Project: 2018 ASU Canoe Prelim
Date: Tue 3/13/18

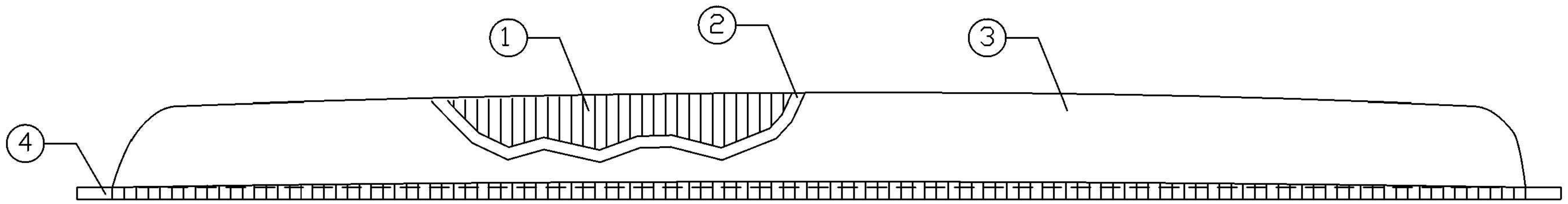
Milestone ◆ Summary Task Baseline



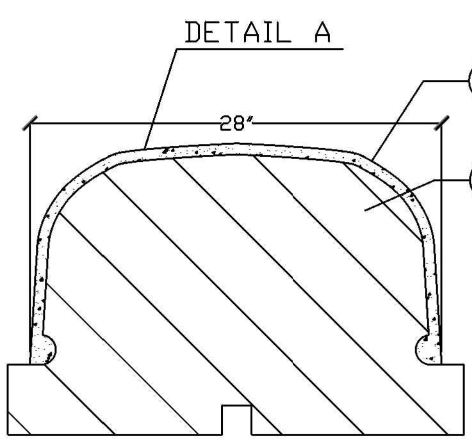
CANOE PLAN VIEW



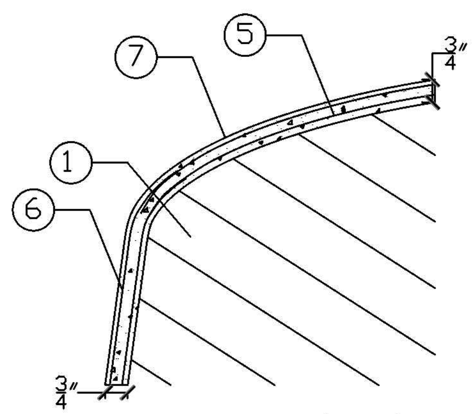
CANOE ELEVATION VIEW



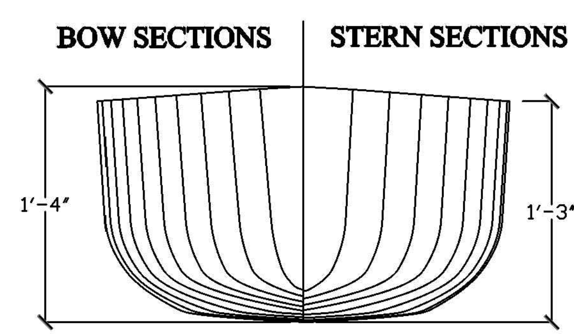
MOLD ELEVATION VIEW



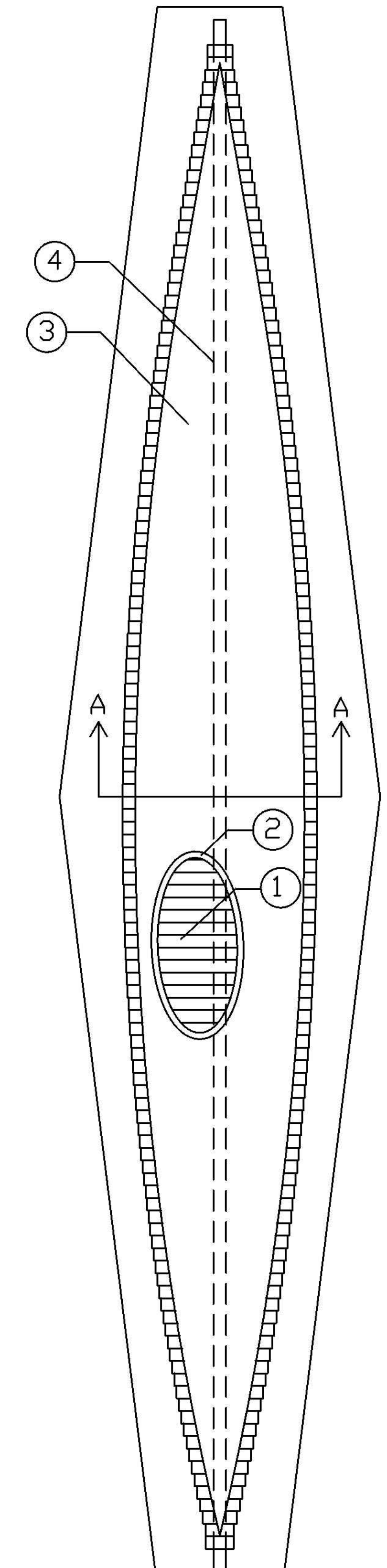
SECTION A-A (WIDEST SECTION)



DETAIL A
MESH REINFORCEMENT



CROSS-SECTIONS



MOLD PLAN VIEW

BILL OF MATERIALS

Part	Qty	Description
1	120	EXPANDED POLYSTYRENE FOAM
2	3 gal	FOAM COAT
3	65 sf	RELEASING AGENT
4	1	HSS 2"X2"X23'-0"
5	80 sf	FIBERGLASS MESH LAYER 1
6	80 sf	FIBERGLASS MESH LAYER 2
7	5.11 ft^3	Concrete (Per Mix Design Appendix B)
8	2 gal	BARACADE WB 244 SEALER

BULLET BILL

DESIGN BY:	CONNOR FEGARD
DRAWN BY:	CONNOR FEGARD
APPROVED BY:	NATALIE MILLER
SCALE:	NTS
SUBMITTED: 3/15/2018	PAGE: 12

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APPENDIX B – MIX PROPORTIONS

MIXTURE DESIGNATION: STRUCTURAL MIX – PIGMENT ADDED TO OUTSIDE LAYER OF CANOE ONLY

CEMENTITIOUS MATERIALS

Component	Specific Gravity	Volume (ft^3)	Amount (mass/volume) (lb/yd^3)	
Ordinary Portland Cement, ASTM Type I	3.15	1.567	307.98	Mass of all cementitious materials, cm **632.17** lb/yd^3
Class F Fly Ash	2.30	1.129	162.09	
Metakaolin	2.50	0.416	64.84	
VCAS-8	2.60	0.599	97.26	w/cm ratio **0.32**

FIBERS

Component	Specific Gravity	Volume (ft^3)	Amount (mass/volume) (lb/yd^3)
GRACE Micro Fibers	0.91	0.055	3.10

AGGREGATES

Aggregates	Abs (%)	MC_{stk} (%)	SG	Base Quantity (lb/yd^3)		Volume, SSD (ft^3)	Batch Quantity (at MC_{stk}) (lb/yd^3)
				OD	SSD		
Clay Shale (Fine)	80.0	6.62	0.85	60.85	109.53	2.011	107.173
Clay Shale (Crushed Fine)	80.0	9.33	0.84	40.79	73.43	1.363	71.854
Clay Shale (10 Mesh)	80.0	8.39	0.83	20.05	36.09	0.686	35.318
3M Glass Bubbles	0.0	0.42	0.15	24.89	24.89	2.602	24.357
Poraver (0.1-0.3)	70.0	0.31	0.90	58.57	99.57	1.735	97.430
Poraver (0.25-0.5)	60.0	0.31	0.68	23.34	37.34	0.861	36.536
Poraver (0.5-1.0)	50.0	0.31	0.47	99.57	149.36	4.983	146.145
Poraver (1.0-2.0)	40.0	0.31	0.41	35.56	49.79	1.908	48.809

ADMIXTURES

Admixture	lb/gal	Dosage (fl.oz/cwt)	% Solids	Water in Admixture (lb/yd^3)	
AEA 92	8.5	10.0	6.0	3.93	Total Water from All Admixtures **8.32** lb/yd^3
ADVA Cast 575	9.1	5.0	41.0	1.32	
ACRYL 60	8.6	10.0	28.0	3.07	

SOLIDS (LATEX, DYES AND POWDERED ADMIXTURES)

Component	Specific Gravity	Volume (ft^3)	Amount (mass/volume) (lb/yd^3)
Davis Colors Powdered Pigment	4.80	0.0136	14.71

WATER

	Amount (mass/volume) (lb/yd^3)	Volume (ft^3)
Water, lb/yd^3	396.26	9.41
Total Free Water from All Aggregates, lb/yd^3	182.72	
Total Water from All Admixtures, lb/yd^3	8.32	
Batch Water, lb/yd^3	587.30	

DENSITIES, AIR CONTENT, RATIOS AND SLUMP

	cement	fibers	aggregates	solids	water	Total
Mass of Concrete, M, (lb)	632.17	3.1	567.62	2.36	385.01	1590.26
Absolute Volume of Concrete, V, (ft^3)	3.711	0.055	16.15	0.04	6.17	26.126
Theoretical Density, T, (= M / V)	60.87	lb/ft^3	**Air Content** [= (T – D)/D x 100%]			0.612%
Measured Dry Density, D	60.50	lb/ft^3	**Slump, Slump flow**			0 in.
water/cement ratio, w/c:	0.61		**water/cementitious material ratio, w/cm:**			0.32

(1) The First step is to determine batch volume. For purposes of testing, 0.13 ft^3 was chosen

(2) A w/cm ratio of 0.32 was selected from extensive testing

(3) Optimal gradation was found using a 0.45 power chart. From experimentation, the ratios were optimized for the aggregate and cementitious material amount (lb/yd^3)

Clay Shale : 18.88%
Clay Shale : 12.66%
Clay Shale : 6.22%
3M Glass : 4.29%
Poraver (0.1-0.3) : 17.16%
Poraver (0.25-0.5) : 6.44%
Poraver (0.5-1.0) : 25.75%
Poraver (1.0-2.0) : 8.60%

OPC : 48.72%
Fly Ash : 25.64%
Metakaolin : 10.26%
V-CAS : 15.39%

(4) Following the same order as in step 3, the percentages translate to amounts

107.17 lb/yd^3
71.85
35.32
24.36
97.43
36.54
146.15
48.81
Σ567.62

307.98 lb/yd^3
162.09
64.84
97.26
Σ632.17

(5) Batch weight found for each material

$$\text{weight} = \frac{\text{amount}}{27 ft^3/yd^3}(\text{batch volume})$$

$OPC = (307.98/27)(0.13) = 1.483 \text{ lb}$

$\text{Fly Ash} = (162/27)(0.13) = 0.780 \text{ lb}$

$VCAS = (64.84/27)(0.13) = 0.312 \text{ lb}$

$\text{Metakolin} = (97.26/27)(0.13) = 0.468 \text{ lb}$

$\text{Fine Shale} = (107.17/27)(0.13) = 0.516 \text{ lb}$

$\text{Crushed Shale} = (71.85/27)(0.13) = 0.346 \text{ lb}$

$\text{10 Mesh} = (35.32/27)(0.13) = 0.170 \text{ lb}$

$\text{Glass Bubbles} = (24.36/27)(0.13) = 0.117 \text{ lb}$

$P(0.1-0.3) = (97.43/27)(0.13) = 0.469 \text{ lb}$

$P(0.25-0.5) = (36.54/27)(0.13) = 0.176 \text{ lb}$

$P(0.5-1.0) = (146.15/27)(0.13) = 0.704 \text{ lb}$

$P(1.0-2.0) = (48.81/27)(0.13) = 0.235 \text{ lb}$

⑥ To find batch volume, the specific gravity of the materials was obtained from manufacturers.

	G	B, Batch Weight (lb)	Batch Volume (ft^3)
OPC	3.15	1.483	$B/(G \cdot 62.4) = 0.008$
FlyAsh	2.30	0.78	$B/(G \cdot 62.4) = 0.005$
Metakolin	2.50	0.312	$B/(G \cdot 62.4) = 0.002$
VCAS	2.60	0.468	$B/(G \cdot 62.4) = 0.003$
Fine Shale	0.854	0.516	$B/(G \cdot 62.4) = 0.010$
Crushed Shale	0.845	0.346	$B/(G \cdot 62.4) = 0.007$
10 Mesh	0.825	0.170	$B/(G \cdot 62.4) = 0.003$
Glass Bubbles	0.15	0.117	$B/(G \cdot 62.4) = 0.013$
P(0.1-0.3)	0.9	0.464	$B/(G \cdot 62.4) = 0.008$
P(0.25-0.5)	0.68	0.176	$B/(G \cdot 62.4) = 0.004$
P(0.5-1.0)	0.47	0.704	$B/(G \cdot 62.4) = 0.024$
P(1.0-2.0)	0.41	0.235	$B/(G \cdot 62.4) = 0.009$

⑦ 0.15 lb of glass fiber are then added from experimental results

⑧ Water for Cement Hydration

$$W_c = \text{(cementitious amount total)}(w/cm)$$

$$W_c = (632.17\ lb/yd^3)(0.32) = 202.29\ lb/yd^3$$

Water for aggregates

Σ(aggregate amount)(% absorption)

$$W_a = \frac{(97.43)(0.7) + 36.54(0.6) + 146.15(0.5) + 48.81(0.4)}{100}$$

$$W_a = 182.72\ lb/yd^3$$

(9) Batch volume of water

Water for Aggregates SSD:

$$B_a = \frac{(182.72\ lb/yd^3)}{(27ft^3/yd^3)}(0.13ft^3) = 0.880\ lb$$

(10) Admixtures are added by dosages of mL, and were determined from previous experimental data

	Batch Volume (mL)	Weight of Water (lb)
ACRYL 60 :	9	3.07
AEA 92 :	9	3.93
SPC :	4.5	1.32
		Σ 8.32

(11) Total water accounting for admixtures is then calculated

$$W_{ad} = W_c - 8.32lb = 202.29lb - 8.32lb = 193.97lb/yd^3$$

$$B_{ad} = \frac{(193.97lb/yd^3)}{27ft^3/yd^3}(0.13ft^3) = 0.934\ lb$$

$$\boxed{W/C = \frac{(W_c + W_a)}{632.17lb/yd^3} = 0.61 \qquad W/Cm = \frac{W_c}{632.17lb/yd^3} = 0.32}$$

(12) Wet unit weight was found experimentally right after mixing the concrete

$$2\times4\ \text{cylinder: } V = \frac{\pi(1in)^2(4in)}{(12in/ft)^3} = 0.00727ft^3$$

$$\gamma_1 = 0.504lb/0.00727ft^3 = 69.30pcf$$

$$\gamma_2 = 0.509lb/0.00727ft^3 = 69.99pcf$$

$$\gamma_3 = 0.506lb/0.00727ft^3 = 69.58pcf$$

$$\gamma_4 = 0.508lb/0.00727ft^3 = 69.86pcf$$

$$\boxed{\gamma_{avg} = 69.68\ pcf}$$

(13) Gravimetric Air Content

$$A=\left[\frac{(\gamma_{wet}-\gamma_{water})}{\gamma_{wet}}\times 100\right]=\left[\frac{(69.68-62.43)}{69.68}\times 100\right]$$

$$\boxed{A=10.40\%}$$

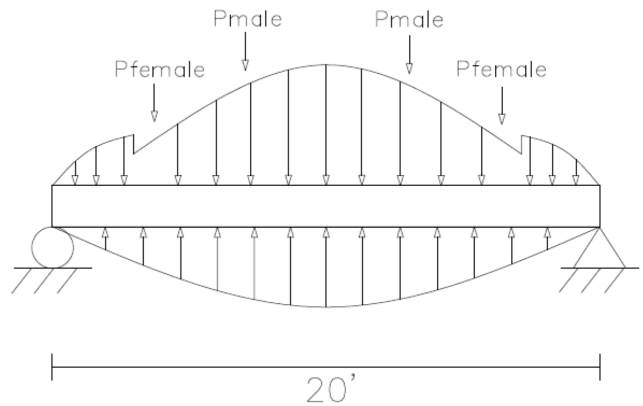
APPENDIX C—STRUCTURAL HAND CALCULATIONS

Longitudinal Analysis:

Assumptions:

Table 8: Analysis Properties	
Analysis Properties	
Canoe Density	62 pcf
Canoe Weight	250 lbs.
Male Paddler Weight	190 lbs.
Female Paddler Weight	130 lbs.
Center of gravity	10.16 ft
Simply-Supported	

Free Body Diagram:



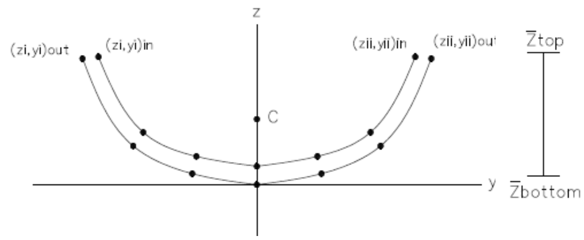
Structural Analysis Approach:

The weight of the canoe distributed load was computed by integrating spline equations of each cross section at 2 in. intervals to find the net cross-sectional area, which was multiplied by 2 in. intervals and unite weight to compute the cross-sectional weight. The moment of inertia and centroid were also computed by integrating the spline equations. To perform the analysis, more than 10 splines were used for each cross section. This analysis was performed on MATLAB and the following demonstrates the algorithm.

Numerical Integration Procedure:

Based on the geometry of the spline, the general equation is derived as the following:

$$y_i = a_i z^2 + b_i z + c_i$$



At each spline, the area, moment of inertia, and centroid are computed.

$$A_{XS} = \sum_{i=1}^{n}\left[\frac{1}{3}a_i(z_{i+1}^3 - z_i^3) + \frac{1}{2}b_i(z_{i+1}^2 - z_i^2) + c_i(z_{i+1} - z_i)\right]$$

$$I = \sum_{i=1}^{n}\left[\frac{1}{5}a_i(z_{i+1}^5 - z_i^5) + \frac{1}{4}b_i(z_{i+1}^4 - z_i^4) + \frac{1}{3}c_i(z_{i+1}^3 - z_i^3)\right]$$

$$Centroid = \frac{1}{A}\sum_{i=1}^{n}\left[\frac{1}{4}a_i(z_{i+1}^4 - z_i^4) + \frac{1}{3}b_i(z_{i+1}^3 - z_i^3) + \frac{1}{2}c_i(z_{i+1}^2 - z_i^2)\right]$$

Computed using MATLAB, the center cross-section, the moment of inertia, and centroid are as follows:

$$I_y = 787in^4, \bar{z}_{out} = 5.07in, \bar{z}_{top} = 9.94in$$

With the known cross-sectional properties, the loading on the canoe is then computed. The buoyant force was computed using a system of equations. A cubic function was chosen in order to the meet three criterion: (1) force is zero at the ends, (2) down force equates to area under cubic function, and (3) the centroid of the cubic functions aligns with the downward center of gravity.

$$W_{buoyant} = ax^3 + bx^2 + cx + d$$

The forces will be computed acting on the bow and stern of the concrete canoe.

Bow:

1) $0 = a(0)^3 + b(0)^2 + c(0) + d \rightarrow\rightarrow d = 0$

2) $2P_{Male} + 2P_{Female} + W_{Canoe} = a(20')^4 + b(20')^3 + c(20')^2$

3) $C.o.G\left(\sum P_{Male} + W_{Canoe}\right) = a(20')^5 + b(20')^4 + c(20')^3$

Stern:

1) $0 = a(0)^3 + b(0)^2 + c(0) + d$

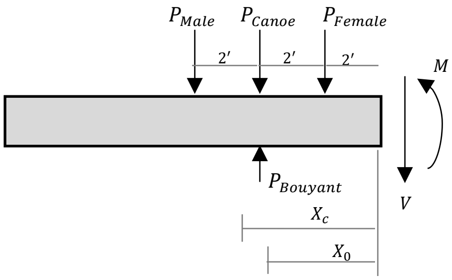
2) $900lbs = a(20')^4 + b(20')^3 + c(20')^2$

3) $9144ft - lbs = a(20')^5 + b(20')^4 + c(20')^3$

$$\begin{bmatrix} 20^3 & 20^2 & 20 \\ 20^4 & 20^3 & 20^2 \\ 20^5 & 20^4 & 20^3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 900 \\ 9144 \end{bmatrix} \rightarrow \begin{Bmatrix} a & & -7.681 * 10^{-5} \\ b & = & -1.986 * 10^{-4} \\ c & & 0.0521 \end{Bmatrix}$$

Internal Forces: Cut was taken at the center and distributed loads were connected to point loads.

Cut Free Body Diagram:



$X_C = 4.35', X_0 = 4.00', P_{Bouyant} = 442.3lb$

$$\sum F_y = 0 = -V + 442.3lb - 190lb - 130lb - 127.6lb$$

$$V = -5.3lb$$

$$\sum M_{cut} = 0 = -M - 442.3lb(4.00') + 190(2') + 130lb(6') + 127.6lb(4.35')$$

$$M = -54.14lb - ft$$

Bending Stress:

$$\sigma_c = \frac{M\bar{z}_{bottom}}{I_y} = \frac{-54.14lb - ft(12)(5.07in)}{787in^4} =\rightarrow 4.19psi$$

$$\sigma_T = \frac{M\bar{z}_{top}}{I_y} = \frac{-54.14lb - ft(12)(9.94in)}{787in^4} =\rightarrow 8.21psi$$

Hull Thickness/Reinforcement Calculations

Thickness:

Layers

Three (3) structural layers at ¼” each

Reinforcement

Two (2) layers of Fiberglass Grid White Mesh = (2)(1/128”) = 0.0156”

Gunwale Rails

Rail radius = 1.0”

Wall:

Total wall thickness: (3)(0.25”) + (0.0156”) = 0.7656”

Total Mesh

Total reinforcement thickness = 0.0156”

Total reinforcement thickness/Total wall thickness = 0.0204 < 0.5 ***Acceptable Ratio***

Gunwale Rails and Ribs:

Total rail/rib thickness = 1.0” + 3(0.75”) + 0.0156” = 1.7656”

Total Mesh

Total reinforcement thickness = 0.0156”

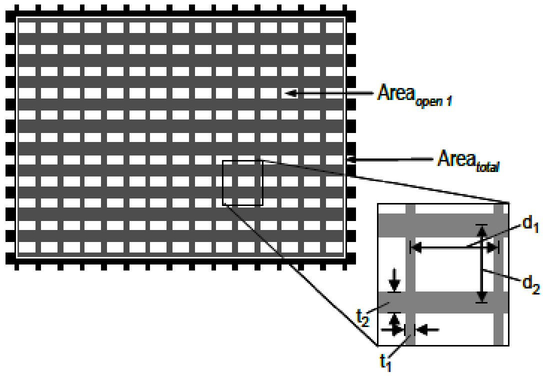
Total reinforcement thickness/Total rail/rib thickness = 0.009 < 0.5 ***Acceptable Ratio***

Bulkhead:

Total bulkhead thickness = 1”

No reinforcement

Percent Open Area



Annotation:
n_1: Number of apertures along sample length
n_2: Number of apertures along sample width
d_1: Spacing of reinforcing (center-to-center) along the sample length
d_2: Spacing of reinforcing (center-to-center) along the sample width
t_1: Thickness of reinforcing along sample length
t_2: Thickness of reinforcing along sample width

Equations:

$$d_1 = \text{aperature dimension} + 2(t_1/2)$$
$$d_2 = \text{aperature dimension} + 2(t_2/2)$$
$$\text{Length}_{\text{sample}} = n_1 d_1$$
$$\text{Width}_{\text{sample}} = n_2 d_2$$
$$\sum \text{Area}_{\text{open}} = n_1 \times n_2 \times \text{Area}_{\text{open 1}}$$
$$\text{Area}_{\text{total}} = \text{Length}_{\text{sample}} \times \text{Width}_{\text{sample}}$$
$$\text{POA} = \sum \text{Area}_{\text{open}} / \text{Area}_{\text{total}} \times 100\%$$

White Mesh: Mesh is made up of fiber glass and thread. The thread is woven between the fiberglass strands.

$t_1 = 2.0\ \text{mm} \quad t_2 = 1.0\ \text{mm}$
$d_1 = 4.0\ \text{mm} + 2(2.0\ \text{mm}/2) = 6.0\ \text{mm}$
$d_2 = 4.0\ \text{mm} + 2(1.0\ \text{mm}/2) = 5.0\ \text{mm}$

$$\text{Length}_{\text{sample}} = 19(6.0\ \text{mm}) = 114.0\ \text{mm}$$
$$\text{Width}_{\text{sample}} = 14(5.0\ \text{mm}) = 70.0\ \text{mm}$$
$$\sum \text{Area}_{\text{open}} = 19 \times 14 \times 16.0\ \text{mm}^2 = 4{,}256\ \text{mm}^2$$
$$\text{Area}_{\text{total}} = 114.0\ \text{mm} \times 70.0\ \text{mm} = 7{,}980\ \text{mm}^2$$
$$\text{POA} = \frac{4{,}256\ \text{mm}^2}{7{,}980\ \text{mm}^2} \times 100\% = \boxed{53.33\ \%}$$

$t_1 = 0.067\ \text{in} \quad t_2 = 0.033\ \text{in}$
$d_1 = 0.167\ \text{in} + 2(0.067\ \text{in}/2) = 0.234\ \text{in}$
$d_2 = 0.15\ \text{in} + 2(0.033\ \text{in}/2) = 0.183\ \text{in}$

$$\text{Length}_{\text{sample}} = 4(0.234\ \text{in}) = 0.936\ \text{in}$$
$$\text{Width}_{\text{sample}} = 4(0.183\ \text{in}) = 0.732\ \text{in}$$
$$\sum \text{Area}_{\text{open}} = 4 \times 4 \times 0.025\ \text{in}^2 = 0.4\ \text{in}^2$$
$$\text{Area}_{\text{total}} = 0.936\ \text{in} \times 0.732\ \text{in} = 0.685\ \text{in}^2$$
$$\text{POA} = \frac{0.4\ \text{in}^2}{0.685\ \text{in}^2} \times 100\% = \boxed{58.4}$$