SAFE CRIB

ME 450- Design and Manufacturing III

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Professor Alan Wineman

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safecrib@umich.edu

Danielle Cendrowski

Laura Maddox

Kelly Vanston

Iyabo Williams

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INTRODUCTION

Cribs are the most significant cause of injury and death in infants with an average of 35 deaths and an additional 12,000 hospitalizations per year [14]. This project aims to redesign a crib to improve its safety with these statistics in mind. It was presented by the non-profit organization Kids In Danger, which is dedicated to improving children's product safety and to increasing the public's awareness of dangerous children's products.

Crib manufacturers must abide by government-imposed manufacturing safety regulations; however there are still no mandatory testing standards. Thus, some cribs may not be safe for use. Most cribs are not safe because of hardware failure. It is the main cause of injury to children in cribs. Often the hardware will come loose which increases gaps that may have already been present between crib components (See Figure 1 on p. 4). As these gaps increase in size, children can often get caught within them. This can cause injury or lead to suffocation. Hardware failure may also cause the crib mattress to fall, leading to injury or suffocation. In addition, human error in the assembly of the crib often leads to injury. Most cribs are assembled by the customer and dangers can arise if the crib is assembled incorrectly or the screws and other hardware have not been tightened properly [3, 4, 6, 7].

Figure 1: Gaps Already Present within Existing Crib Design Prior to Hardware Failure

The crib produced by this project has been designed to reduce the possibility of hardware failure or loosening and to make the crib easier for the consumer to assemble without error. If it is successful and the crib is reasonably priced and marketable, it could compete with current crib designs and decrease the number of deaths and injuries to children resulting from cribs.

ENGINEERING SPECIFICATIONS

The redesigned crib meets both the customer requirements as well as the engineering specifications. These are shown and analyzed in the project Quality Function Deployment (QFD) in Figure A2 on p. 42 in the Appendix. The customer requirements are listed in the first column of the QFD. They are then given a weight based on their importance between one and six, with six being the most significant factor. The most important of those requirements is that the crib must meet government requirements. Other customer specifications, listed in order of importance and weight, are that the hardware in the crib does not fail, the crib is easy to assemble, there are a minimal number of small parts, the crib must be durable, and inexpensive. Reasons for choosing these specifications are further discussed below.

Reasons for Chosen Engineering Specifications

The engineering specifications of the crib are given in the top row of the QFD. These specifications are: the crib must weigh enough so that a child could not tip it over, the crib mattress support beams must be able to individually support a force of 25 lbs for 15 seconds without significant bending [9], and the crib walls must be able to withstand a force of 100 lbs for 35 seconds without failing [9]. These values are given by the American Society of Testing and Materials (ASTM). In addition to the wear of a child sleeping in the crib, additional fatigue wear could be caused by a parent rocking the crib to help a child fall asleep. This fatigue lifetime should be 350,000 cycles which includes a safety factor for the crib to be reused with multiple children, or approximately 4 years of use. According to government regulations for a full-size crib, the interior length must be 52 3/8 ± 5/8 inches and the interior width must be 28 ± 5/8 inches [5]. Our crib will have four height settings. Three of these settings include the legs of the crib and the fourth one is obtained without using the legs or having them completely recessed into the crib basket. These settings are 29, 34, 37, and 40 inches for ease of use by people of varying heights; these heights are not governmentally specified. The average height of current cribs that do not use a drop railing is 37 inches; this value was used in determining the three leg height settings of 34, 37 and 40 inches [5].

Relationship between Engineering Specifications

The top triangular part of the QFD shows the relationship between the engineering specifications. If two specifications are related to each other, a "+" is put in the box that relates the two. The boxes that are formed by the rows of the customer requirements and the columns of the engineering specifications house the relationship between the two. The relationship is represented by a number between one and nine, with nine having the strongest relationship.

The strongest relationships in the QFD between the customer requirements and engineering specifications are between meeting the government standards, the forces it must be able to withstand, and the crib dimensions. This is because the dimensions given in the engineering specifications are the dimensions that the government requires for all full-size cribs. In addition, there are government standards that mandate that the crib must be able to withstand the same forces that the redesigned crib will support. Other strong relationships are between the forces that the crib must be able to handle, its durability and hardware failure.

CONCEPT GENERATION

In order to increase crib safety, concepts were generated to focus on hardware, current mechanisms, and overall structure. Five of the six main concepts are described below, the sixth and chosen design can be found in detail starting on p. 11 and further minor designs can be found in the Appendix on p.44.

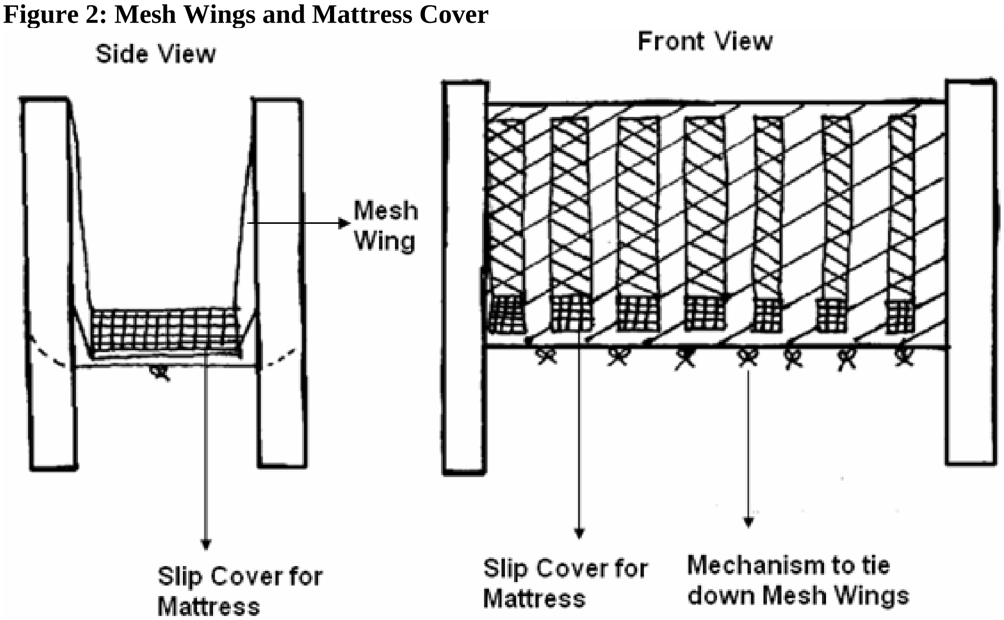
Concept 1: Mesh Wings and Mattress Cover
The mesh wings and mattress cover is sketched in Figure 2 on p. 6.

Motivation for Concept: There were three objectives that drove this design. The first of these is that the mesh wings eliminate the gap between the mattress and the side crib walls caused by hardware failure. This problem is caused by hardware failure that occurs by either fatigue on the hardware over time or improper installation of the hardware. If the hardware fails, the crib side walls separate from the mattress. This separation causes a gap into which a child can roll and suffocate. To solve this problem, the mesh is attached to the mattress in two ways. There is a mattress cover for the mattress to slide into. The two mesh wings go up and over the crib side walls to attach under the bottom of the crib. This eliminates the danger of a gap forming between the crib side walls and the mattress. If a gap forms, the child would roll into the mesh on the sides.

The second main objective for the mesh wings and mattress cover is to provide a secondary support system to hold the mattress. With the current crib design, the mattress is supported by four removable hinges and a board, on which the mattress is then placed. Since the hinges are removable mechanisms, they can come out of place. This causes the mattress to tilt, and the child to fall into the gap between the mattress and crib side walls. With the mesh wings for the mattress, there is a second support system. Therefore, if the hinges fail, then the mesh wings can hold the mattress up until the hinge is secured.

The third objective with this concept is its adaptability. This concept could be bought separately from the crib. Therefore, it could be used in any crib on the market today and parents could buy this product without having to buy a new crib.

Figure 2: Mesh Wings and Mattress Cover



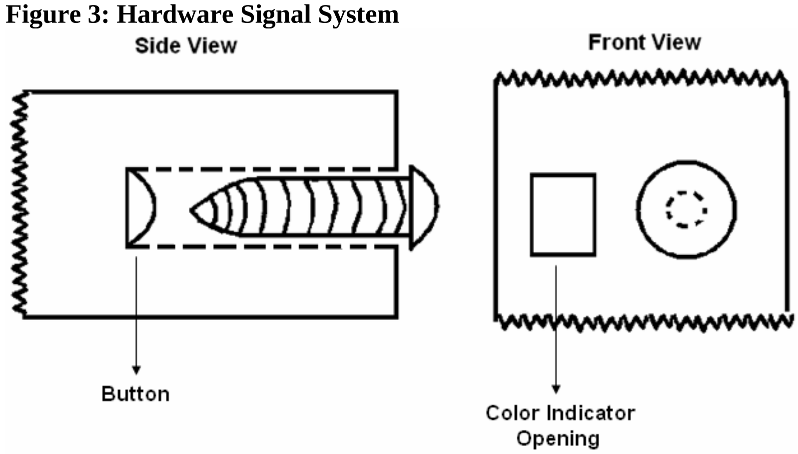
Problems Associated with Concept: There are several problems associated with this design. One is that the mesh material could create a climbing wall. An older child could use the mesh to climb out of the crib and fall. In addition, if the mesh were to rip or tear, the entire system would fail, thus providing no increase of safety from the current design. Another problem is that the airflow and cross ventilation in the crib may be hindered. A decrease in ventilation is suspected to be a factor in Sudden Infant Death Syndrome (SIDS) related deaths. This concept may also cause a false sense of security for the parent in that it prevents a complete mattress failure but is not intended to be a permanent mattress support.

Concept 2: Hardware Signal System

The hardware signal system is a mechanical system that would indicate whether or not the screws are properly secured. A button would be located inside the hole where the screw would be inserted. Once the button is completely compressed by a sufficiently tightened screw, an opening located on the outside of the crib next to the screw hold would show the color green. However, if the screw became loose and the button is not fully compressed, then the panel would rotate to show the color red. A sketch is shown in Figure 3 on p. 7.

Motivation for Concept: The objective of this concept was to provide a visual indication when there was something wrong with the way the crib was put together. This is an issue because in the time that a crib is stored after one child is finished with it and before another child starts using it, the hardware needed to properly assemble the crib is often lost. When the crib is assembled, the hardware signal system would show the consumer whether or not they had all hardware installed and secured.

Figure 3: Hardware Signal System

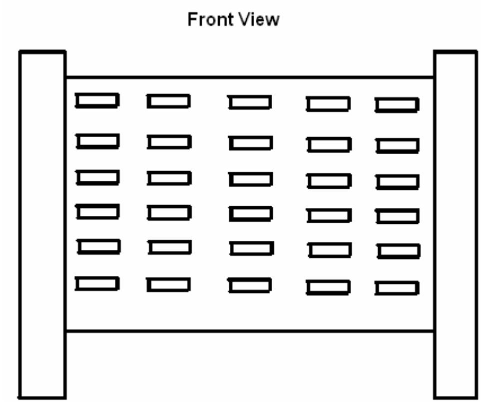


Problems Associated with Concept: There are two major problems associated with the hardware signal system. One problem is that the consumer would have to buy a new crib with the system (unlike the Mesh Wing and Mattress Cover system). It is not a separate system that would be installed on an already purchased crib. Also, there are no government regulations that would require a crib manufacturer to implement the system in their designs. Therefore, there is no incentive for the system to be manufactured on a universal scale. According to the team's sponsor, Nancy Cowles, most manufacturers are not motivated to redesign their cribs to incorporate an additional voluntary mechanism. Additionally, the signals do not prevent hardware failure, but rely on the customer to recognize and fix the problem.

Concept 3: Reconstruction of Side Slats

The reconstruction of the side slats is a concept created to decrease the possibility of babies getting their arms or legs stuck in between the slats and the possibility of the slats falling out. There are two different designs generated for the reconstruction of the side slats. The first idea is shown in Figure 4 on p.8.

Figure 4: Reconstruction of Side Slats-Design 1

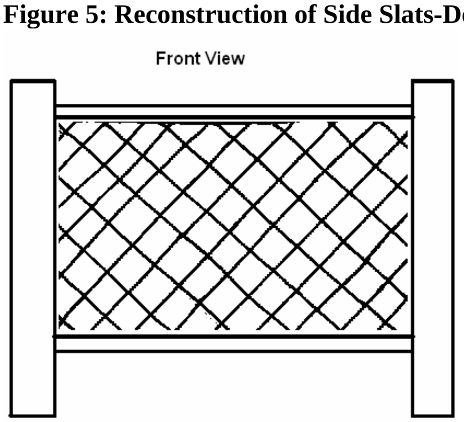


Design 1 Motivation: The first concept was to make horizontal slats in addition to the vertical slats. The holes in between the vertical and horizontal slats would be small enough that the child's arm or leg would not be able to fit. However, the size would be large enough so the child's finger would not get caught.

Design 1 Problems: The main problem with the first concept is the significant decrease in cross ventilation throughout the crib. Considerable air flow in a crib is essential to the child's health as previously discussed. Furthermore, the horizontal slats could create a climbing wall for the child. Thus, an older child could climb out of the crib which poses a serious problem.

Design 2 Motivation: The second concept was to make the side panels out of mesh instead of wood or plastic. This way there was no hole or room for the child's legs or arms to get trapped on the side panel, thereby increasing the safety of the crib. A sketch of the second concept is shown in Figure 5 on p.8.

Figure 5: Reconstruction of Side Slats-Design 2

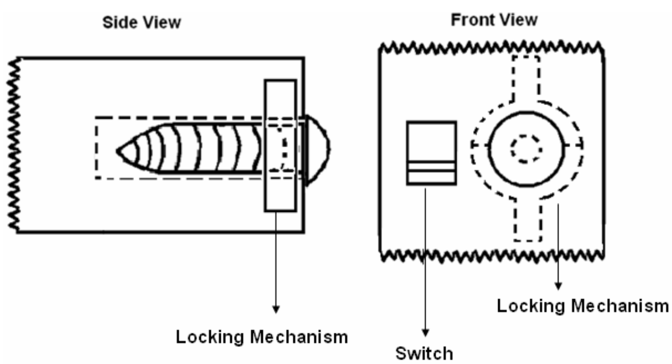


Design 2 Problems: There are many problems associated with the second concept. If the mesh were to tear or rip, then there is potential for the child to fall out of the crib and onto the floor. Moreover, depending on the strength of the mesh, if the mesh becomes worn, there is a possibility of a gap forming between the mesh wall and the mattress. Additionally, like in the first concept, the mesh may not provide enough air flow throughout the crib.

Concept 4: Locking System for Screws
The locking system for screws, as shown in Figure 6 on p. 9, was specifically designed to prevent screws from becoming too loose and/or coming out. A lock would be lowered from above and raised from below so that it fits snugly around the screw body and behind the screw head. On the outside of the crib next to each screw, there would be a switch. If the switch was up, the screw would be unlocked and could be removed. Likewise, if the switch was down, the screw would be locked and could not move.

Motivation for Concept: With the lock over the screw, the screw would not be able to come out of its hole. This would significantly reduce the possibility of hardware failures.

Figure 6: Locking System for Screws



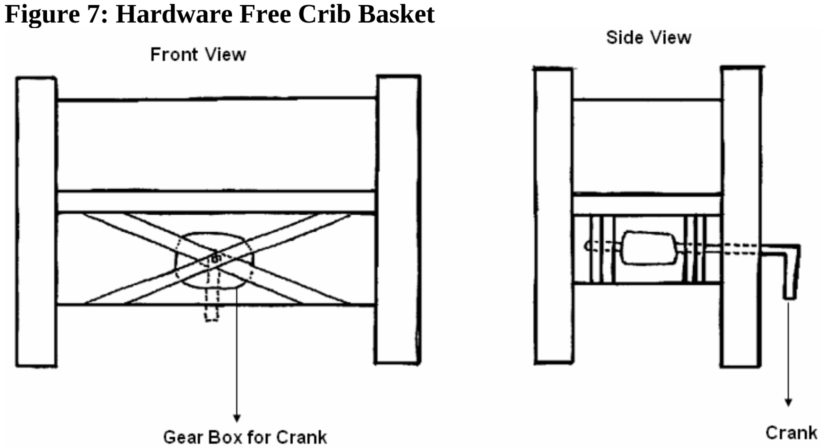
Problems Associated with Concept: The main problem with the locking system is that it would require a lot of manufacturing changes. The locking system is not a separate piece that could be installed in an already manufactured crib. A manufacturer would have to begin manufacturing completely new cribs with the locking system. This would require new manufacturing equipment and a possible increase in production time.

Concept 5: Hardware Free Crib Basket with Adjustable Legs and Mechanical Lift
The hardware free crib basket incorporates many of the ideas behind the other concepts. These ideas include: adjustable crib legs, a new mattress support system, and a hardware free crib basket. The crib basket resembles a laundry basket. The basket would need to be made by injection molding because the side panels and the bottom would be connected without any hardware. The sketch of the concept can be seen in Figure 7 on p.10.

Motivation for Hardware Free Crib Basket: The hardware free crib basket was designed to eliminate the core problem with cribs today by eliminating all hardware.

Problems with Hardware Free Crib Basket: The main problem with the hardware free crib basket is it would be hard to store or transport. Trucks would not be able to transport as many cribs per trip as with today's cribs that are transported in flat boxes.

Figure 7: Hardware Free Crib Basket



Motivation for Adjustable Legs: The adjustable legs serve as a replacement for the drop-down gate that has been removed from the vast majority of cribs currently on the market. According to research from *Babies 'R' Us*, the majority of the cribs on the market today have abolished the use of the drop-down gate due to its failure. The drop-down gate is dangerous because if either the hardware fails, or the parent forgets to put the gate back up, children can either fall or climb out of the crib. However, not having the drop-down gate is inconvenient to mothers and fathers that are shorter in height because they may struggle to reach over the side walls to place the child in the crib. Therefore, the hardware free crib is designed to have adjustable legs to allow parents to have four different height settings. Three of these settings use the legs and the fourth setting is with the legs completely inside the leg holes of the crib. Adjustable legs allow for adaptability in the environments in which the crib could be used.

Problems with Adjustable Legs: By making the legs adjustable, the team was forced to introduce four screws. Each screw will be a place of weakness in the design; a place of possible failure.

Motivation for Mechanical Lift: The mechanical crank for the mattress was chosen to replace the current four hinge mattress support method. The support has often been the location of hardware failures. In particular, when a hinge fails, the mattress tilts, causing the child to fall into a gap which poses a suffocation hazard. The mechanical crank would be positioned on the base of the crib basket with a board above it to hold the mattress. A handle for the crank would be located on the outside of the crib and would fold into the side of the crib when not in use. The crank would allow the mattress to have different height levels. Also, it does not require more than one user to adjust the mattress height.

Problems with Mechanical Lift: The problems with the mechanical lift are that the lifts available on today's market are not suitable for use in a crib. They are used specifically for industrial applications which lift in excess of 1 ton. In addition, to keep the mattress and mattress board level, a synchronized system of lifts would be needed. This greatly increases the complexity of the crib. Furthermore, if the handle for the crank is on the outside of the crib, this creates a danger if the handle is not folded into the side of the crib. In addition, a child outside the crib could severely injure themselves or inadvertently change the height of the mattress by hitting the crank handle.

CONCEPT SELECTION PROCESS

In selecting the alpha design, the team used the Pugh chart as a guide to choose the final design. It was also important that the crib could be easily used by one person and that the overall design is innovative. The criteria that appeared in the Pugh chart are listed in Table 1 on p.11. These criteria were weighted on scale of 1-3 with 3 being the most important. The Pugh chart can be seen in Figure A1 on p. 44 in the Appendix.

Table 1: Pugh Chart Criteria

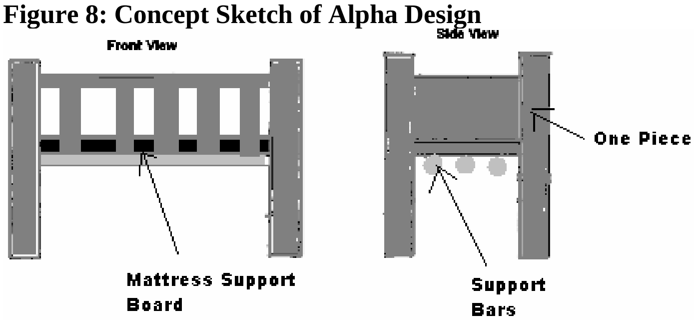
Pugh Chart Criteria	Weight
Screws do not come out	3
User will not lose necessary small pieces	2
Assembly is simple	3
Design is simple	2
Reduces likelihood of child injuries	3
Minimizes number of small parts	2

To analyze each concept, the team determined if the concept had a positive (+), negative (-), or no correlation (0) to the design criteria and totaled the scores.

Alpha Design Decision

The team agreed with the Pugh chart and decided that the 6th design, the hardware free crib basket with a beam supported mattress, is the best. It not only met all of the criteria, but it was the most innovative design option and could easily be used by one person. The hardware free crib basket with a beam supported mattress incorporates many components that increase the safety of the crib. These components are adjustable crib legs, a new mattress support system, and a hardware free crib basket. The hardware free crib basket resembles a laundry basket except that it has no bottom. The basket would need to be made with injection molding because the side panels are to be connected without any hardware. The team preferred this design concept over the 5th concept because the mattress support system of this concept appeared more reliable and simple. This different mattress support system is the only difference between the alpha design and the fifth design concept. A sketch of the alpha design concept is in Figure 8 on p.11.

Figure 8: Concept Sketch of Alpha Design



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Problems with Adjustable Legs: By making the legs adjustable, the team was forced to introduce four screws. Each screw will be a place of weakness in the design; a place of possible failure.

Motivation for Beam Supported Mattress: The beam supported mattress would be easy for one person to use, would reduce the required hardware necessary for the mattress support, would decrease the number of small crib components, and would distribute the load of the mattress and child over a greater area.

Problems with beam supported mattress: By supporting the mattress with beams and a support board the manufacturing costs can be expected to increase.

ENGINEERING DESIGN PARAMETER ANALYSIS

Many tools and resources were used in the engineering design analysis to determine the specific parameters of the final design. Among these are internet research, free body diagrams, and singularity functions. Specific properties analyzed included the moment of inertia for the mattress support beams, the support forces exerted by the crib head/foot boards, the maximum beam deflection, the tensile/compressive stress of the mattress support beams and mattress support board, the compressive stress exerted on the crib legs and the moment required to tip the crib over. In addition, sections on material selection, manufacturability and safety are also included below.

Material Selection

The materials for the final design were chosen based on their material strength, safety, and density. Comparisons were made between several materials using internet research. The material chosen for the crib basket, legs, and mattress support board is Bapolene® Grade PP5026 Polypropylene, Extrusion/Injection Grade. The material chosen for the mattress support beams is

X10Cr13 Stainless Steel. The reasons behind these decisions are discussed in the two subsequent sections.

Material for Crib Basket, Legs, and Mattress Support Board: The Bapolene® Grade PP5026 Polypropylene, Extrusion/Injection Grade was chosen primarily for its safety. Bapolene® Grade PP5026 Polypropylene is an Impact Copolymer Polypropylene (ICP). From American Chemistry, "ICP is a crystalline polymer, which exhibits high stiffness, excellent impact strength and good electrical insulation properties… ICP is also the leading material used in car seats and high-back boosters [13]." This ensures that the material is safe enough to be used around children. According to MatWeb.com, this type of plastic can be used for child safety products and meets FDA regulation 21 CFR 177.1520 [2]. This regulation requires that the product be suitable for food container applications. Children, while teething, may chew on the crib itself. Therefore, it is important that crib is safe for them to chew on and does not exhibit toxic fumes. Since this plastic is already used for child safety products and is suitable for food container applications, it is safe for use on a crib. Additionally, IPC's large color variability, low cost, and ability to be injection molded makes it a good choice for this application.

Since this material is plastic, the strength of it is based on a flexural modulus of 191 ksi. Also, it has a tensile strength of 3,900 psi and density of 0.0326 lb/in^3. According to MatWeb, the plastic has superior balance of thickness and impact strength. This ensures that any rocking of the crib will not severely harm the material [2].

Material for Mattress Support Beams: X10Cr13 Stainless Steel was chosen for its safety and strength. It is used for medical instruments; so the team was confident that it would be safe to be used around a child [15]. The strength of X10Cr13 Stainless Steel is very high. According to MatWeb, it has a modulus of elasticity of 29,000 ksi. The yield tensile strength is 39,900 psi, and the ultimate tensile strength is 70,300 psi [15].

Moment of Inertia for T-shaped Beam

Using the parallel axis theorem, the moment of inertia for the Y-shaped bar was determined to be 0.0084 in.^{4}. The dimensions of the beam are specified in Figure 37 on p. 30. The moment of inertia was then used to determine the deflection and the tensile/compressive stresses for the beams.

The moment of inertia was determined using Matlab after singularity functions were constructed for the support beam stress and strain. Modifications to the dimensions of the T-beam were made until the moment of inertia calculated implied that the beam would provide the support specified in the engineering specifications.

Standard dimensions for mass-produced T-bars could not be found. The dimensions of the T-shaped beams could be adjusted if a standard T-shaped bar was found that still met all of the engineering specifications.

Free Body Diagrams

Free body diagrams were constructed for the structural analysis and are discussed below.

Support Beams: In order to simplify all analysis, the best and worst case scenarios, or the extreme scenarios, were the only cases considered. Thus, two free body diagrams were constructed for the analysis of each individual beam for both cases. The first scenario, or the best case, would occur when the beam is first inserted into the crib and there is no wear on the insertion hole. This scenario is represented as a built-in supported beam as shown in Figure 10 on p. 14. The second scenario, or the worst case, would be represented as a simply supported beam as shown in Figure 9 on p. 14. This would display the free body diagram for the beam if, after an extended amount of time, wear caused large tolerances in the support holes.

In both Figure 9 and 10 on p. 14 the weight of the child is represented as a point force, which is the worst case scenario, standing at some given distance from the headboard. The weights of the mattress and the support board are summed and divided by three. This weight is then represented as a distributed load across the length of each of the three beams. The support forces are represented as point forces at the ends of the beam. These forces represent the forces exerted on the beam by the crib walls. For the built-in scenario, a moment was also added to each end of the beam to represent the moments caused by the crib walls on the support beams.

Figure 9: Free Body Diagram of Simply Supported Beam (Worst Case Scenario)

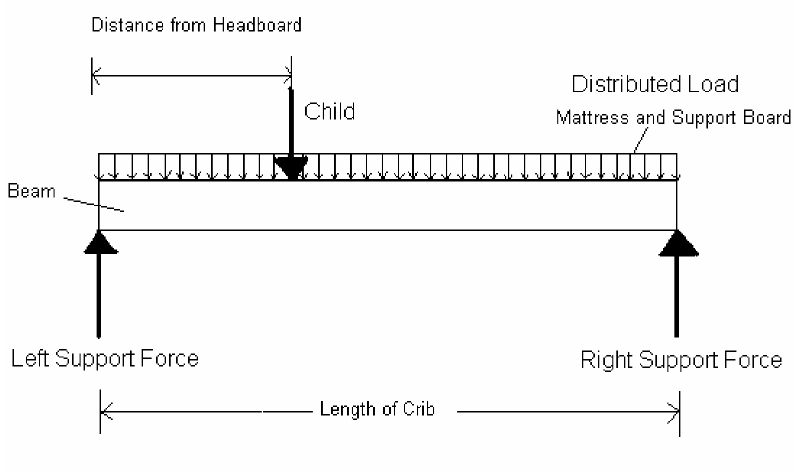
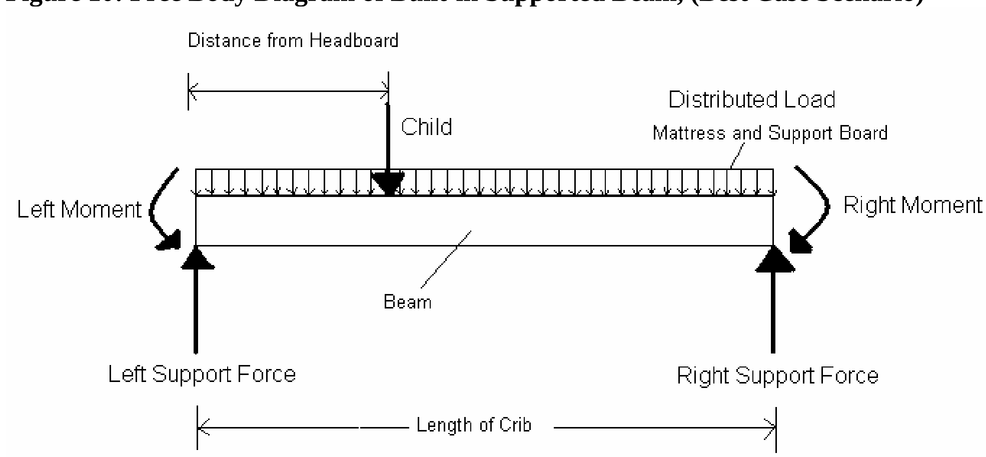
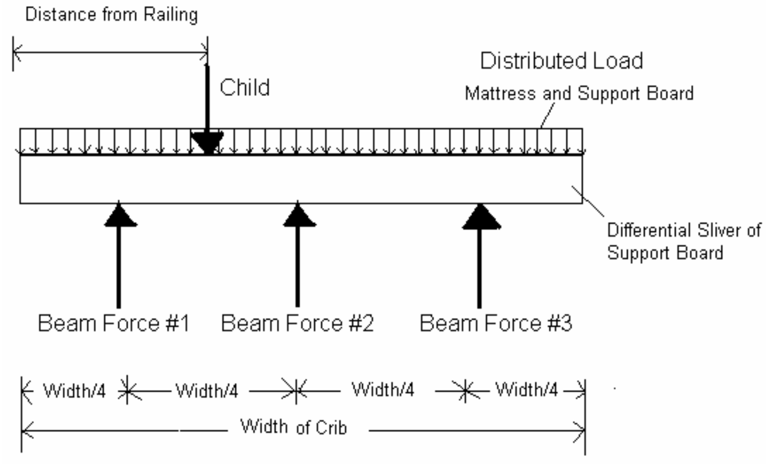


Figure 10: Free Body Diagram of Built-in Supported Beam, (Best Case Scenario)



Mattress Support Board: For all analysis of the mattress support board, the free body diagram shown in Figure 11 on p.15. This free body diagram represents the mattress support board as a beam whose length is the width of the crib, whose height is the support board height, and whose width is a differential segment from the length of the crib. Like in the support beam free body diagrams, the weight of the child is represented as a point force standing at some given distance from the headboard. The weight of the mattress is represented as a distributed load across the length of the differential board segment. The upward forces from the three support beams are represented as point forces at equivalent distances along the width of the crib.

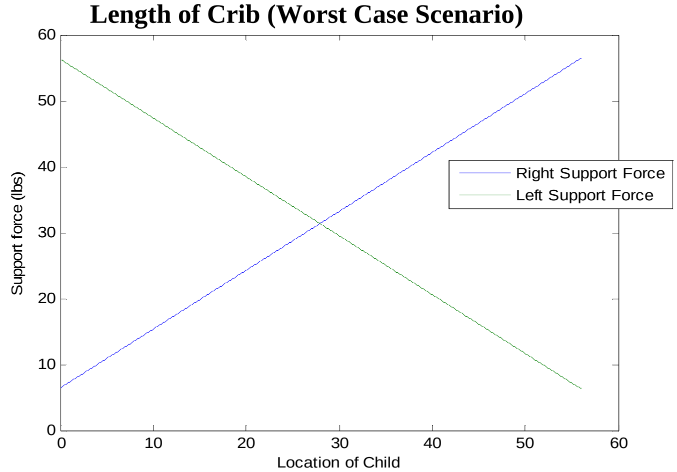
Figure 11: Free Body Diagram of Sliver of Mattress Support Board



Crib Walls Support Force Analysis

Analysis was completed for the support forces exerted on the crib walls to determine if the head/foot boards would buckle or shear under the force from the beams in the vertical direction. Using the sum of the forces in the vertical direction and the sum of the moments about the vertical axis, for a static analysis, the left and right support forces were found for a 50 lb child as he/she walked the length of the crib interior. The results of this analysis can be found in Figure 12 on p.15. The maximum support forces exerted on the head/foot boards will be roughly 57 lbs.

Figure 12: Right & Left Support Forces as Child Walks Length of Crib (Worst Case Scenario)



Knowing the maximum support forces exerted on the crib wall, the team was able to determine if the crib wall would buckle or shear under the pressure. Using Eq. 1 on p.16, where F and A represent the support force and the contact area respectively, the maximum stress on the crib walls was found to be less than 30 psi. This is significantly lower than the yield stress of 6,820-7,250 psi for compression for polypropylene [2]. Therefore, the crib walls can withstand the forces from the beams.

$$\sigma = F / A \qquad \text{(Eq. 1)}$$

Beam Deflection

Next, the deflection of the beams was analyzed for both the best and worst case scenarios. Deflection of the beam was a concern because if it is too large, the deflection could cause a large depression in the mattress and pose a suffocation hazard.

To determine the deflection, singularity functions were used in conjunction with the free body diagrams of Figures 9 and 10 on p.14. Since the beams are supported only at the ends, the child was assumed to be at the center of the beam, which is the worst possible position for the deflection calculations. The results of these calculations can be found in Figures 13 and 14 on p. 16 and p.17, respectively, for the worst and best case scenarios, respectively. In the worst and best case scenarios, the maximum deflection is roughly 0.87 in. and 0.22 in., respectively.

Figure 13: Maximum Deflection of the Beam with Child Standing at the Center (Worst Case Scenario)

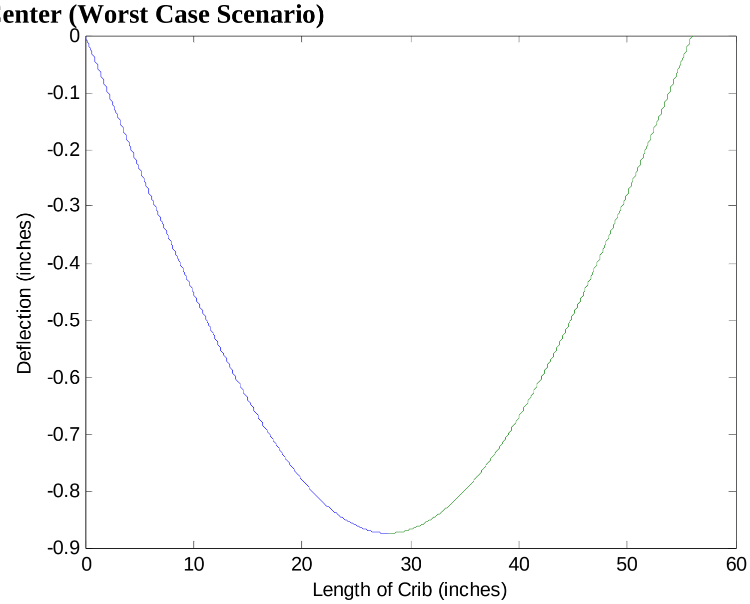
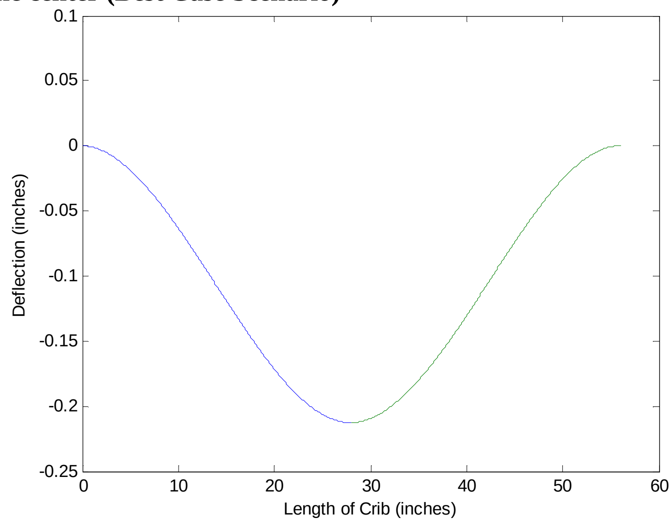


Figure 14: Maximum Deflection of the Beam with Child Standing at the center (Best Case Scenario)



Tensile/Compressive Stress

Analysis was completed to determine the maximum tensile and compressive stresses experienced by both the support beams and the mattress support board.

Beam Stress: Using the moment of inertia for the beams, the free body diagrams, and the singularity function for the moment, the maximum tensile and compressive stresses were found for each beam. Using Eq. 2 on p. 17 and the knowledge that the maximum stress would occur at the top and bottom of the beam, the tensile/compressive stresses were found for when the child stands in the center of one beam. These results are shown in Figures 15 - 18 below and on p. 17-19.

$$\sigma = \frac{My}{I} \qquad \text{(Eq. 2)}$$

Figure 15: Tensile Stress of the Beam when Child at Beam Center (Worst Case Scenario)

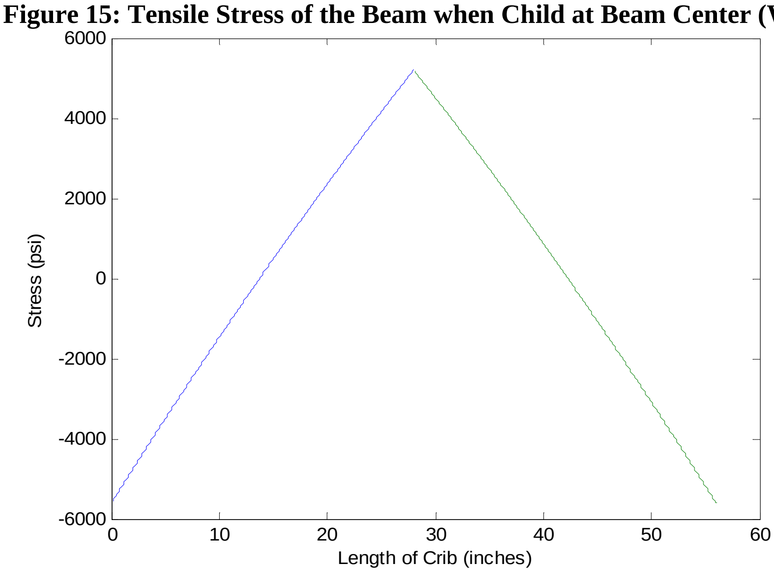


Figure 16: Tensile Stress of the Beam when Child at Beam Center (Best Case Scenario)

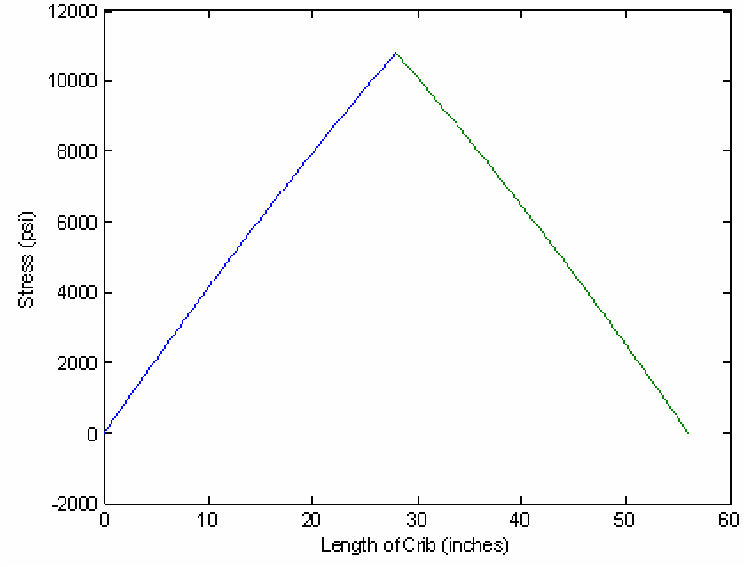


Figure 17: Compressive Stress of the Beam when Child at Beam Center (Worst Case Scenario)

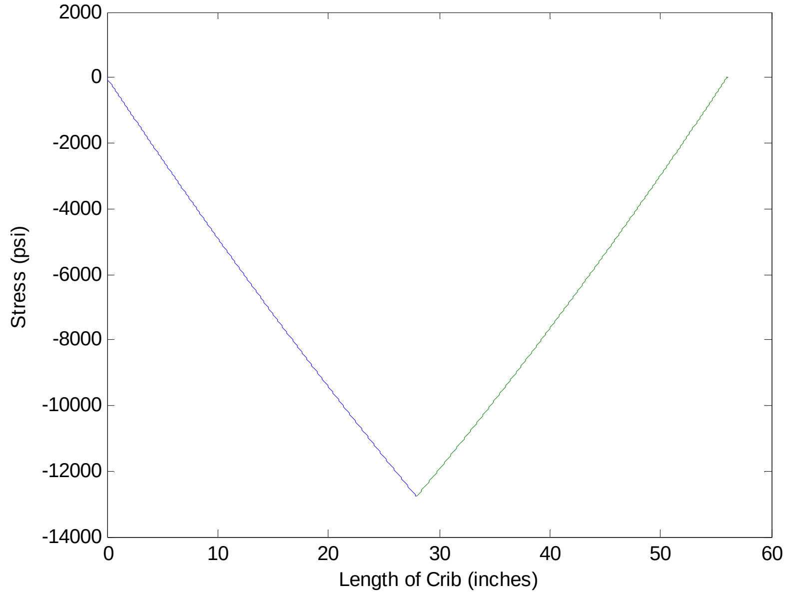
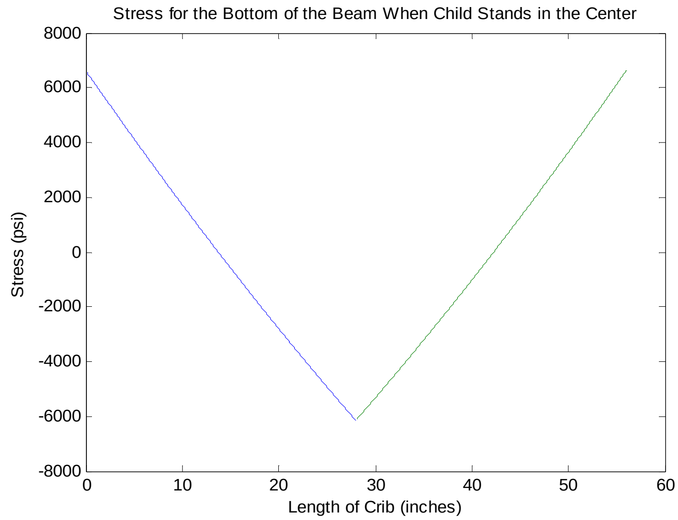


Figure 18: Compressive Stress of the Beam when Child at Beam Center (Best Case Scenario)



From Figures 15-18 on p. 17-19, it can be seen that the beams never experience a stress greater than the yield stress of 39,900 psi and therefore, yielding is not a concern. Further, there is a safety factor of at least 3 in every scenario.

Mattress Support Board Stress: Using the free body diagram, the singularity function for the moment, and the height of the mattress support board, the maximum tensile and compressive stresses were found. Analysis was completed for two different cases, when the child stands 3 in. away from the railing and when the child stands directly between two of the support beams. Then using Eq. 3 on p. 19 the maximum tensile stresses were found for the mattress support board where *M*, *y* and *h* represent the moment, the distance from the center of mass to the top of the board, and the board height respectively [17]. These results can be found in Figures 19 and 20 and p.19 and 20, respectively.

$$\sigma = \frac{12My}{h^3} \qquad \text{(Eq. 3)}$$

Figure 19: Maximum Stress for the Mattress Support Board for Child 3" from the Railing

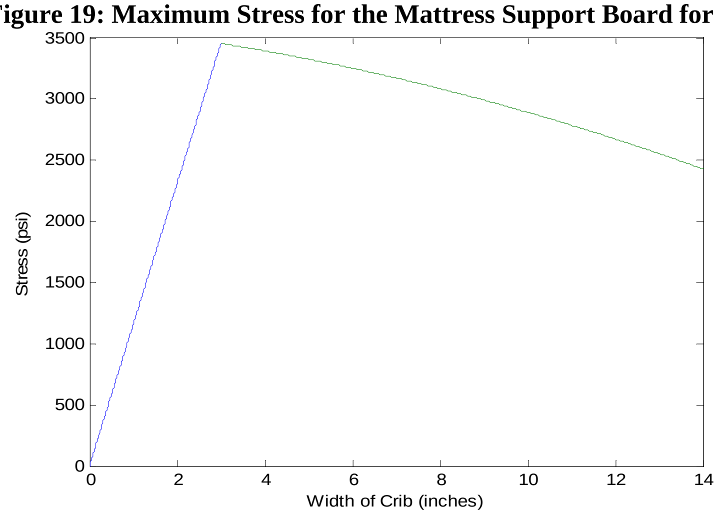
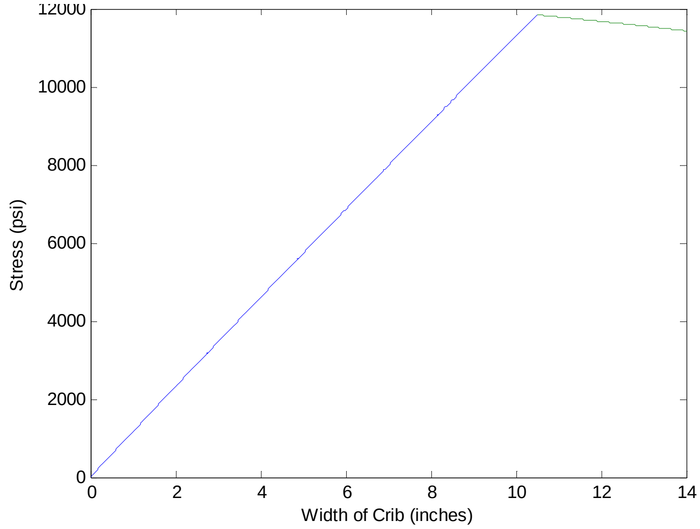


Figure 20: Maximum Stress for the Mattress Support Board for Child Centered Between the Two Beams



From Figures 19 and 20, it can be seen that the mattress support board is never exposed to tensile stresses greater than the yield stress of 39,000 psi for the polypropylene. Therefore, the mattress support board will not yield and will have a safety factor of at least 3 always.

Analysis for Crib Legs

Static analysis on the legs was performed to examine the forces on the interface between the screw and the hole. The modes of failure that were examined were failure due to end tearing and failure due to yielding from compression.

End tearing: The formulas for the end failure were found in the second edition of Pilkey's "Formulas for Stress, Strain and Structural Matrices". The expression for end tearing is shown in Eq. 4 on p.20, where σ_u is the ultimate tensile strength of the polypropylene, P is the load acting on the leg due to the weight of the crib, the child, the mattress support board and the support beams, t is the thickness of the leg, and e is the distance to the next leg opening or the bottom of the leg. To ensure a conservative analysis, all of the weights used to calculate P were rounded up to the nearest 5 lbs. The weights used are summarized in the Table 2 on p.20.

$$\sigma_u \geq \frac{2 \cdot P}{t \cdot e} \qquad \text{(Eq. 4)}$$

Table 2: Weights used to Calculate Ultimate Tensile Stress for End Shearing Analysis

Parameter	*Value*
Crib Basket	205
Child	50
Mattress Support Board	25
Mattress Support Beams	10
Total	290
Force per Leg	**72.5**

The value for t is 2.5 in. The values for e are 3 in. and 7 in. for the distance between holes the distance to the bottom of the leg respectively. From these values the minimum value of ultimate tensile strength is 19.33 psi. This value is significantly smaller than the material's tensile strength of 3,900 psi which gives a safety factor of 202. Therefore, end tearing is not a concern.

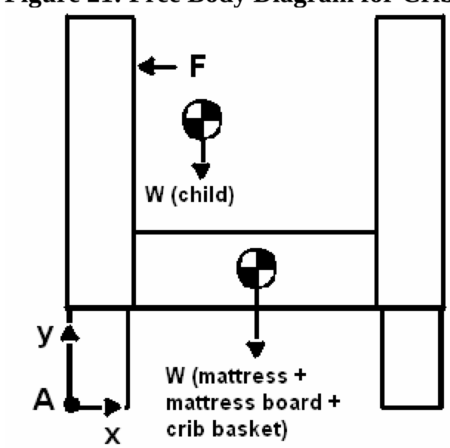
Compression Yielding: To determine if the leg would fail by compressive yielding the team analyzed the forces exerted on the leg by the screw. In order to simplify the problem, the area considered was a rectangle with width equal to the screw's diameter and length equal to the width of the leg. The expression for the minimum compressive strength is shown in Eq. 5 below, where σ_c is the compressive strength, d is the screw diameter [20]. The screw diameter is 0.5 in. The minimum value of the compressive strength is 58 psi. This value is significantly smaller than the average compressive yield strength of 7,035 psi, which gives a safety factor of 121 [21]. Therefore, compressive yielding is not a concern.

$$\sigma_c \geq \frac{P}{t \cdot d} \qquad \text{(Eq. 5)}$$

Stability of Crib

The crib must be stable enough to handle any force (F) exerted on it by a child without tipping over. Therefore, static moment analysis was taken with respect to point **A** shown in Figure 21 on p.21. The figure shows a free body diagram of the crib. The weights of the child, crib basket, mattress board, and mattress are located at their center of gravity.

Figure 21: Free Body Diagram for Crib Moment Analysis



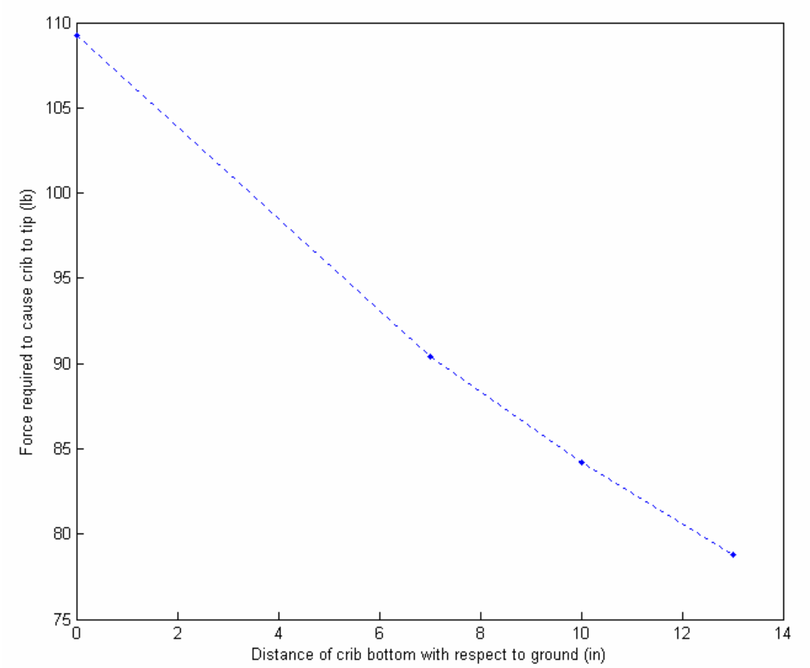
Without the force exerted by the child, the weight of the child and the weights of the crib basket, mattress board, and mattress produce a negative moment at point **A**. Thus, when the moment about point **A** becomes positive, the crib has the potential to tip.

The position of the force was based on two criteria. First, the greater the distance the force is from point **A** in the y-direction, the larger the moment the force will generate a point **A**. This helps create the most extreme case that could occur. Also, the maximum average height of a child in a crib is 33.70 in. [16]. The force was positioned at this height in the crib when the analysis was calculated.

Figure 22 on p. 22 shows the force that must be exerted by the child to cause the crib to tip at various crib leg heights. For example, if the crib bottom is on the ground, the child must exert a force of 109.22 lb to cause the crib to tip. However, if the crib bottom is 7.0 in. off the ground, the child has to exert a force of 90.44 lb for the crib to tip.

The maximum weight of a child in a crib is 27.2 lb [16]; however analysis was completed for a child of 50 lb to include a safety factor in the calculation. The minimum force required by the child to tip the crib is 78.82 lb at a crib height of 13.0 in. off the ground. This force is very difficult for a child to generate since it is over 1.5 times their weight. Therefore, the crib is stable enough to handle a force exerted by the child in the crib.

Figure 22: Force required to Tip Crib at Various Crib Heights.



Design for Manufacturability

This project was intended to be designed for mass production. Thus standard sizes and hardware were chosen whenever possible. This desire explains the choice of the two standard sized bolts from BoltDepot.com as described in the final design section. While the team had hoped to use readily available materials to reduce the overall crib manufacturing costs, the need for the materials to be child safe forced the design to use a more customized plastic and steel. Since the remainder of the crib design is made via injection molding, the specific dimensions were not considered in designing for manufacturability or cost since the only initial cost or manufacturing concern would be the mold. Thus all remaining crib dimensions were chosen to satisfy government full size crib requirements and aesthetic appeal.

Failure/Safety of Final Design

At this time, the final design has at least a safety factor of 3 for both the support beam stress/strain, mattress support board stress/strain, the force required for tipping, end tearing, or compressive yielding for the legs. These conclusions were drawn from the varying engineering analyses performed in the previous sections of the Engineering Design Parameter Analysis. Furthermore, since the safety factors were determined from highly conservative analysis the team is confident that the final design's support beams, mattress support board, legs, and overall crib stability are sufficient.

At this time, the only safety/failure concerns not addressed are for the crib basket itself. Lacking the knowledge and resources required to perform the necessary engineering analysis, the crib wall strength was unable to be tested at this time. However, after performing the analysis for the mattress support board the team is confident in the crib wall's strength. This is because the crib walls have a thickness much greater than the mattress support board thickness and the mattress support board was designed to withstand a higher load than what would be required of the crib walls.

If further safety/failure analysis was performed on the final design, the support beam, the mattress support board, the crib legs, and the crib walls should all be further analyzed using more advanced software, such as software used in finite element analysis. This analysis should be completed to further explore the probability of failure by tensile or compressive yielding and shearing. However, at this time the final design is believed to be safe for the use of 4 years, or approximately two children.

FINAL DESIGN DESCRIPTION

The final crib design is very similar to the alpha design and its main components will be explained in the following sections. Figure 23 on p.23 shows a CAD image of the final design.

Figure 23: CAD Image of Final Design

Manufacturing Method of Crib Basket- Injection Molding

The final crib design will be made out of a plastic so that the crib basket can be manufactured as one piece through injection molding. This eliminates the possibility of the slats falling out and the failure of the hardware that holds the head/foot boards to the side rails. Furthermore, an injection molded crib was appealing because it would be easy to manufacture, would greatly simplify the assembly for the user, and would decrease the possibility of user error.

Crib Basket Material- Plastic
The final crib design will be made out of Bapolene® Grade PP5026 Polypropylene, Extrusion/Injection Grade, for reasons previously discussed in the Materials Selection of the Engineering Design Parameter Analysis section on p.12-13.

Overall Crib Basket Shape
The overall shape of the crib basket was kept very similar to the cribs' currently on the market for two reasons. First, the team and sponsor saw no current problems with the overall shape that needed to by this project. Secondly, the team decided to focus its energy solely on developing innovative solutions to the aspects of a crib that make the current ones unsafe. A CAD figure illustrating the crib basket (the head board, foot board, and side walls) can be seen in Figure 24 on p. 24. Also, Figure 25 on p.25 shows the crib basket with all of its dimensions. The only adjustment between the final crib basket design and current cribs is that the final crib design has rounded edges to better fit a mattress. Rounding the inside edges of the crib decrease the amount of room between the mattress and the crib corner walls which in turn reduces the possibility that a child could get a body part lodged there.

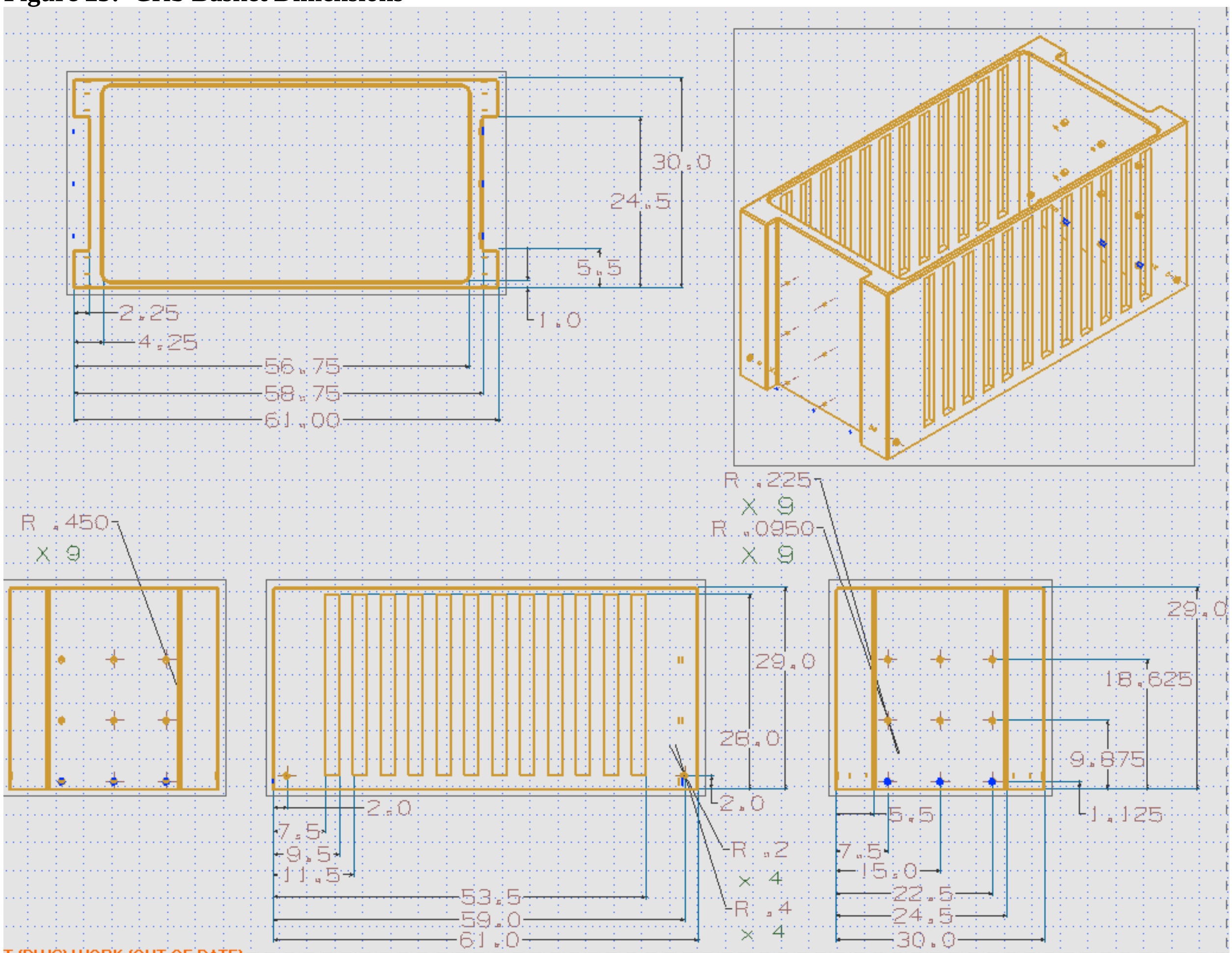
Figure 24: Crib Basket

The specific dimensions for the crib basket can be found below in Table 3 and Figure 24. The majority of dimensions were determined by the requirements of the United States Consumer Product Safety Commission (USCPC) [5].

Table 3: Crib Basket Dimensions [4]

	USCPSC (in.)	Final Design Dimensions (in.)
Interior Crib Basket Width	28 ± .625	28
Exterior Crib Basket Width	N/A	30
Interior Crib Basket Length	52.375 ± .625	52.6
Exterior Crib Basket Length	N/A	61
Distance Between Top of Rail and Lowest Mattress Height	≥ 26	29
Distance Between Top of Rail and Middle Mattress Height		19.125
Distance Between Top of Rail and Highest Mattress Height	≥ 9	10.375
Distance Between Slats (No Applied Force)	≤ 2.375	2

Figure 25: Crib Basket Dimensions



Adjustable Legs to Support Crib Basket

The leg design chosen to raise the crib basket off of the floor is simply a rectangular prism. This design was chosen for its stability, ease of manufacture, and adaptability to the adjustable crib height feature. With the design as illustrated in Figures 26 and 27 on p. 26, the height of the crib can be chosen by locking the crib into one of the various holes within the legs. The height of the top of the crib in the different height settings are 29, 34, 37 and 40 in. with the 29 in. setting referring to the case when the crib is sitting on the floor with the legs completely recessed into the body. A display of the crib in its traveling or storage position can be seen in Figure 27 on p. 26.

Reasons for Leg Design: This type of adjustable leg was introduced to add to the design some of the convenience of a drop-down railing without the danger of one. The design allows parents or care-givers who are shorter in height to be able to reach into the crib with more ease than they could with the taller cribs that are currently on the market. Similarly the crib height can be adjusted so taller parents or care-givers could use it easily. In addition, the legs are removable/recess into the body to make shipping, travel and storage the crib easier and more economical. Additionally this means that the components of the crib can always be kept together to reduce the possibility of losing any parts. Dimensions for the crib legs are shown in Figure 28 on p.26.

Reason for Lack of Casters: Unlike many current crib designs, the final design will not have casters on the legs. This was decided because, though the crib may be harder for a parent to move, it will also be difficult for an older child to move and thereby harm him/herself.

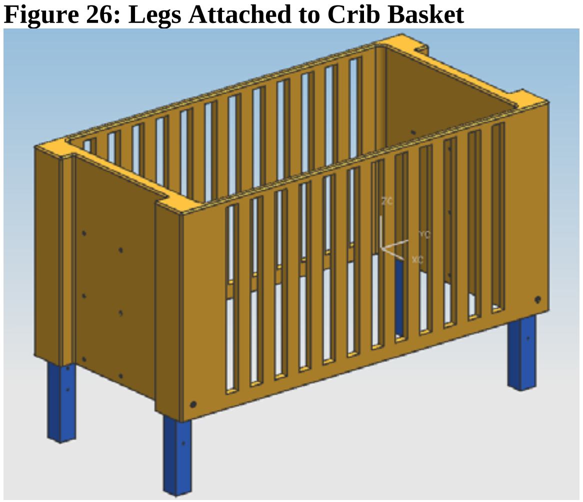


Figure 26: Legs Attached to Crib Basket

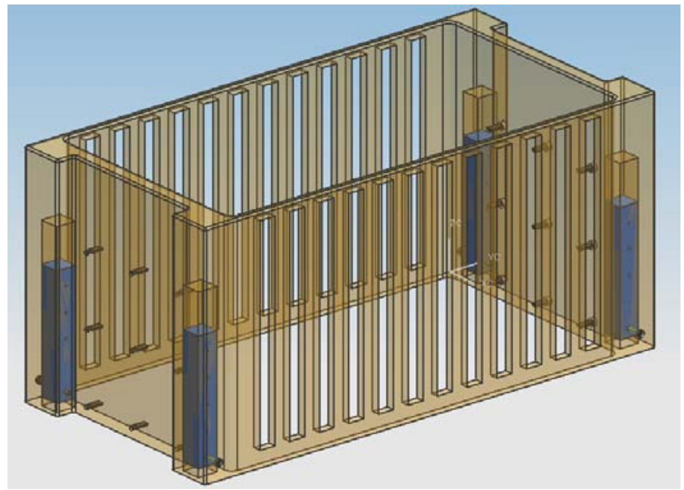


Figure 27: Crib Legs in Storage Position

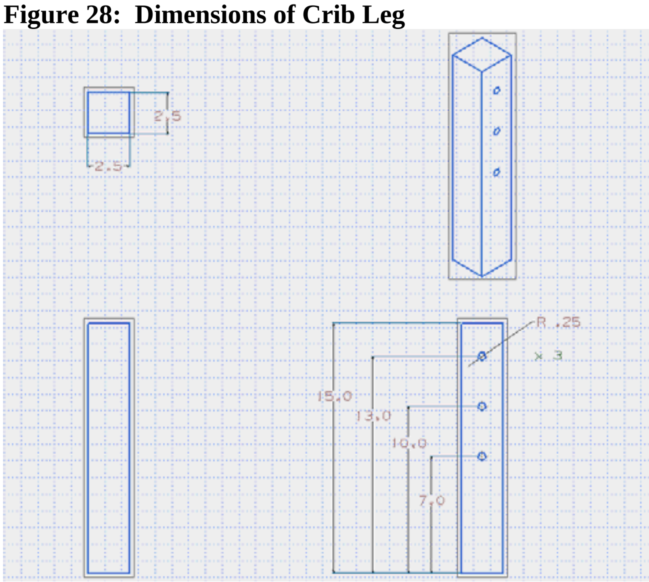


Figure 28: Dimensions of Crib Leg

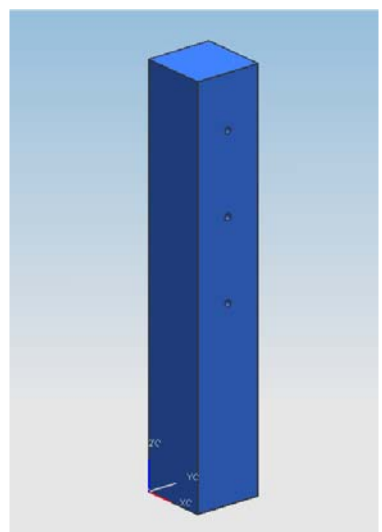
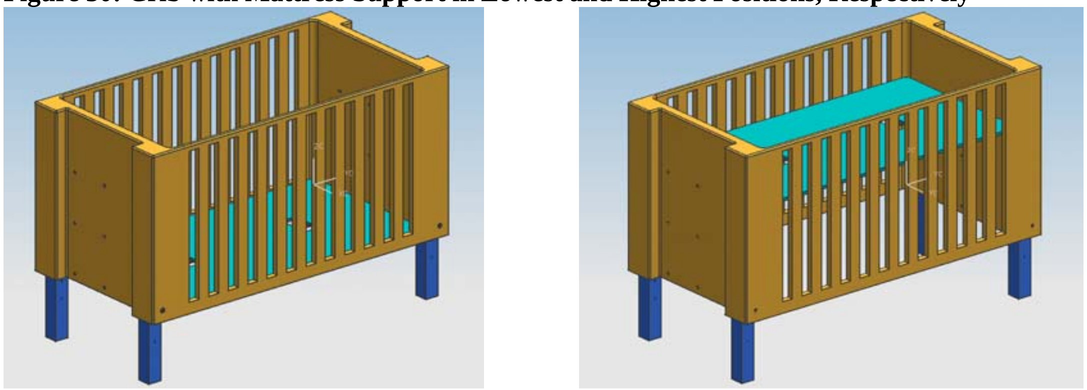


Figure 29: Adjustable Crib Leg

Adjustable Mattress Height Feature

The adjustable mattress height feature is currently standard on most cribs that are on the market today. This feature allows the crib to be functional from the time that the child is an infant until he/she is a toddler. At the highest level the infant will be at a comfortable height for the parents to reach, yet will still have enough railing to prevent them from falling out of the crib. As the child grows and learns to sit and then stand, the mattress can then be lowered so that the railing is still high enough to prevent the older child from falling or crawling out of the crib (See Table 3 on p. 24 for dimensions). The lowest and the highest height are determined by government regulations. CAD figures illustrating the mattress in its highest and lowest positions can be seen in Figure 30 on p. 27.

Figure 30: Crib with Mattress Support in Lowest and Highest Positions, Respectively



Mattress Support

The last aspect of the final crib design is the mattress support. The team chose to use three stainless-steel beams and a plastic mattress support board as illustrated in Figure 31 on p.27 for its mattress support. The T-shaped beams to run the length of the crib and are secured in the head and foot boards. The mattress support board is then placed on top of the beams. On one end of the beam, there will be a threaded hole into which a metal screw will pass. This screw will pass through both the crib body and then the hole within the T-shaped beam until is it flush with the crib wall as shown in Figure 33 on p. 28 Attached to the other side of the beam (Figure 34 on p. 28) is a circular stop along with a ring which will act as a handle for removing the beam. Both the circular stop and the ring are larger in diameter than the T-shaped bar's largest dimension and countersunk into the crib body. Thus, the beam will be inserted into one side and the screw will lock it place on the other side. The combination of the screw and the circular stop prevent it from moving laterally.

The mattress support board, shown in Figure 35 on p.28 will be of the same material as the crib basket (Bapolene® Grade PP5026 Polypropylene, Extrusion/Injection Grade) and snugly fit within the crib basket. It will also have two cut-out handles. The dimensions of the mattress support board are shown in Figure 36 on p. 29.

Figure 31: Mattress Support Design

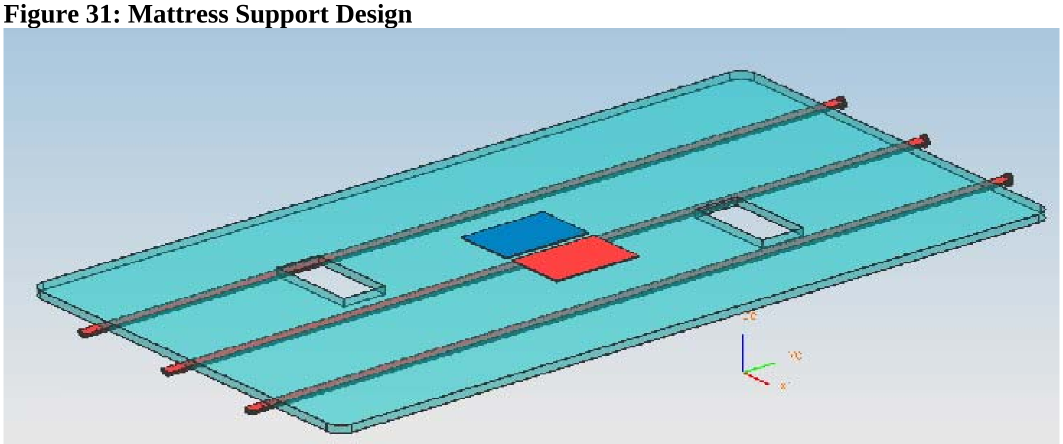


Figure 32: Screw Side of Support Beam

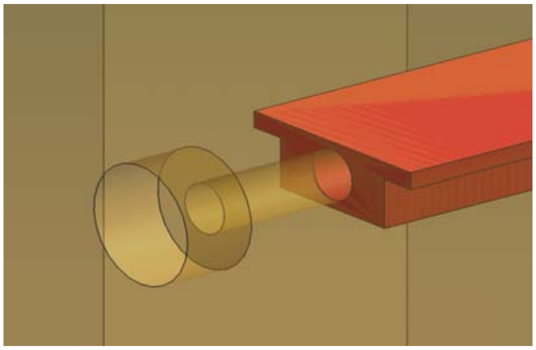


Figure 33: Screw Side of Support Beam

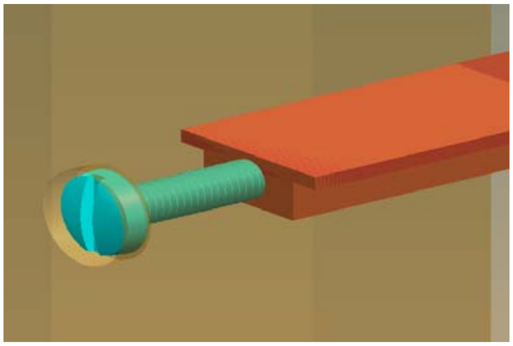


Figure 34: Ring Side of Support Beam

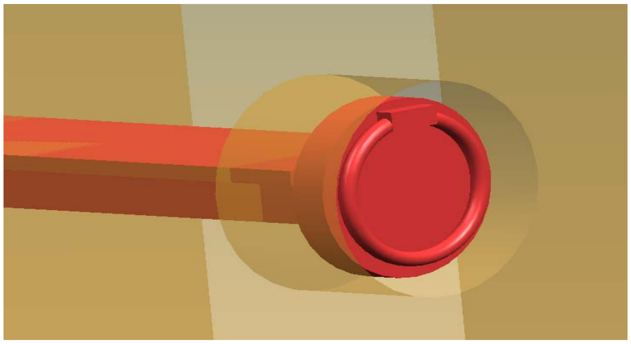


Figure 35: Mattress Support Board with Cut-out Handles

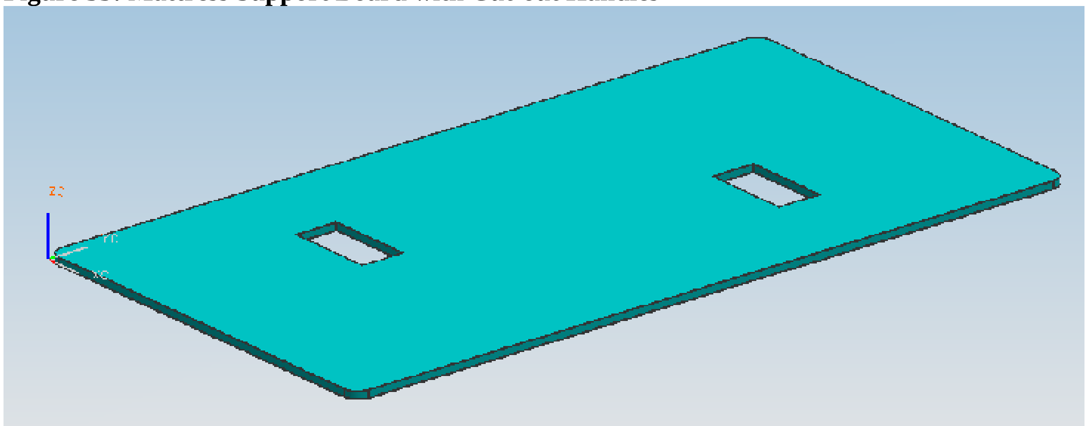
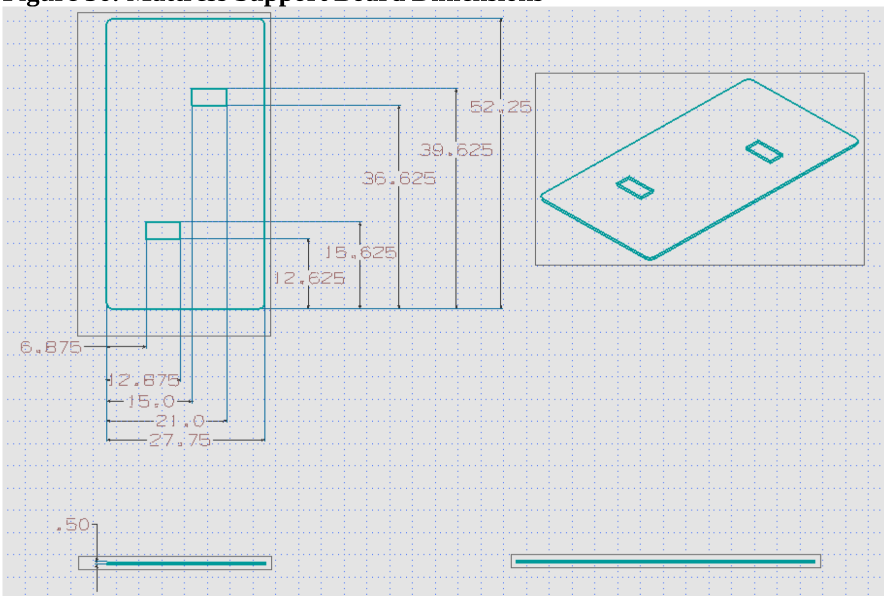


Figure 36: Mattress Support Board Dimensions

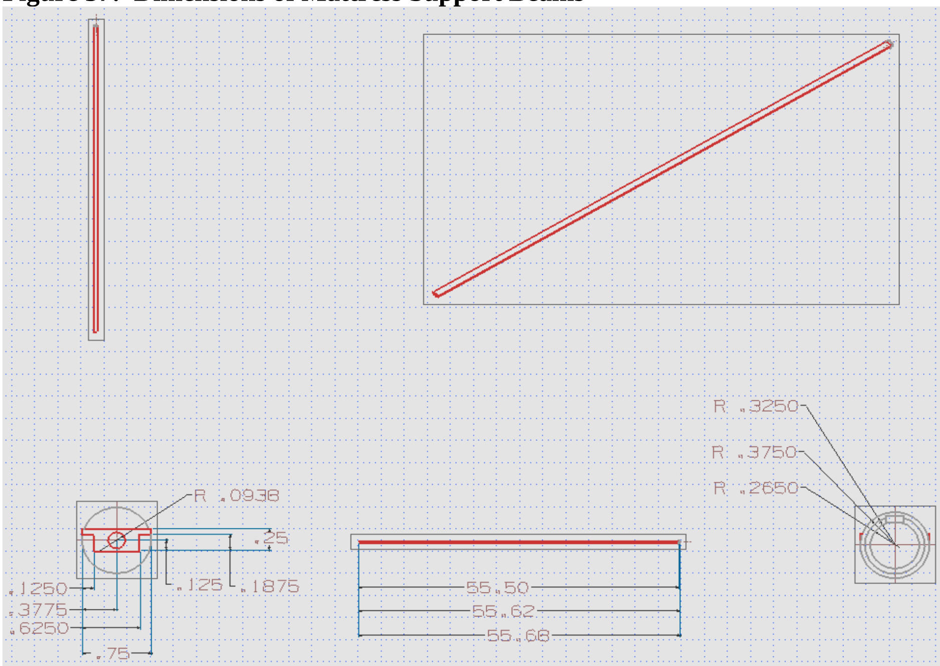


Reasons for Mattress Support Design: The primary reason three beams were chosen to carry the mattress support board because they dispersed the load from what had been four points on current crib designs to six. These beams will be made out of X10Cr13 Stainless Steel and their dimensions are shown below in Figure 37 on p. 30. Three beams also provide support and disperse the load of the child over a greater area of the mattress. The team chose to make the beams T-shaped because this shape eliminates material that would not carry a significant amount of the load. This was important because the team wanted to make each component as light as possible and as cost-effective as possible.

The countersunk screw and ring on either end of each of the three beams will serve as a built-in indicator to the user concerning the "tightness" of the hardware. Therefore, if anything is sticking outside of the crib basket, the user will know that they need to tighten one of the screws in the mattress support system. Unlike current crib designs, if a beam support screw did come loose the mattress support will still function safely and will at the same time indicate to the user the malfunction. In this design, the screw would have to come completely out of the beam and then the beam would have to move laterally the thickness of the crib basket wall for the beam support system to fail. Furthermore, even if one beam failed, there would still be two beams of support holding the mattress in place. In current designs the loosening of a screw is catastrophic because it can result in a slanted mattress, a gap, or even the complete collapse of the mattress to the floor.

A snug plastic mattress support board with a cut-out handle was chosen because it provided adequate support for the entire mattress. The mattress support board is only an eighth of an inch smaller in both its length and width than the interior walls of the crib basket so that any sort of motion of the board within the crib basket would be highly limited. In addition, the mattress support board can be easily removed from the crib using the handles cut out of the board. These are shown in Figure 35 on p. 28.

Figure 37: Dimensions of Mattress Support Beams



Method of Adjusting the Mattress Support: The first step to adjusting the mattress support height is to remove the mattress support board using the cut-out handles. The next step is remove the screw from the first beam, and use the ring on the opposite side of the crib basket to pull the beam out of the crib basket. This would be repeated for all three beams. Next, the beams would be passed through the crib body again at the desired height setting and the screw will be screwed back into the beam. This is also repeated for all three beams. Lastly, the support board is replaced on top of all three beams in their new height setting.

Countersunk Screws

The design will have seven countersunk screws. These screws attach the legs to the crib basket and lock the mattress support beams in place. The goal was to remove all hardware from the design, but the seven screws that remain are necessary. Four screws are used to attach the legs to the crib body. These bolts will also be purchased from Bolt Depot and they will be the Hex Head Cap Screw which will be 5 in. in length with a threading that is approximately 1 ½ in. in length with a 1/2"- 20 thread [18]. Three screws are used to secure the mattress support beams. The screws that will be used to do this will be purchases from Bolt Depot and are 1 ½ in long with a 10-32 thread [19]. The screws and bolts that will be used in the final design can be seen below in Figure 38 and 39 on p. 31.

Because the crib still has some hardware, all of the screws are countersunk. Countersinking the screws makes them flush to the crib basket. When the screws are no longer flush to the crib body, the user will be alerted that a screw is not tight enough. Also if the screws are countersunk, there is no longer the danger that a child or parent will get hurt on the screw.

Figure 38: Bolts used to Attach Legs

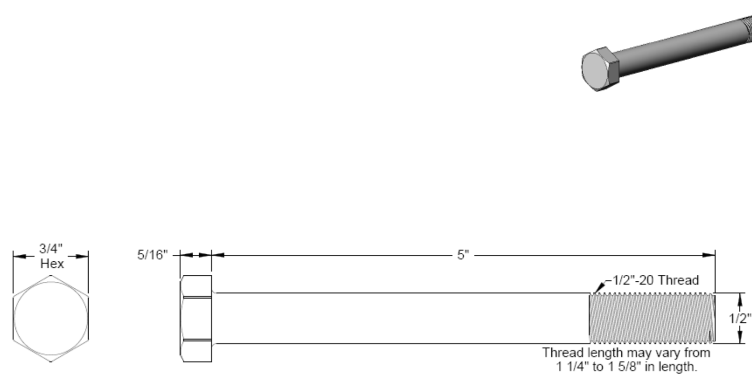
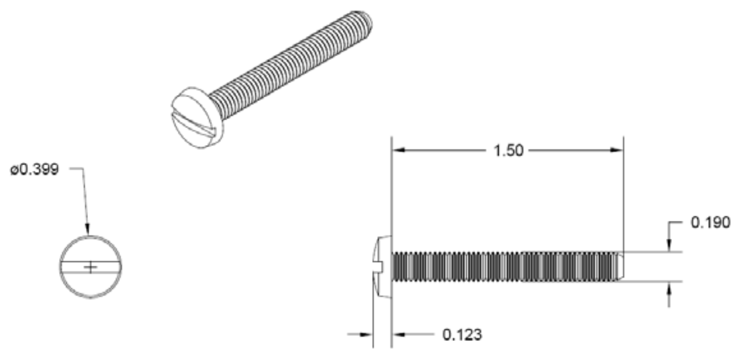


Figure 39: Screws used to Attach Beams



Inscribed Instructions

The crib assembly instructions will be inscribed on the crib itself so that they can not be lost. This will be done by printing the instructions onto the mattress support board. With this addition to a crib, a consumer can reuse the crib with another child and still have all the information on how to assemble the crib. In addition, the outside of the headboard will be inscribed with the following: "WARNING Infants can suffocate on soft bedding. Never add a pillow, comforter or padding. See mattress support for additional warnings." The mattress support board will include all the crib warnings inscribed in it as well. Crib warnings visible from the outside of the crib will soon be required on all cribs by law [8].

PROTOTYPE DESCRIPTION

The prototype is not an exact representation of the final design. Since the crib is designed to be injection-molded, the resources are not available to make a full-sized functioning prototype. Injection-molding is extremely expensive; therefore, the prototype crib was made via rapid prototyping. This reduced the variety of materials available to make the prototype. Hence, the material of the prototype was not the same as that of the final design. In addition, as a result of budget constraints, the prototype was a scaled down version of the final design. Also, due to budget constraints, a shortened prototype of the support beam was also manufactured. The following paragraphs will describe the two components of the prototype in detail, specifically their relationship to the final design, and lastly, how the two prototypes show the most important elements of the final design.

Scaled Down Rapid Prototype
The following sections will explain the scaled down prototype made via rapid prototyping.

Prototype Dimensions: The prototype is a scaled down version of the final design. It is exactly 15% of the final design dimensions as listed in Table 2 on p. 20.

Material of Prototype: Rapid prototyping can only been done with a limited number of materials. As a result of budget constraints, the prototype was not made of a plastic, but rather of plaster with an epoxy fill. The rapid prototyping was completed by the 3D Printing Lab in the Duderstadt Center at the University of Michigan.

Prototype Hardware Mechanisms: Since the prototype is made of plaster, it is difficult to place and use hardware in such a way to make a fully functioning prototype with that material and at a 15% scaling of the full-sized model. Therefore, the bolts used to secure the legs were illustrated with bass wood dowels and the support beams are not locked into place with any sort of hardware.

Mattress Support Beams: The prototype has support beams made out of wooden dowels to show how the mattress is supported in the crib. They are not made of the same material or shape as the final design and thus do not have the same strength. Further, the wooden support beams do not display the restriction of lateral motion from the final design; neither is there a ring with which to remove the beams due to their small size.

Crib Basket: The crib basket is a 15% scaled down version of the final design except for the holes for the mattress support beams and the leg screws. The holes were made larger so that beams would be able to support the weight of the support board and the leg screws could support the crib weight.

Support Legs: The support legs for the prototype were made to be hollow to cut down on rapid prototyping costs. Further, these holes were enlarged to make the legs and the bolts to attach the legs more manageable for the prototype.

Shortened Mattress Support Beam
Since the detail of the final design's mattress support beams can not be seen properly at 15%, the team manufactured a replica of the final design's support beam. It maintains the cross-sectional dimensions of the beam and the circular stop and ring, but not the length of the actual beam. Additionally, the material used was aluminum, not the stainless steel specified in the material selection section. Lastly, the prototype used a flat head screw from the ME450 shop rather than the one seen in the final design because of the minimum quantity and therefore cost of screws that needed to be ordered from McMaster Carr extremely high.

Main Aspects of Prototype
The prototype was used to illustrate four main aspects of the final design: 1) a one piece crib basket, 2) the adjustable legs, 3) a new adjustable mattress support system, and 4) a reduction in the number of hardware components. Through rapid prototyping, the consumer was able to see the one piece design of the crib basket that would be achieved by injection-molding in the final design. The adjustable legs will show the innovative components of the final design. In addition, the two illustrations of the mattress supports beams, one shown in the rapid prototyped model and the other manufactured by a lathe and a mill, demonstrates the structure, stability, and minimal use of hardware of the final design. Therefore, the prototype, while not complete, will convey the primary characteristics of the final design.

MANUFACTURING PLAN

The manufacturing plan consists of two parts, the manufacturing of both prototypes and the final design. The manufacturing of the prototype displayed at the design expo consisted of two different plans for the two parts and is discussed further below. The manufacturing plan for the final design is also included in the following section.

Prototype Manufacturing Plan
The prototype manufacturing plan consists of two parts, the 15% scaled prototype of the final crib design and the shortened mattress support beams. They are both further explained below.

15% Scaled Prototype of Final Crib Design: The crib prototype was made by the 3D printing lab that used rapid prototyping to produce a model of the design that was 15% of the size of the actual crib design. This prototype showed the main concept of the final crib design, which is the fact that the crib basket was made out of one piece of plastic. In order to have a 3D printed prototype, a complete CAD model was sent to the 3D Printing Lab in the Duderstadt Center at the University of Michigan. The prototype was then given an epoxy finish in the 3D printing lab. Finally, the team sanded all of the parts and purchased and cut wooden dowels for the mattress support beams.

Mattress Support Beam Prototype: The team displayed the mattress support beam by manufacturing a dimensionally correct T-beam of shortened length and different material. The prototype beam was made out of a scrap aluminum bar which was milled into the correct dimensions in the ME 450 machine shop. This was done by using a 0.25 in. end mill running at 1200 rpm. In addition to this bar, the stopper at the end of the beam was also made out of scrap aluminum found in the ME 450 machine shop. It was then given the correct diameter using the lathe. The T-bar and stopper were then welded together. A ring was purchased and then also welded to the stopper. The T-bar shaped end of the beam also had a threaded hole for the screw. This was made using a 3/8 in. drill bit.

Final Crib Design Manufacturing
The body of the crib design will be manufactured using injection molding. This will be done by initially creating molds for the crib basket, mattress support board, and legs. Once the molds are completed, the crib will be manufactured by injection molding using polypropylene plastic.

Although the initial molds for these parts will be expensive, this will be a low cost manufacturing method as injection molding is a cheap manufacturing method and will lower the cost of production.

The mattress support beams will be purchased from a supplier and then will be welded together with the circular stopper as was done in the beam prototype. They will be made of stainless steel and the holes in their end will already be threaded. The additional screws will be purchased in mass quantities from a supplier. If possible, standardized t-beams of the same steel could be substituted to reduce manufacturing costs.

In addition, all other hardware required will be purchased in bulk from a supplier such as McMaster.com. Also, within the manufacturing of the final crib, some finishing steps (such as sanding) may be required.

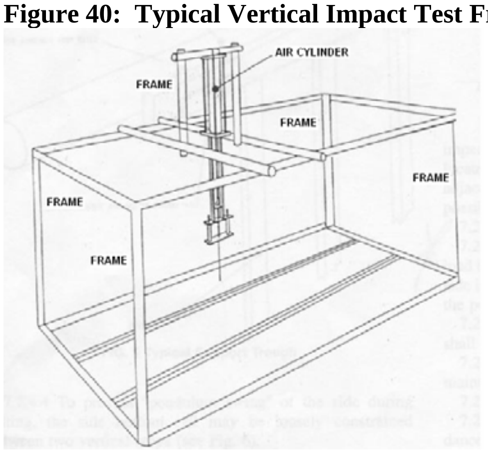
VALIDATION PLAN

Because the team could not manufacture a full-functioning prototype, relevant testing could not be performed on the prototype. However, if a full-functioning prototype was available, many tests would be completed to validate the design. Required tests are outlined by the American Society of Testing and Materials (ASTM) [1]. The tests include a mattress support system vertical impact test, crib side tests that include a side cyclic and static test and crib side spindle/slat torque test, and a mattress support system test.

Mattress Support System Vertical Impact Test

Based upon the ASTM testing standards, the mattress support system vertical test as shown in Figure 40 on p. 34 is used to evaluate the structural integrity of the crib assembly. The test is preformed by repeatedly dropping a 45 lb weight onto a foam pad supported by the crib mattress support system. The weight should be able to free fall 6 in. when the mattress support system is in its lowest position. This should be done for 500 cycles within 0.25 in of the geometric center of the mattress area and for 100 cycles done simultaneously in opposite corners 9 in. away from the corners.

Figure 40: Typical Vertical Impact Test Frame



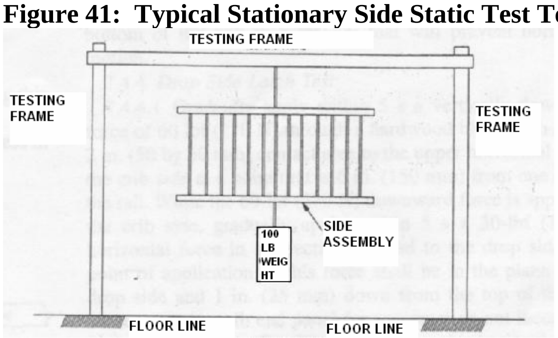
Crib Side Test

The crib side test would be conducted following ASTM testing standards [1] and consists of three different tests. They are the stationary side cyclic test, stationary side static test, crib side spindle/slat torque test.

Stationary Side Cyclic Test: The stationary side cyclic test is conducted by hanging the crib basket in a stationary position which prevents pendulum-like swinging. A rubber stopper is placed on the bottom rail of one of the crib sides between two spindles as close to the center of the rail as possible. Next, a 30 lb. weight is dropped 250 times on the rubber stopper from a height of 3 in [1].

Stationary Side Static Test: The stationary side static test is conducted by again hanging the crib and then applying a 100 lb. weight to the center of the bottom rail of the crib. The weight would be applied gradually for a period of 5 seconds and then would be maintained for an additional 30 seconds. The testing setup for this test is shown below in Figure 41 on p. 35 [1].

Figure 41: Typical Stationary Side Static Test Testing Frame

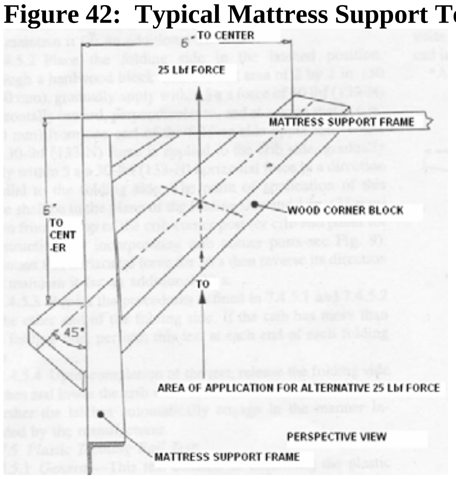


Crib Side Spindle/Slat Torque Test: The crib side spindle/slat torque test is completed by applying a torque of 30 lbf-in at the geometric midpoint of each slat. This is defined by the ASTM testing standards [1].

Mattress Support System Test

The mattress support system test is conducted without a mattress in the crib. The crib is prevented from upward motion during the test as a force of 25 lbf is gradually applied to the mattress support for 5 seconds and then maintained for an additional 10 seconds. This force is applied to the mattress support system through a diagonally positioned test member such that the centerline of this test member contacts the underside of the mattress support at points 6 inches from the corner of the support. This setup can be seen below in Figure 42 on p. 36. This test only needs to be done for one of the mattress supports as all the supports are the same.

Figure 42: Typical Mattress Support Test Frame



ENGINEERING CHANGE NOTICE

There were a few changes to both the prototype and final design.

Prototype Design Changes

There were very few changes between the prototype described in Design Review #3 and the final prototype. These changes are as follows. The support beams are not made of plaster; they are 3/16 by 3/16 bass wooden dowels. All of the holes within the plaster crib had to be made larger. The holes were made larger so that beams would be able to support the weight of the support board. A beam that was 15% of the full size would not be able to support the weight of the support board. Additionally, the legs were made hollow to conserve material and decrease the cost of the manufacturing process. Both the leg bolts and the support beam screws are also made from the same bass wooden dowels. The leg bolt that is presented alongside the prototype is the exact one that is described in Design Review #3. The screw used in the support beam prototype is one from the ME Student Manufacturing Lab instead of the one described in Design Review #3. The screw from the Manufacturing Lab has a Phillip's head and the one described in the report has a flat head.

Final Design Changes

The only design change to the final crib design was to increase the diameter of the circular stop on the mattress support beams from ¾ in. to 1 in. The reason for the increase was to ensure that any sized finger could fit within the ring.

DISCUSSION

The main goal of the crib design was to prevent gaps from forming between the mattress and crib side walls that is often caused by hardware failure. This was accomplished by making all four walls of the crib one piece. The design also reduced the number of small pieces used in the crib. The only screws are used to attach the legs to the crib and secure the mattress support beams. Although the design did not include a drop down railing, it catered to users of varying heights by allowing the crib height to be changed. The new mattress support system supported the mattress more evenly which reduced the stress experienced by each joint. This was done by supporting the mattress by three beams which had a total of six joints instead of four hinges with four joints.

Although the crib design has many strong points and is expected to meet all engineering and customer specifications, improvements could be made to the design. The most significant improvement would be to reduce the weight of the crib. Currently the crib weighs 250 lbs. which is well over what a single person could lift by themselves. Either using a different material or somehow using less material could reduce the weight of the crib. If either of these changes were made, analysis would have to be performed to ensure the structural stability of the crib. The next improvement that could be made is in reference to the ease with which the crib could be transported or stored. Because it is hard to store, many families would be unable or unwilling to keep the crib between children and therefore it may not be worth their investment. Transporting the crib could be very expensive as well because of this the price of the crib may increase. The crib is also not very aesthetically pleasing. Although the crib design allows for different colors of plastic to be used, it still may not be aesthetically pleasing for a potential consumer.

RECOMMENDATIONS

For Kids In Danger and future teams, there are a couple aspects of the design that should be addressed. A question asked multiple times during the Design Expo was, "how would this product compete on the competitive design market?" The final design was not made to be aesthetically pleasing to the consumer. Consequently, it may not be as appealing as, for example, a cherry wood crib. Therefore, a future team could try and make the design more marketable to the public while maintaining its safety features.

The final design's weight is also a feature that could be a focus in redesigning. The weight of the crib is significantly higher than most cribs on the market today. The majority of the cribs on the market weigh less than 100 lbs. However, the final design crib including the legs, crib body, T-beams, and mattress support board weight 250.29 lbs. As a result, a future team should try to minimize the weight of the crib so that it is more manageable without compromising the safety features of the existing design.

The size of the final design could also be an aspect that a future team addresses. Since the crib body is one piece, it makes the crib difficult to store and transport. Transportation costs are a major component in business and manufacturing. Thus, a future team could find a way to optimize the manner in which the crib could be stored and transported to minimize cost or to find additional uses for the crib while it is storage.

CONCLUSIONS

Kids In Danger is a non-profit organization that brings awareness to the dangers of children's products. The Safe Crib team was introduced to the hazards of baby cribs as result of this organization. After researching the problem, the Safe Crib team found that the most significant cause of child injury was due to hardware failure and human error. To address this issue, they aimed to design a crib that increased the safety of the crib and the ease of assembly while meeting all government regulations.

The final design of the crib included an injection molded, one-piece crib basket made of Bapolene® Grade PP5026 Polypropylene, Extrusion/Injection Grade. The material was chosen because of its current use in child car seats and its FDA approval for use in food container products. This insured the safety of the crib material for use around children. Since the body is one piece there is no drop-down railing. Therefore, the team decided to make the leg heights adjustable to improve the cribs usability for parents of various heights. The legs of the crib were made of the same material as the crib basket and are attached to the crib by an 18-8 Stainless Steel Hex Head Cap Screw. The mattress support system was redesigned to include three T-shaped beams made of X10Cr13 Stainless Steel that extend across the length of the crib. This material is also used in medical devices, making it safe for use in the crib design. Located at one end of the T-beam is a circular stopper with a ring attached for removal. At the other end of the beam there is an 18-8 SS Binding Head Slotted Machine Screw used to secure the T-beam to the crib body. There are three different mattress height settings that are regulated by the United States government. The mattress sits on top of a mattress support board. The mattress support board is made of the same material as the crib body and includes two offset cut-out handles for the ease of removal. Further, inscribed warnings and instructions are located on the mattress support board to ensure that the user does not misplace them.

The prototype of the final design was shown at the University of Michigan Design Expo on Thursday, December 7, 2006. The prototype was made of plaster by the University of Michigan 3D Printing Lab. It was 15% of the final design size due to financial restrictions. Also, a model T-beam was showcased with the same dimensions as the final design except for a shortened length. The prototype T-beam was made of aluminum rather than stainless steel. This prototype showed the main aspects of the final design: the one piece crib body, the minimization of hardware, the adjustable mattress and leg heights and the redesigned mattress support system.

From consumer feedback at the Design Expo, there are several recommendations that the team would make for future teams. Since the crib is made by injection molding, it is not as aesthetically pleasing as many of the cribs that are currently on the market. Therefore, a future team could design the crib to be more marketable for the consumer while maintaining this crib design's safety features. In addition, the weight and size of the final design crib could be redesigned by a future team. The weight needs to be minimized since it is approximately 150 lbs. greater than the average crib on the market. The size of the crib needs to be addressed with respect to transportation and storage of the crib.

The Safe Crib team feels that the final design meets all customer and engineering specification goals. Although some improvements could be made, engineering analysis shows that it is safer than the cribs on the market today.

ACKNOWLEDGEMENTS

The success of our crib redesign project was due in large part to several people who were generous enough to contribute to our project. A special thanks needs to go out to Nancy Cowles and the organization Kids In Danger. Nancy was the project sponsor and initially brought the problem to our attention. Nancy was a great help in getting the project started with a conference call and then giving feedback after watching the first design review presentation. In addition, Nancy was always available through email to give direction and feedback on the crib redesign.

Professor Wineman was another vital contributor to the project. As the project section instructor, he was frequently available to meet us and to give us feedback and suggestions. In addition, he played a large role in determining the best way to analyze the stability of the design.

The manufacturing of the crib prototype would not have been possible without the 3D Printing Lab in the basement of the Duderstadt Center. Their work was greatly appreciated. Bob and Marv from the ME 450 machine shop were also contributors in guidance on producing the mattress support beam prototype. They were also available to weld the beam parts together.

Lastly, we would like to thank Professor Shih for his management of the class, Adrian Vine for his organization and help in the X50 lab, and Kathy McCrumb and Trikia Bennett for thier help with financial reimbursements.

INFORMATION SOURCES

The following sections discuss the preliminary informational and manufacturing sources, as well as missing information.

Preliminary Information

Preliminary information was obtained from www.KidsInDanger.org [14], the United States Consumer Product Safety Commission (CPSC) [4-8], the American Society of Testing and Materials International (ASTM) [1], and personal interviews. The CPSC provided the team with the specific government regulations for the design of cribs and a summary of the problems associated with cribs including recalls and safety hazards that have caused injuries and deaths of babies and infants as a result of cribs. ASTM provided the team with recommended crib testing standards. The Kids In Danger website provided pertinent information regarding product hazards, relevant news publications, and programs to help keep babies safe in cribs. A conference call with the Kids In Danger Executive Director, Nancy Cowles, took place on Thursday, September 14th, 2006 in which the primary cause of concern for crib safety was discussed. Furthermore, the team was furnished with incident records of injuries and deaths of babies from cribs from Nancy Cowles. Lastly, the team consulted a former child furniture store owner, Mary Currie [9]. She was able to share with the team her experience as a retailer who sold cribs for over 10 years.

To gain further understanding of the cribs that are currently on the market, the team traveled to the retailer *Babies "R" Us.* While there, the team interacted with and took pictures of several of the cribs on the market today. An associate in the store named Jonathan was able to provide valuable information to the team regarding recalls and the main problems that the company and its customers currently face. In addition, the *Babies "R" Us* website has been used to determine benchmark prices and styles for cribs currently on the market.

Manufacturing Information

The team has started the process of contacting various manufacturers to obtain quotes on how much it would cost to generate a model of the prototype. The companies that have been contacted are the 3D Printing Lab in Duderstadt Center, Cideas Inc., Accelerated Technologies Inc., Xpress 3D and Materialise. These companies have all responded to requests for a quote for the prototype with the price that they would charge to produce a prototype. The current quotes range from $150 to $1,500. These prices have given the team a general idea of how much it could possibly cost to have the prototype generated by an outside firm.

The team completed extensive searching to determine the types of lifting mechanisms available on the market to use for design concept #5. The majority of the searching took place via the internet. In this internet searching, the team realized that there was no mechanism on the market already that would perform the task that was desired in the scale desired. The majority of the already existing mechanisms were for applications in which several tons were being lifted, not 25-50 pounds. To further research the possibilities, the team visited a hardware store to see if there was anything there that could meet their needs. The team talked with a member of the staff at the hardware store to inquire if they had anything there that would be able to lift 25-50 pounds from beneath. Once again the only products made for lifting were made for lifting several tons and themselves weighed several pounds.

While generating the CAD model of the prototype crib, the team consulted several sources. The main source consulted were the guidelines provided by the CPSC for the construction of full-sized cribs. Additionally, the team made a survey of cribs and mattresses on the market to aid in choosing appropriate dimensions for the crib. Also, suggestions from the staff at the 3D Printing Lab in Duderstadt Center aided in generating a design that was more economically conservative.

Material Selection

The team researched the type of materials that are currently used in child products, however, specifics on these materials was difficult to find because of company privacy policies. They were able to find that the plastic most often used to make child car seats is impact copolymer polypropylene [13]. They then assumed that this material was strong, safe to use around children and would not release toxins into the air that could harm the child. The team found a type of impact copolymer polypropylene that was used in child safety products and was also safe to use around food which they determined to be a good material to use in the crib design. They were able to find this material at the material property data website MatWeb [2]. The material chosen to make the mattress support beams was also selected from MatWeb [15]. It was known that stainless steel was a non-toxic metal and the selected material is used for medical purposes so we knew that it would be safe to use around children. In addition, the properties of this steel met the strength requirements of our design.

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APPENDIX

Concept Generation- Minor Concepts

The following ideas could be incorporated as additional components to the five main concepts discussed on p. 5. Since the crucial goal of the crib design is to increase safety, the subsequent elements discussed below would help reach that goal.

Countersink Screws: Countersinking screws will eliminate the protuberance of the screw and show indication if installed properly. Any protruding or sharp elements located on the inside and outside of the crib increase the risk of injury for the child and others around the crib. From research done at *Babies 'R' Us*, the majority of the screws on cribs today are not countersunk. The overhang of the screw outside of the crib can cause injury to the child if they are walking or playing around the crib. Additionally, if the screws are countersunk, the user will have an indication if the screw is installed properly. When the screw is not installed accurately, it will stick out from the side of the crib signaling to the parent that it needs to be tightened.

Hardware Storage: The hardware storage is an idea developed to try and eliminate the loss of crib hardware over time. When a family had additional child, they tend to use the same crib as their first child. Hardware becomes lost in storage over the years, and the risk of the crib not being put together properly a second time is high. Therefore, a storage area would be placed next to each screw hole in the crib frame. This would provide an easily accessible area for the parent to place the screw. The hardware storage area would help to eliminate the misplacement of hardware over time.

Color-Coded Part Identification: Instructions are repeated uses of a crib similar to hardware misplacement. After the crib and its assembly instructions have been in storage, assembly instructions may be misplaced or have be thrown away. This leads to the improper assembly of a crib after the first child. The color-coded part identification would make the color of each screw correspond with its respective hole. Also, if two parts need to be connected, the edges that need to touch would have matching colors. The color-coding helps parents who have lost the instructions for the crib and are trying to assembly the crib correctly.

Figure A1: Pugh Chart of Six Generated Designs

		Design #1 Mesh Support and Mattress Cover	Design #2 Hardware Signal System	Design #3 Reconstruction of Slats	Design #4 Screw Locking System	Design #5 Hardware Free Crib Basket w/ Crankable Mattress Support	Design #6 Hardware Free Crib Basket w/ Bar Supported Mattress
Design Criteria	**Weight**						
Screws do not come out	3	0	+	0	+	+	+
User will not lose necessary small pieces	2	0	0	0	0	+	+
Assembly is simple	3	-	+	0	-	-	+
Design is simple	2	+	+	+	+	-	+
Reduces likelihood of child injuries	3	+	+	+	+	+	+
Minimizes number of small parts	2	-	-	-	-	+	+
Total		**0**	**9**	**3**	**3**	**5**	**15**

Figure A2: Quality Function Deployment

1	Not related
3	Weakly related
5	Neutral
7	Moderately related
9	Strongly Related

	Customer Requirements / Engineering Specifications	Normalized Importance to Customer (Relative Weight)	Weight of Crib	Force Mattress Support Bars Must Handle (30 sec)	Force Stationary Sides Must Handle (30 sec)	Fatigue Lifetime	Manufacturing & Development cost	Interior Length	Interior Width	Height 1	Height 2	Height 3	Interior Rail Height (Low Mattress Setting)	Interior Rail Height (High Mattress Setting)	Distance Between Slats	TOTAL - CUSTOMER REQUIREMENTS	RANK
USER-PERCEIVED QUALITY	Easy Assembly	4.0	7	1	1	1	5	3	3	7	7	7	7	7	1	140	3
	Meets Government Requirements	6.0	7	9	9	7	5	9	9	3	3	3	9	9	9	366	1
	Hardware does not Fail	5.0	3	9	9	9	5	1	1	7	7	7	1	1	1	255	2
	Simple Design	2.0	5	3	3	3	7	7	7	7	7	7	7	7	3	98	4
	Inexpensive	1.0	7	7	7	7	9	1	1	1	1	1	1	1	1	41	6
	Minimize Number of Small Parts	3.0	1	1	1	1	7	3	3	5	5	5	3	3	1	81	5
	Units		lbs	lbs	lsb	cycles	$	in	in	in	in	in	in	in	in		
	Current Crib Designs		65	25	100	250,000	100	52	28	N/A	37	N/A	26	9	2.5		
	Target (Plan)		65	25	100	250,000	150	52	28	34	37	40	26	9	2.5		
	Total		105	119	119	107	119	95	95	111	111	111	111	111	73		
	Rating (%)		8%	9%	9%	8%	9%	7%	7%	8%	8%	8%	8%	8%	5%		
	Ranked Importance		10	1	1	9	1	11	11	4	4	4	4	4	13		

Figure A3: Bill of Materials

Quantity	Item	Source	Catalog Number	Cost
1	18-8 SS Hex Head Cap Screw 5” length, ½”-20 thread, ½” diameter	Bolt Depot*	5297	$5.97
1	18-8 SS Philips Head Machine Screw 10-32 Thread, 1-1/2” length	ME 450 Machine Shop	N/A	$0.00
1	3D Rapid Prototype Printing	University of Michigan 3D Printing Lab	N/A	$181.30
1	Aluminum, rectangular stock	ME 450 Machine Shop	N/A	$0.00
1	Aluminum, cylindrical stock	ME 450 Machine Shop	N/A	$0.00
1	Aluminum Ring	Carpenter Brothers Hardware Store	N/A	$0.17

*http://www.boltdepot.com

See Attached p. 46 for **Figure A4: Gantt Chart**