Design and Prototyping of a Modular Human-Powered Swing Carousel

by

Emily E. TenCate

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2015

Signature of Author: Signature redacted
Department of Mechanical Engineering
May 18, 2015

Certified by: Signature redacted
Maria C. Yang
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: Signature redacted
Anette E. Hosoi
Associate Department Head for Education
Chairman, Undergraduate Thesis Committee

Design and Prototyping of a Modular Human-Powered Swing Carousel

by
Emily TenCate

Submitted to the Department of Mechanical Engineering

On May 18, 2015 in Partial Fulfillment of the
Requirements for the Degree of Bachelor of Science in
Mechanical Engineering

Abstract

The annual East Campus dormitory carnival at the Massachusetts Institute of Technology creates a unique learning experience by allowing undergraduate students to design and fabricate carnival rides for human riders. This thesis documents the design and fabrication process for a modular four-person swing carousel that was subsequently constructed in the East Campus courtyard. The ride was designed over the course of three months, focusing on administrative and technical constraints such as size restrictions, modularity, ease of assembly, and compliance with safety protocols. The final product operated smoothly for the entire duration of the carnival event (4 hours of continuous operation). The ride remained operational for a further two weeks of intermittent operation before its scheduled disassembly and removal. In total, over 250 riders used the swing carousel. From measurements made during ride operation, these riders experienced up to 0.68 g's of force in a radial direction and traveled at linear speeds of up to 15mph. A post-project safety review was also performed, and potential mitigation strategies for are described.

Thesis Supervisor: Maria C. Yang
Title: Associate Professor of Mechanical Engineering

Acknowledgements

Thanks are due, first and foremost, to all of the East Campus residents who helped me with design, fabrication, construction, and especially assembly: to Hat Mike for providing design consultation and sometimes sarcastic but frequently productive support throughout the project and for clever solutions to all the small problems; to Little James for the original idea and design suggestions; to the East Campus REX chairs (Phoebe Whitwell, Jes Parker, and Mike Flynn) for helping to streamline coordination with MIT's Environmental Health and Safety office and being responsible for procuring materials; to Cappie Pomeroy for teaching me how to use a waterjet and for explaining how waterjets can cut on the inside or the outside of a profiles and then staying up late to re-cut slots and tabs that didn't fit together; and also to Marvin Romero, Taylor Pearl, Andrew Chen, Trevor Mulchay, Stephen Face, Martin McLaughlin, Darci Reed, and Ian Martin for helping with the construction effort and, in Marvin's case, baking tiny motivational cupcakes; and finally to the many, many MIT freshmen who were excited to cut, drill, lift, and hold pieces of lumber in place.

Thanks also to Professor Maria Yang for her patience in advising this thesis; Craig Bryer of the MIT Environmental Health and Safety office for calculation confirmations and timely responses to email questions; Christoph Hahm and Kerstin John for buying me afternoon coffee and providing frequent design critiques and SolidWorks advice, and for not thinking it was weird when I stayed late at work on nice summer evenings to check CAD; Brandy Baker, the amazing course administrator for mechanical engineering at MIT, whose constant support and helpful deadline-reminder-emails played a large part in this project's completion; my lovely mom for reading and providing comments; and finally to Tej Kanwar, Lauren Herring, and everyone I live with for moral support and pushing me endlessly to finish things.

Contents

List of Figures

Chapter 1: Introduction and Background

The Massachusetts Institute of Technology (MIT) offers numerous opportunities for individual student enrichment. The East Campus dormitory, during a period of freshman orientation every fall called "Residence Exploration" (REX), invites dormitory residents of all years to participate in the design and realization of large-scale construction projects intended for human use. Typically, these construction projects include several human-powered carnival rides designed and built by current students. The annual carnival for which the ride was built is a staple of the East Campus dormitory's tradition. The goal of REX is to allow incoming students to explore potential living groups, including East Campus.

This thesis describes and documents the design and construction process for a modular, student-built four-person swing carousel, which was built in August 2013.

1.1 History of the East Campus Carnival

REX at MIT is a new construct. Freshman Orientation at MIT began in 1926 as "Freshman Conclave," originally focused on allowing freshmen to meet other members of their class. Freshman Conclave took place off-campus, at nearby camps in Massachusetts, until 1950, when the freshman class became too large to host at neighboring camps.[1] The Freshman Conclave was relocated to MIT's campus, renamed Freshman Weekend, and expanded to focus on introducing freshmen to MIT activities, including tours of research laboratories and dormitories.[2]

In 1968, the Intra-fraternity Council and the Dormitory Council voted to create "Residence/Orientation Week," or R/O Week, which was intended to focus specifically on helping incoming freshmen explore the variety of living groups at MIT.[3] R/O Week existed until 2002, at which point it was renamed and redefined as "Residence Exploration Week" (REX).[4]

Even prior to the official beginning of REX in 2003, dormitories participated in dormitory rush, wherein dormitories hosted a series of events in order to showcase their culture and encourage incoming freshmen to live in the dormitories.

East Campus (EC) is one of many on-campus dormitories at MIT. It is the second-oldest dormitory, and consists of two long, narrow parallel buildings with a large courtyard between them.[5] The courtyard is an ideal venue for events including large-scale temporary construction projects due to its central location and lack of landscaping.

East Campus participated in dormitory rush from the beginning of dormitory rush, but began to run its now-traditional carnival even prior to the official beginning of REX. In 1994, MIT's student newspaper mentions a carnival in the courtyard of East Campus. However, the carnival in its current incarnation, a week-long construction extravaganza in the courtyard, seems to have begun around the year 2000.[6]

Previous rides at the East Campus carnival have included the "spinning ride of death" from 2001, a swinging Viking pendulum ship, a double pendulum (which was declared unsafe for human riders), several rollercoasters, a hamster wheel, and a couch swingset.[7]

1.2 The swing carousel

The swing ride (also called "chair swing ride," "swing carousel," "swinger," and "Chair-O-Planes"; referred to here as "swing carousel") in its basic form is conceptually simple: it features swings hanging from chains or ropes, which rotate about a central pole. An external torque is applied to the rotating section to achieve rotation. In the earliest swing carousel rides, people or animals provided this using push bars for leverage; modern designs perform this action with a motor. The swings are not completely fixed to a rotating platform as in the traditional, floor-mounted platform carousel and are instead tethered only at the top. They are free to move about the main rotational column of the ride in reaction to the rotating motion: as the carousel rotates faster, the swings displace further from the central axis and therefore lift higher because they are tied in by cables.

1.2.1 Historical and modern designs

The swing carousel is a variation of a standard platform carousel. The carousel originated as a jousting game for training knights and eventually became popular as a ride for entertainment-seekers at fairs and gatherings in the early 18th century. The earliest carousels were not platform-based: animal figures, which riders sat upon, were tethered on chains, which spun out as the ride was rotated.[8] As platform-based carousels were developed in the 1900s, carousels of both kinds continued to be popular. The swing carousel has since appeared in many configurations.

The Nielsen's Grove Swing Carousel was built around 1880 at the Nielsen's Grove Park in Orem, Utah. The design featured a rotating pole embedded in a concrete footing containing rollers; the upper platform had swings attached to cantilevered beams which were supported by struts from below and an additional cable from above, as demonstrated in Figure 1. Power was provided by horse, attached to a pusher arm at a given radius from the center of rotation for leverage. The horse was driven in a circle to power the ride.[9, 10]

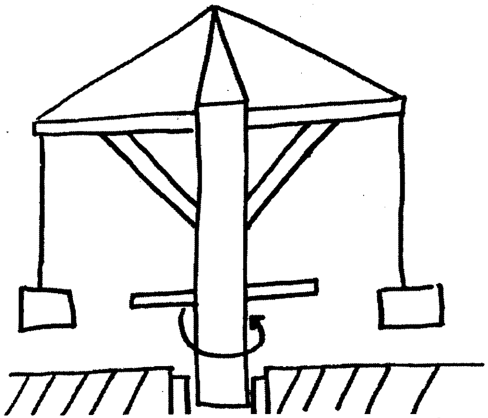

Figure 1: Design sketch of the Nielsen's Grove ride. The entire column (center) rotates on rollers in the ground, and the cantilever beam supports and push bar are attached to the central rotating column.

Idora Park, a Victorian trolley park constructed in Oakland, California, in 1904, also featured a swing carousel ride called the "Flying Swing." The Flying Swing had a similar basic design but added extra height to the ride with a central metal tower that had a rotating mechanism around 10 meters above the ground. Cables connected decorated swings to the rotating mechanism and additional struts and cables provided support for the swing arms. Figure 2 illustrates the Flying Swing's structure.[11]

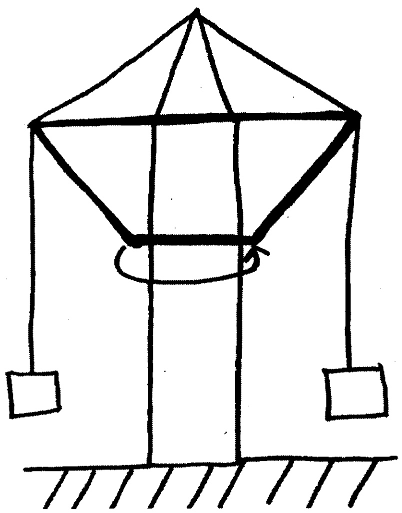

Figure 2: Design sketch of the Flying Swing's operation; the main column (center) was stationary, and the swings hung on long cables from a rotating rigid support structure at the top. This ride was significantly taller than the Nielsen's Grove ride.

The swing carousel is still a popular attraction, though modern manufacturers have added even more height and speed, and some versions feature a variety of complex motions including tilting and vertical oscillations. The largest modern manufacturer is Zierer, which calls the ride a "Wave Swinger," and patented a new design in 1983.[12] Zierer's largest commercially available Wave Swinger rotates at 40 ft above the ground and can move up and down and tilt.[13] The largest swing carousel currently in operation is the SkyScreamer at Six Flags in Arlington, Texas, which lifts riders 24 stories (242 feet) into the air.[14]

Despite featuring advanced materials and motorized rotation mechanisms, modern designs fundamentally retain similar structural layouts to their predecessors.

1.2.2 Fundamental physics of the swing carousel

The goal of analyzing the physical swing carousel is to describe the motion of the carousel in order to develop equations to calculate the maximum speed and angle of the swings, both with and without riders. These calculations are critical for designing the size of components for safety and structural integrity.

The actual physical system is very complex, but these calculations can be simplified by analyzing limiting conditions. The following simplifications are made in the calculations below: it is assumed that there is no air drag on the riders and no friction in the bearings, and that riders are even and balanced on the ride.

In a resting position, the swing ride has zero angular velocity, ω, and the angle of the riders from vertical θ is zero. When power is added, an external torque is applied with some angular velocity to the rotating mechanism. As the rotating mechanism carrying the swings begins to rotate, swings and riders also rotate about the central axis, and the tethered swings move outwards and upwards.

Central to the operation of a swing carousel is centrifugal force, which is the apparent force that causes the rotating swings to be drawn away from the center of the spinning mechanism. The riders, in a rotating and accelerating reference frame, feel as though they are being pushed away from the center of the ride. Even if there is no input torque, and the riders are rotating at a constant angular speed, they are accelerating because they are changing direction. Inertia dictates that riders should continue moving in a straight line, tangent to the circle of motion, but they are being pulled inwards by the horizontal component of the tension force in the rope. The force they feel pushing them outward is the force opposing the linear inertia. In an inertial reference frame, each rider's inertia propels him or her directly forward and away from the center of the ride, tangential to the circle of motion. However, because the riders are attached by a cable or rope of fixed length, moving farther from the center also forces them to move upwards.

As the riders move farther away from the center of the ride, the moment of inertia increases, making it harder to cause the ride to accelerate or decelerate. The moment of inertia for several point masses at some distance *r* from a rotational center is given by

$$I = \sum_i m_i r_i^2 \qquad (1)$$

where m_i is the mass of the rider.

In designing for human riders, it is also relevant to calculate the maximum angle to vertical that a rider could attain and what their maximum speed could be. In theory, the frictionless carousel discussed at the beginning of the section could achieve riders who are perpendicular to the ground, but there are physical limitations that should now be considered.

To calculate the maximum possible angle and speed a rider could attain with manual power, it is convenient to begin by looking at a single swing on a section of the swing carousel.

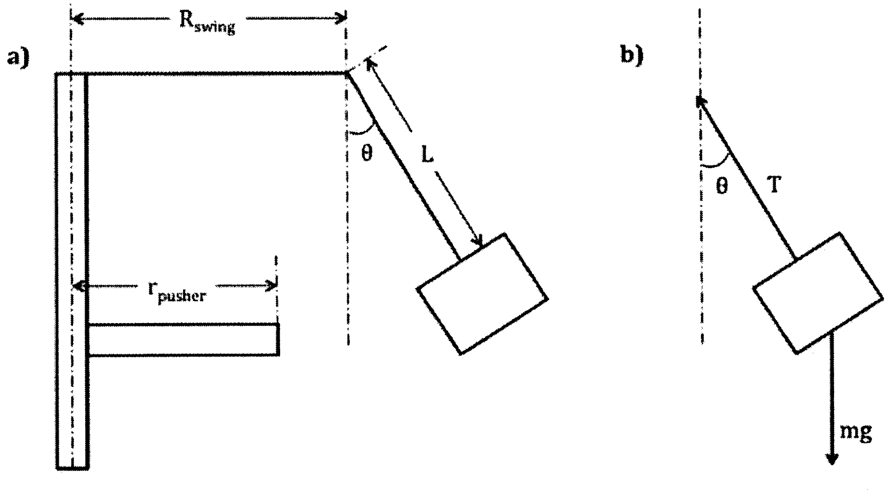

Figure 3: Free-body diagrams of a single swing. (a) Single swing on a swing carousel, with a push bar and swing; **θ** is the angle the rider rises from vertical as the ride spins, beginning at 0; (b) A free-body diagram for a single swing, with T as tension in the swing cable.

From an inertial reference frame, there are only two forces on the swing: tension from the rope and gravity. The tension vector, T, can be split into horizontal and vertical components and then a force balance can be completed in the x and y directions:

$$\sum F_x = T\sin\theta = \frac{mv^2}{r} \tag{2}$$

$$\sum F_y = T\cos\theta - mg = 0 \tag{3}$$

where r is dependent on the angle of the swing,

$$r_{rider} = R_{swing} + L\sin\theta \tag{4}$$

where θ is the rider's angle from vertical as depicted in Figure 3, and R_{swing} and L are respectively the radius from the center of the ride to the swing attachment point and the length of the swing cable from the ride to the seat, also depicted in Figure 3. Substituting r_{rider} into the above equations creates two equations that can be solved to eliminate the unknown tension in the cable T, and generate an equation to describe the linear velocity of the rider in terms of the angle of the swing:

$$v_{rider} = \sqrt{g\frac{\sin\theta}{\cos\theta}(R_{swing} + L\sin\theta)} \tag{5}$$

Interestingly, the mass of the rider cancels out in this equation: regardless of the rider's weight, the swing will spin out to the same angle given a certain velocity.

If there is a push bar for the manual power at a smaller radius (see r_{pusher} in Figure 6, above), using the relation $v=r\omega$, with $\omega = \omega$, the following equation can be used to relate the speed of the pusher to the speed of the rider (and thus to the angle):

$$\frac{v_{rider}}{r_{rider}} = \frac{v_{pusher}}{r_{pusher}} \tag{6}$$

where r_{rider} is dependent on θ as shown in equation 4, and v_{pusher} can be defined as the maximum speed of the pusher for purposes of finding a theoretical maximum rider speed and angle to the ground.

Push bars for manual power utilize the principal of leverage to allow pushers to be more effective, and are far from the center of the ride so that the pusher can exert less effort. When equation 6 is solved for v_{rider} and substituted into equation 5, the resulting equation relates the speed of the pushers, v_{pusher}, to the angle they attain from vertical, θ:

$$v_{pusher} = r_{pusher}\sqrt{\frac{g\tan\theta}{R_{swing} + L\sin\theta}} \tag{7}$$

where v_{pusher}, r_{pusher}, L, and R_{swing} are all design parameters. This equation, in conjunction with structural parameters and safety considerations, can be used to estimate the maximum displacement of the swing in the rider, as well as the tension in the cables and a limiting velocity for the pushers for a given desired angle from vertical.

Friction is not accounted for in these calculations. Because friction and air drag in the physical system are retarding forces, this equation provides an upper limit on the parameters of concern.

1.2.3 Known swing carousel safety issues

Swing carousels have myriad potential safety issues, especially due to the single-point rotation common to most designs. However, there is no apparent trend in reported accidents; most common are a variety of anomalous mechanical failures. In 2001, a Family Swinger (manufactured by Zamperla) in New York tipped over because it was not properly anchored.[15] In May 2008, several Yo-Yo Chair Rides (manufactured by Chance Rides) experienced point failure at the swing arm joint and the poles supporting the swings collapsed due to a suspected failure to complete regular maintenance.[16]

More recently, the seat back on a ride in Edinburgh fell off during operation; a man on a swing ride in China fell out of a spinning seat due to a cable failure and was catapulted away from the ride; a Serbian swing carousel split in two; a ride in Connecticut lost power and came to a sudden stop causing swings to collide; and in December of 2014, empty seats in a 200-ft-tall swing carousel in Cardiff began to swing out of sync due to heavy winds and reportedly crashed into other riders. The ride was stopped but not immediately lowered, and swings continued to crash in the heavy wind.[17,18,19,20]

Further safety issues specific to this project will be discussed in Section 2.3.

Chapter 2: Design and Calculations

The following section provides design logic as well as safety calculations for critical aspects of the modular swing ride.

2.1 Design goals and constraints

The construction of the ride took place during REX 2013; construction took place over a period of six days. Deconstruction was required to take place no more than two weeks later due to the high-traffice construction area and the beginning of the school semester, for a maximum operational period of 15 days. The ride was required to be operational for a minimum of 4 hours, preferably fully-functional for the entire duration of the 15-day period between completing construction and required disassembly and removal. As the ride was to be built outdoors in the courtyard of East Campus, the designer also needed to consider the possibility of inclement summer weather (heavy rain and winds) and account for irregularities in the ground upon which the ride was to be built.

The budget for the project was limited to $400. Primary structural materials were limited to wood because of cost and convenience; smaller parts were not limited in material type but rather by cost.

A safety plan was required for approval by the MIT Environmental Health and Safety Office (MIT EHS). Motors are prohibited by MIT EHS, so the ride was required to be human-powered while still being safe for both operators and riders.

Special consideration was also needed concerning the fabrication of parts and overall assembly of mechanisms: the construction crew was to consist of 6-10 undergraduate students with various experience levels in construction and assembly, and incoming freshmen were encouraged to participate in construction efforts. Thus, build plans needed to account for time spent in training in appropriate construction techniques and use of hand and power tools.

2.2 Specific design

The 4-person swing carousel was designed so that components could be constructed in parallel and subsequently assembled. Which necessitated building much of the ride on the ground. The design was therefore modular: split into an upper, rotating section and the lower, stabilizing base. Each section consisted of 2-3 major subcomponents.

Historical rotating mechanisms involved rotating the entire structure, drilling a deep footing hole, filling it with concrete, and placing rollers for rotate the structure (refer to Section 1.2.1). Unfortunately, a deep hole for the footing was not feasible given the temporary nature of the structure and its location in a high-traffic area. Instead, a self-contained stabilizing platform and an alternative rotational mechanism was developed, as shown in Figure 4.

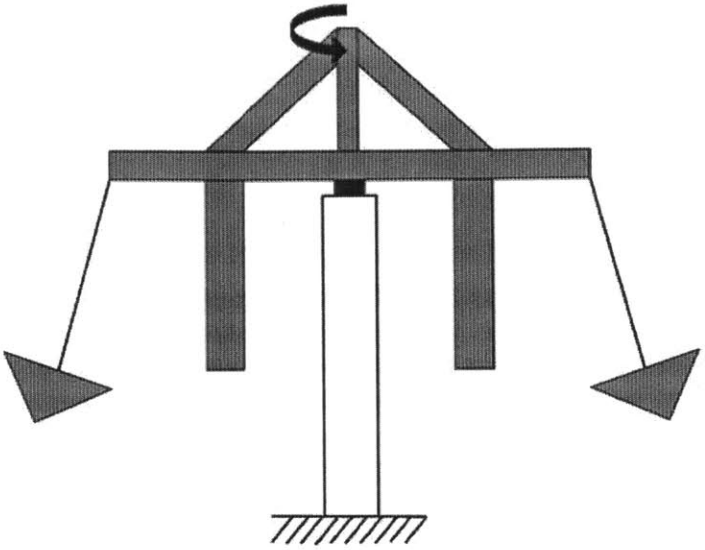

Figure 4: Functional diagram of modular swing ride design. The shaded (top) section rotates, while the white (bottom) section is fixed. Support beams are on top of the cantilevered beams, rather than below.

There are 5 critical sub-units for design consideration: (1) the cantilevered swing beams and the central rotational cage containing the beams, (2) the rotational element of the ride, (3) the structural base of the ride, (4) the pushing mechanism, and (5) the swings for riders.

2.2.1 Cantilevered beams and central rotational cage[22, 23]

The primary structural feature of the swing carousel is cantilevered beams with large end-loading. Safety and structural stability typically requires extra support to minimize deflection beyond fixing the beam at the end. Unfortunately, the modular rotational design hindered the placement of conventional support struts, which typically support the cantilevered beams from below since the main column is also rotating. In the design developed in this project (Figure 5), top supports were added instead so that they were affixed to the main rotating section while providing additional support for the cantilever beam.

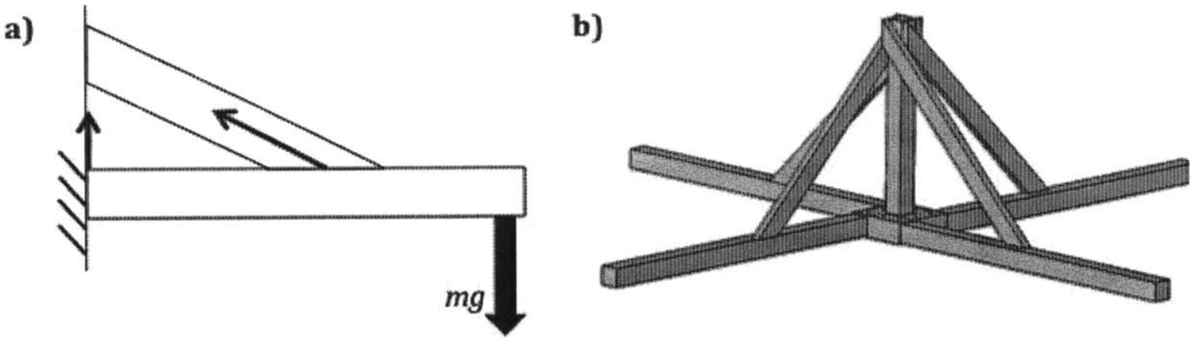

Figure 5: (a) Diagram of a single cantilevered beam with top support; (b) CAD model of 4 top-supported cantilevered beams in a swing ride assembly.

Beam-bending statics describe the loading on the cantilevered beams holding the swing. In order to avoid swings colliding with the center of the ride, the beams were six feet long. Eight inches of the 6-ft beam was enclosed in the central cage, leaving a free cantilever of 64 inches on the end (see Figure 6):

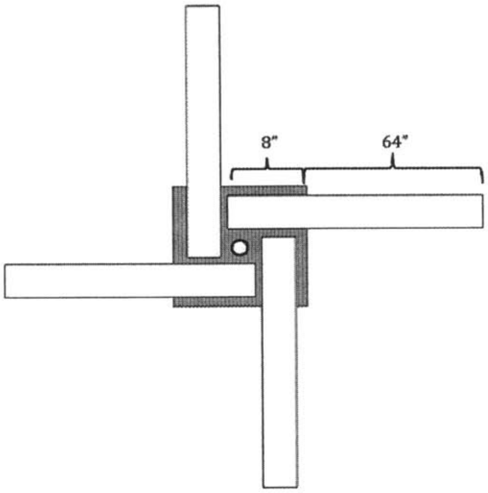

Figure 6: Cantilevered swing arms (white) encased in the central rotational cage (shaded).

To avoid exceeding the material capacity of the wood, it is important to know the maximum possible deflection of the end of the cantilevered beam, and the maximum potential reaction force and moment at the fixed base of the cantilevered beam. To find maximum deflection and reaction forces, the system can be simplified by removing extra support struts and assuming that the 8 inches of beam encased in the support cage are rigidly fixed (see Figure 7a). The simpler system has two forces that impact the overall deflection of the beam and the reaction force at the fixed end: the downward force, F_{rider}, of the weight of the rider at the end of the cantilevered beam, and the distributed downward force from the weight of the beam itself. This calculation only considers vertical forces on the beam.

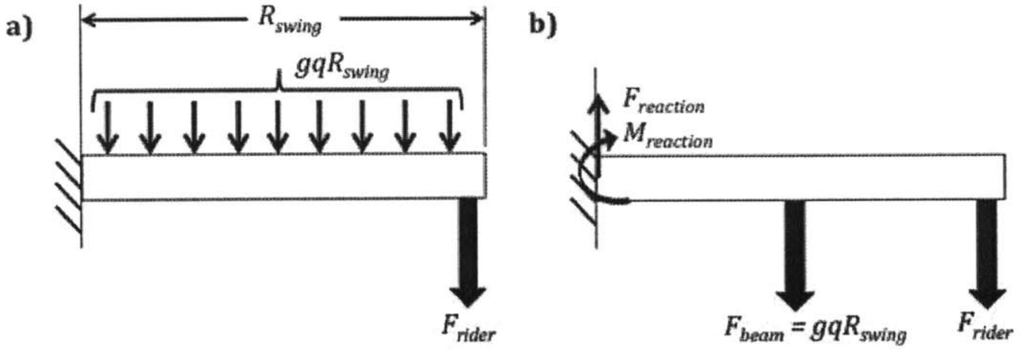

Figure 7: Cantilevered beams showing forces from beam weight and rider, where R_{swing} is the radius of the thing, q is a weight density in pounds per linear inch of wood, g is the acceleration due to gravity, and $F_{reaction}$ and $M_{reaction}$ are reaction force and moment. (a) Cantilevered beam diagram with distributed weight of beam plus the weight of the rider, F_{rider}; (b) Cantilevered beam diagram with distributed weight of beam represented as a point weight at the center of the beam.

The distributed force of the weight of the beam can be represented as a point force at the center of mass (Figure 7b). A force balance in the vertical direction and a moment balance result in the following equations:

$$\sum F_y = F_{reaction} - F_{rider} - F_{weight} = F_{reaction} - qR_{swing}g - mg = 0 \tag{8}$$

$$\sum M = \frac{1}{2}R_{swing}{}^2 qg + R_{swing}F_{rider} - M_{reaction} = 0 \tag{9}$$

where $M_{reaction}$ is the unknown moment at the cantilevered base, $F_{reaction}$ is the unknown force at the cantilevered base, F_{rider} is the weight of the rider, g is the acceleration due to gravity, and q is a weight density of wood in pounds per inch.

Assuming a 400-lb rider, which allows for a safety factor of 2, since the ride was restricted to individuals weighing no more than 200lbs, and a beam density of 0.395 lb/in (for pressure-treated wood), the maximum possible force at the fixed end of the cantilever is 1.89 kN, and the maximum moment is 2982 Nm. The bolts used are rated to withstand 150,000 psi in tension along the long axis, so given a bolt diameter of 3/8" they can withstand 16560 lb-f, or 73.66 kN.

To calculate the maximum possible end deflection of the beam, the principal of superposition is used; the forces on the beam can each be analyzed individually for their contribution to end deflection, and the sum of these components is the final deflection.

The deflection ∂ of the tip of a weightless beam of length R_{swing} with a load at the end of the beam is calculated as follows:

$$\partial = \frac{FR_{swing}{}^3}{3EI} \tag{10}$$

where F is the force at the end of the beam, E is the modulus of elasticity of the wood, and I is the moment of inertia of the beam. This cantilever has a rectangular cross-section of 3.5" x 3.5".

In contrast, the deflection ∂ of a uniformly-loaded cantilevered beam with no end load can be calculated as follows:

$$\partial = \frac{qR_{swing}{}^4}{8EI} \tag{11}$$

where q is the uniform load on the beam in force per unit length, R_{swing} is the length of the beam, E is modulus of elasticity, and I is moment of inertia of the same cross-section as above. By superposition, these two deflections can be added together for the total deflection at the tip of the cantilevered beam.

$$\partial_{total} = \frac{qL^4}{8EI} + \frac{FL^3}{3EI} \tag{12}$$

Given quantities for the pressure-treated 4x4 beam, where q = 0.1792 kg/in, F = 1779 N (assuming a 400-lb rider), I = 0.0151 kgm^2, and E = 8500 MPa for pine, Equation 12 can be solved for the total deflection, with the result that the 64-inch beam deflects by 8 inches over its length, which is well within the tolerance for bending of the wood without breaking.[22] Because of the simplifying approximations, this number represents an upper bound on the actual maximum deflection the beam might experience in the worst case.

The upper triangular support is added for safety; it reduces the moment response at the fixed end of the cantilever and directs more of the force to the center of rotation, keeping the beam well within safe standards for bending (refer back to Figure 5).

The central rotational cage was designed to be as symmetric as possible, while still having the maximum amount of beam encased in the enclosure to allow room for more attachment points, and still having a hole in the center for the rotational pole (refer to Figure 6 and Figure 8).

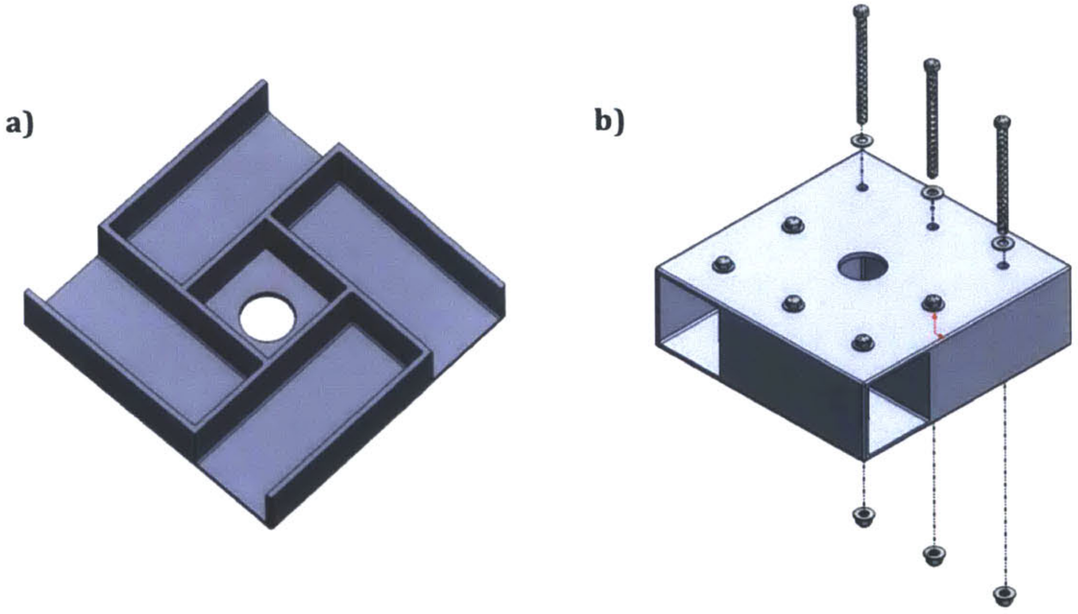

Figure 8: CAD design of welded steel rotational cage. (a) The original design required welding all of the side plates to the base plate and (b) attaching a top cover using bolts (not pictured) in order to make welding possible.

The material for the cage was originally specified as 1/8" thick steel, which was to be welded together to create a pocket for each cantilevered 4x4 to sit in. Due to unavailability of steel, 1/4" aluminum was substituted. Uncertainty about aluminum weld strength necessitated a revised design where each weld joint was replaced with waterjetted slots and tabs. The purpose of the cage was to resist bending, shear, and axial forces; this was achieved by transferring load to the bolts in the cage, as shown in Figure 9.

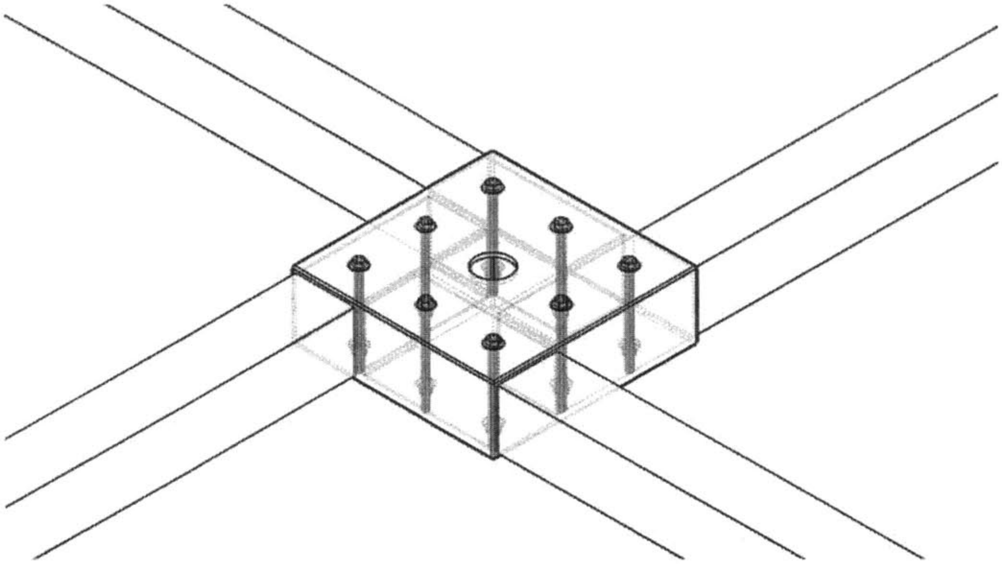

Figure 9: CAD diagram of central rotational cage with bolt placement. Bolts prevent the beam from pivoting within the central cage.

There were redundant bolts for safety: bolts connected the plates of the rotational cage together, connected cantilevered beams to the cage, and prevented radial motion of the cantilevered beam. Bolts were 3/8" steel, rated to withstand 5,000 lbs of force in shear and 150,000 psi in tension.[21] This is more than 30 times the worst-case loading, calculated using Equations 8 and 9 above.

Finally, to stabilize cantilever beams laterally and avoid collisions between individual swings, the swing arms were braced with pieces of 2x4 at several points, as shown in Figure 10.

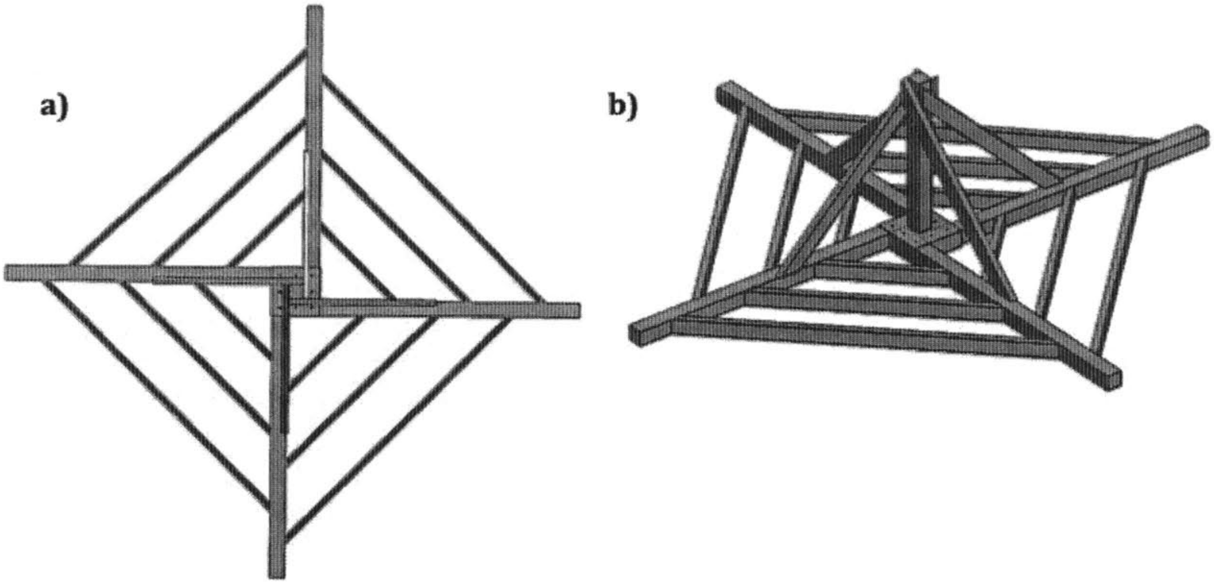

Figure 10: Swing arm bracing beams; top-down view in (a). The central cantilever beam case is visible in (b).

2.2.2 Rotational assembly

A cross-sectional drawing of the rotational assembly is shown in Figure 11. The rotational mechanism consisted of the rotating cage from Section 2.2.1, including flanged sleeve bearings (blue in Figure 11) press-fit into the central rotational cage. The flange of the bottom sleeve bearing rested on an ultra-tough bronze thrust bearing and a steel washer. These elements rotated on an upright steel pole, which is press-fit into the main column of the base assembly. At the top of the main column, an additional thick aluminum collar helped stabilize and hold the pole in place. The collar thickness was constrained by the maximum capacity of the waterjet, which was 1".

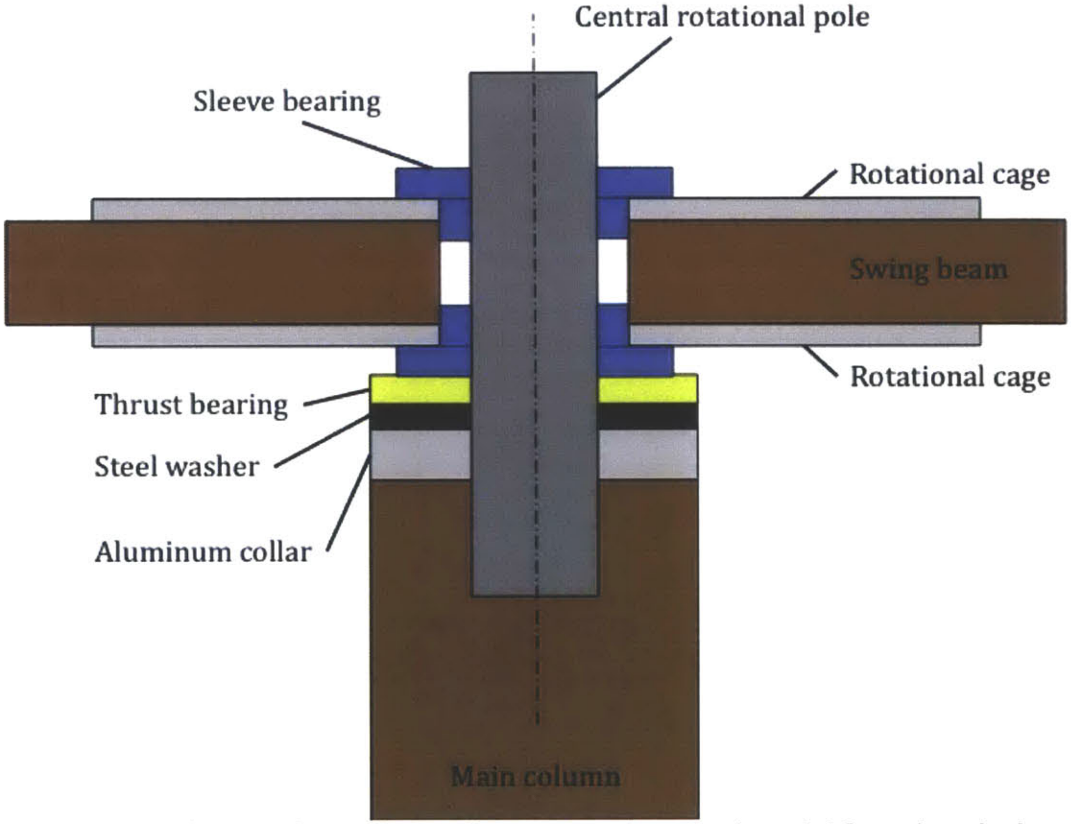

Figure 11: Swing carousel rotational assembly. From bottom upwards: main column 6x6 (brown), steel pole embedded in main column (grey), aluminum retaining collar (light grey), thrust bearing (yellow), sleeve bearings (blue, pressed in plates), and rotational cage. The cantilevered beams, swing cage, and thrust bearings rotate atop the washer and around the steel pole.

The thrust bearing and sleeve bearings can withstand 10 times the amount of force at the speed that the ride would create.[21] The rotating section of the ride was constrained by two flanged sleeve bearings press-fit into the central cage and centered on the steel shaft. The cage itself was prevented from spinning off of the pole due to excess pole above the cage, plus the large weight of the rotational platform.

A steel washer was added between the thrust bearing and aluminum collar to avoid galling due to the high forces between different materials.

The main concern in the rotational system is maintaining the integrity of the central rotational pole, particularly with regards to torque to the top of the pole due to unavoidable eccentricity in the ride.

Compression of the pole into the lumber is not a concern; the bearings rotate around the pole but there is no major force pressing it into the wood. Additionally, lumber is strongest in compression. Radial torsion on the pole itself is mitigated by the sleeve bearings, so torsion causing the pole itself to break is unlikely.

Torque to the top of the pole was a primary concern because of the nature of cut lumber. Wood is orthotropic, with strength primarily along one axis due to the "grain" (see Figure 12). Similar to the concept of chopping/splitting wood, when a hole is drilled perpendicular to the grain, the wood is very strong; however, when one is drilled parallel to the grain, the wood is more prone to splitting due to the structure of its component cells.

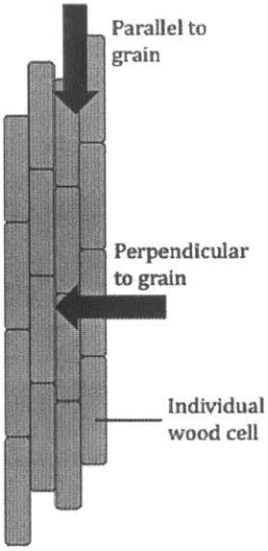

Figure 12: Orthotropic wood; the "grain" goes along with the cells of the wood, making it harder to drill holes perpendicular to the grain but stronger in that direction.

Optimally, the rotational pole should not cause a splitting effect in the main 6x6 column. The critical load case for the ride (the case of maximum eccentricity) is when two swings on the same side are fully loaded, and the other two are not. This was unlikely during actual ride operation, but some eccentricity was unavoidable due to the nature of the ride and its intended audience. It was estimated that despite measures to avoid imbalance, up to 50lb imbalances in riders were probable. Thus, to avoid causing excessive torque on the pole and subsequently splitting the main column (see Figure 13), a number of mitigating efforts were made. First, assembly required careful attention to alignment to ensure that the pole was as parallel to the wood as possible. Furthermore, two shorter sleeve bearings were used instead of one, and they were placed low on the pole to limit the amount of radial torque that could be contributed by an unbalanced cage. An aluminum collar was added atop the main column to relieve stress on the wood in the case of an imbalance. Finally, during operation, attempts were made to assign passengers to swing locations to load the ride as symmetrically as possible.

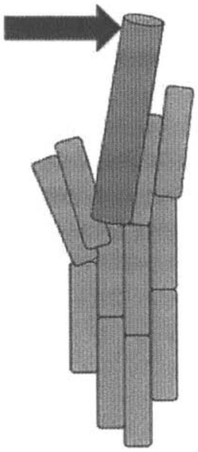

Figure 13: Rotational pole embedded in main column with longitudinal axis parallel to the grain. With a large force to the top of the pole (arrow, top), main column splitting is possible by the pictured mechanism.

2.2.3 Base and platform

The base of the ride needed to support the upright 6x6 central column without tipping. The base included supports in all four directions, with a footprint that spread out over as broad an area as was practical. Given the constraints of the courtyard space, this was a 24-ft square (3 times as wide as the ride was tall; see Figure 14).

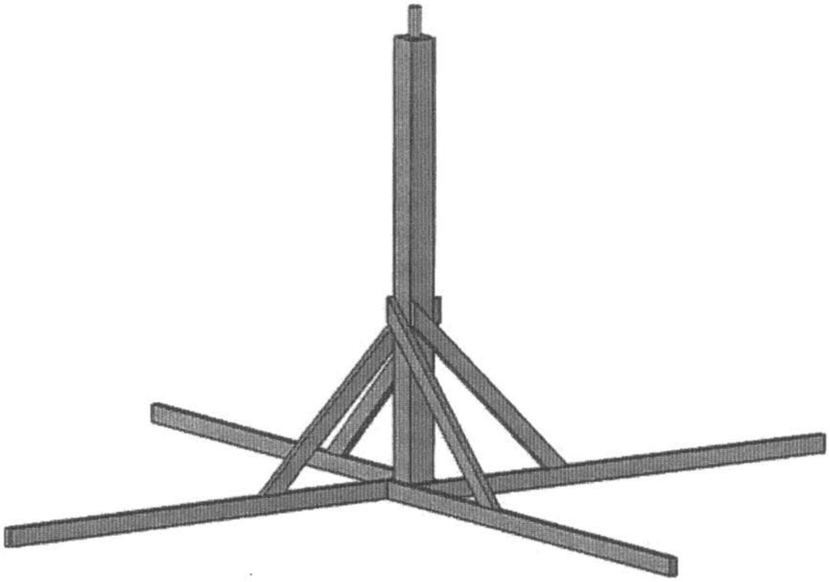

Figure 14: Swing ride base, with rotational pole embedded in the top.

Because human pushers were required to walk around this base while they were pushing the ride, wooden 2x4s interrupting the path was unsafe. Therefore, a plywood floor, made from ¾"-thick plywood, was installed atop the 2x4 beams, and an additional support grid of 2x4s was added below the plywood sheets to keep the floor from breaking. This gave pushers a smooth track to walk on as they pushed the ride (see Figure 15).

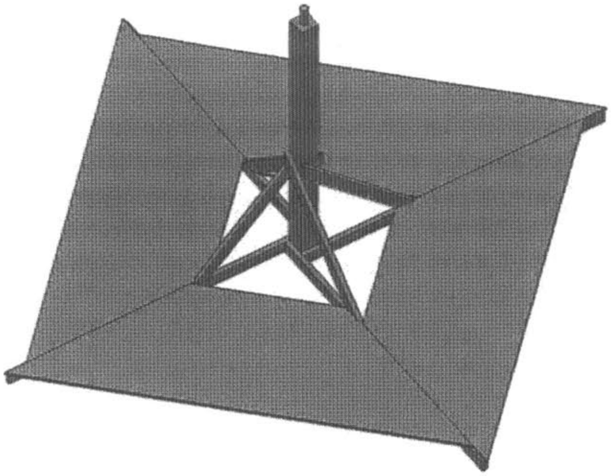

Figure 15: The stationary base of the ride, with additional plywood sheets as platforms for ride pushers. Corners that appear sharp in the diagram were blunted in assembly to avoid unsafe sharp edges.

2.2.4 Powering the ride

The ride was required to be manually powered, so students were asked to push the ride. The push bars were a component of the upper rotational section of the ride; two push bars hung down from the top of the ride at a smaller radius than the swing attachment point (see Figure 16). One pusher would have been adequate to overcome the static friction of the ride bearings, but two push bars were built on opposite sides of the ride to avoid introducing eccentric loading from the weight of or force on a single push bar.

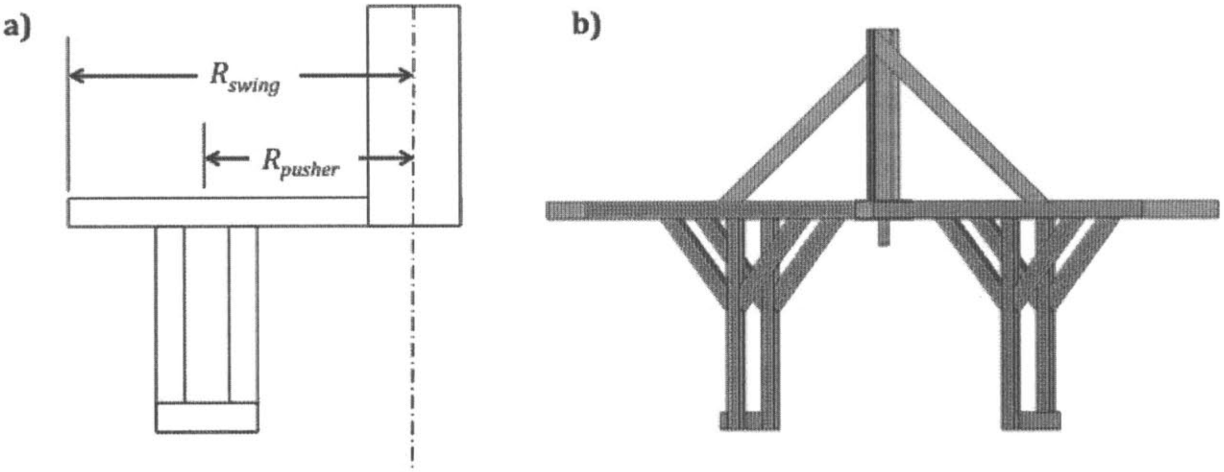

Figure 16: (a) Simplified diagram of push bar location; (b) CAD model of push bars on the swing carousel's upper rotating platform.

Equation 7 in Section 1.2.2 describes the relation between the radius at which the push bars are set, the speed of the pushers, and the speed/angle of the riders. Using v_{pusher} of 2.0 m/s, which is a medium-to-fast walking speed, this equation gives a rider speed of 4.27 m/s (about 9.5 mph) and a rider angle from the vertical of 38 degrees. An angle of 60 degrees speeds riders up to 15 mph, but requires pushers to be moving much more quickly. If rotations per minute are constant, then the relationship between the angle from vertical θ and the speed of the riders is linear.

There is no braking mechanism other than friction, but the push arm can provide leverage for slowing down in the same way that it provides leverage for speeding up.

2.2.5 Swing design

Swing design was simple and modular for quick assembly. Four riders were seated around the ride, at the end of the four cantilevered beams. Riders sat upon a 12"x12" seat of fabricated from 2x4s, with a cable running through a hole in the middle of the seat and secured on the bottom side by a knot (see Figure 17). Riders straddled the rope as they sat in the seat and held the rope in front of their chests during ride operation. The swing cable was tied into a u-bolt attached to the cantilevered beam, as in Figure 17, to avoid chafing between the swing cable and the wooden cantilever beam.

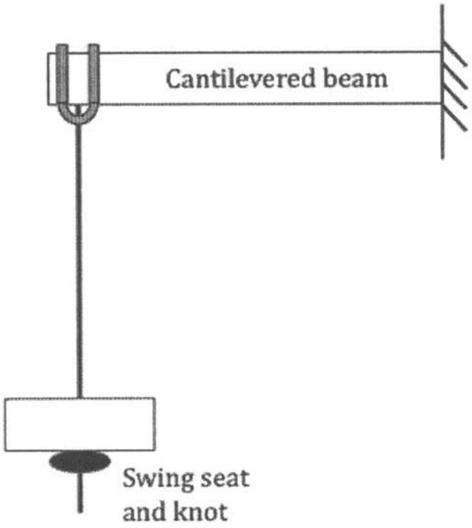

Figure 17: Diagram of swing seat and cable attachment design. The swing is attached to the cantilever beam by a u-bolt to prevent swing cable from chafing wood.

Swing cable length was a compromise; the tower was only 8' tall, and cables needed to be short enough to fit within a safety perimeter even when they spun out and to avoid riders' legs dragging while on the ride, but long enough for riders to board swings comfortably. The end length was 4 ft (48 inches), attached at the ends of the 6-foot swing support beams. Riders were 6 ft from the ride center and 8.5 feet from other riders and therefore were not able to collide. A swing cable length of 4 ft, given the 38-degree angle from section 2.2.4, gave a rider height of 58.2 inches (4.8 ft) above the ground. According to Equation 5, this should be true despite individual rider mass.

The cable used to attach swings was rated to withstand 17.8 kN of tensile force. This was more than 3 times the maximum tension in the swings, given the estimated angle of 38 degrees.

2.3 Overall assembly

The finalized design featured a stable base with a 24' footprint, made of wooden 2x4s with ¾" thick plywood topping the 2x4s to create a smooth platform for safe walking. The central pressure-treated wooden 6x6 column was 8' tall. A rotating platform carrying the swings and two push bars was atop the central column, centered by an aluminum cage. The rotating platform was 3' tall from the cantilevered beams to the top of the support strut attachment column and 140" at its widest point.

The entire ride design stood 11' tall, with a square footprint that was 24' across diagonally. A circular safety perimeter of diameter 30' was also part of the design, in order to prevent flying swings from colliding with passersby. Figure 18 shows a completed assembly of the two main components of the swing carousel design, without the addition of swings or swing cables.

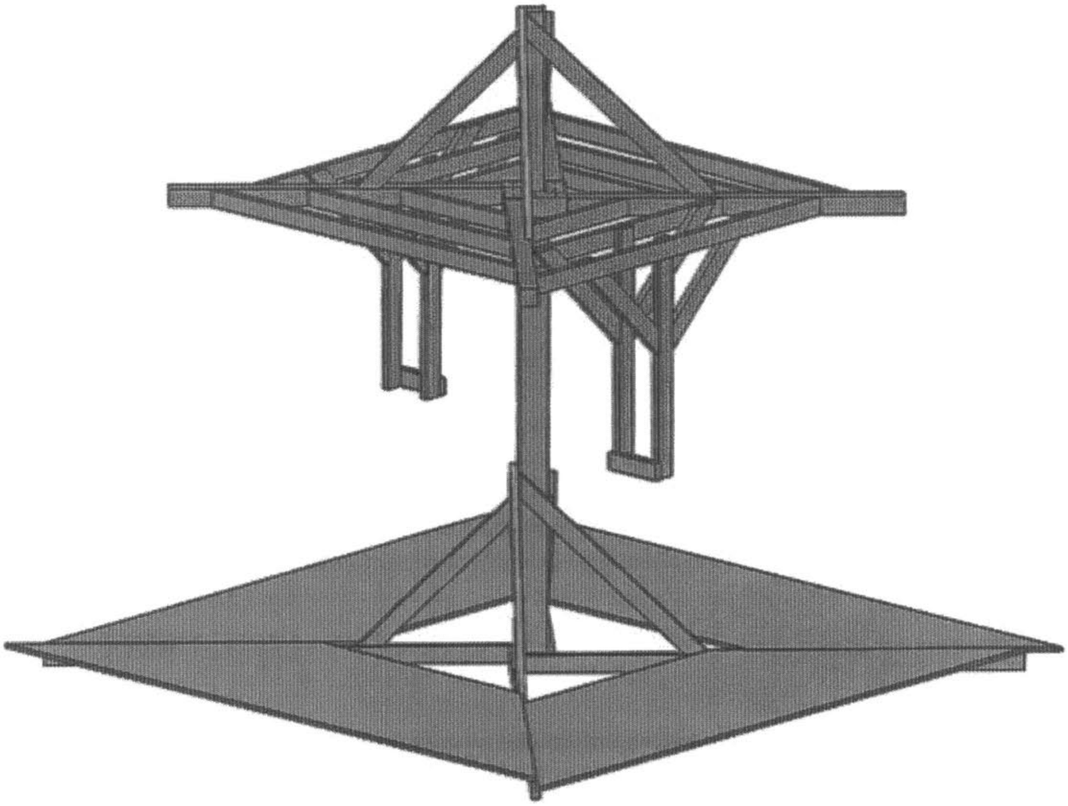

Figure 18: Finalized CAD model of the swing carousel, without attached swings.

Chapter 3: Fabrication and Construction

The design process was two months long, and the project was constructed at the end of the design phase. Due to the short time schedule for construction, iterative design cycles for the entire ride were not possible; however, when issues with certain components arose, redesigns were made.

The remainder of this document addresses manufacture, assembly, installation, and finally removal of various systems and structural components used for the swing carousel. Procedures are presented in chronological order of fabrication and construction.

3.1 Overall assembly process

The overall assembly, presented in Section 2.3, fit together in two parts: the upper rotating section, which was comprised of the central rotational cage and the cantilevered beams and bracing, and the lower base section, including the pole portion of the rotational assembly and the large, stabilizing platform. Once the subcomponents were assembled individually into the upper and lower sections, a lifting team with appropriate safety equipment hoisted the upper subassembly onto the lower subassembly. Finally, the swings and push bars were added to the upper subassembly.

The build plan was designed to make construction as efficient as possible, making use of potentially inexperienced workers. Tasks were categorized according to level of experience required. Some tasks, such as marking wood or holding parts in place, required no prior skills. Other tasks required minimal skill, for example operating basic machinery such as a hand drill and chop saw. The most complex tasks required sufficient skill in operating more complicated shop tools such as a waterjet, cutter, mill, and lathe. Tasks were organized to be performed in parallel, and an efficient build plan spanning the six days of construction was developed. First, complicated components of the rotational cage were fabricated by experienced workers, while wood was marked and cut to size by less experienced workers. Then, the base of the structure was constructed and leveled, followed by construction of the upper rotating section on the ground. The two sections were assembled, and final subassemblies were added to the upper section after it was mounted atop the base.

A core of machine-shop-qualified engineering students was also tasked with training inexperienced students (especially freshmen) to use basic power tools safely: hand drills, drill presses, chop saws, and in some cases jigsaws.

Safety precautions were taken during construction. Workers wore safety glasses and close-toed shoes at all times and hard hats when working below the upper section of the construction. Inexperienced workers were assigned an upperclassman assistant and experienced workers also worked in teams. Workers worked in shifts to ensure that tiredness and fatigue did not degrade judgment.

3.2 Ride base

The main column of the ride was a pressure-treated pine 6x6 central column that was 96" (8 feet) tall. It was stood up at the center of a relatively level section of the courtyard, using three workers to push it up to vertical and hold it in place. A fourth worker held a level to the top to ensure that it was flat, and two more workers installed diagonal supports at the base. Once all four sides had diagonal supports, horizontal base sections were installed.

Larger base supports were added later, and the plywood platform for pushers to run on was the last thing to be attached. Corners of the plywood platform were blunted to avoid sharp wooden corners, and spaces between boards on the top of the platform were filled in and taped over to ensure a smooth surface for walking.

3.3 Rotational assembly

The 6x6 was installed in an upright position prior to installing the rotational steel pole. Drilling a deep vertical hole 1.5" wide in which to press-fit the steel rod was difficult to do in this configuration because the hole location was 8 feet tall, and proper leverage for using a hand drill fitted with a 1.5" Forstner bit was challenging.

However, because it was critically important to the rotational assembly that the steel pole be installed plumb (and additionally important to avoid splitting the main column), a jig was developed to ensure that the rod would be pressed in perpendicular to the main column (see Figure 19).

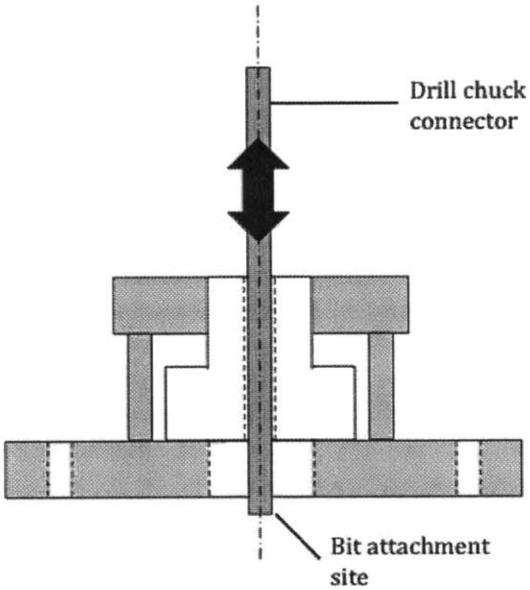

Figure 19: Diagram of jig for drilling the rotational pole hole in the main column. The bottom plate is flat; it is screwed directly onto the top surface of the 6x6 to ensure that the hole is perpendicular to that surface.

The jig was used to pre-drill a straight hole, and then used again to slowly drill a 5" deep hole with the Forstner bit. Once the hole was complete, the steel rod was pressed into place with the assistance of a free-fitting aluminum collar and a level to ensure that the rod was not askew as it was pressed into the main column.

Finally, the 1"-thick aluminum collar was affixed with 3" wood screws to the top surface of the 6x6 to help mitigate torque on the pole caused by rider imbalances. The aluminum collar was machined by waterjet in order to achieve a close fit between the pole and the collar.

3.4 Rotational cage and top-section assembly

The rotational cage was the bottleneck on assembling any portion of the top rotating section because it was required for assembling all of the cantilevered beams, so it was completed first. The first attempt at waterjetting slots and tabs resulted in a poor fit, so a redesign was necessary, increasing the size of the tabs and decreasing their number, with attention to tolerancing for the kerf of the waterjet. The second iteration fit together, although the interior plates were difficult to line up.

The cage was partially bolted together, and then each 4x4 cantilever beam was inserted into its pocket. While in the pocket, pilot holes for the bolts were drilled to line up with the waterjetted bolt-holes, and the 4x4 beams were removed. The holes for bolt clearance in the beam were drilled to their final size independent of the cage. At this time, the u-bolts for the swing cables were also installed into the 4x4 cantilever beams. While these holes were being drilled, the two sleeve bearings were fit into the rotational cage, using a rubber mallet to gently tap them into place. Tapping was performed evenly around the perimeter of the bearing to ensure that it did not skew during installation.

Before installing the large 4x4 beams into the cage, the assembled cage (sleeve bearings and bolts) was tested for rotation atop the main column. The nuts on the end of the bolts interfered with the initially square aluminum collar, so the aluminum collar was removed from the main column, cut into an octagonal shape so that nuts had clearance, and replaced.

The 4x4 beams, including u-bolts for swing cables, were then installed into the cage and bolted in, and additional screws were added between the 4x4 and the cage. This was done on the ground, propping up the assembly with extra pieces of 4x4 to allow easy access for drilling. The completion of the cantilevered beam cage allowed workers to assemble the upper support bracing and side support braces. Not accounted for in the upper support design was the fact that the rotational pole stuck up significantly past the rotational cage; a hole in the underside of the central top support 4x4 was bored, using the Forstner bit and jig for a primary hole and then a chisel to create clearance for the pole.

3.5 Final assembly and operation

The first step of final assembly was to combine the upper and lower section. A team of five tall students lifted the upper rotational assembly and moved it on top of the pole, with four students responsible for lifting and one student responsible for aligning the center of the rotational cage with the pole in the main column.

Final assembly tasks included adding the push bars and constructing and attaching swings. The push bars were assembled onto the ride using clamps; workers used ladders to reach the bracing on the rotational platform, and were required to work in teams of two to make sure no parts fell. Swing seats were assembled on the ground and swing cables were sized and attached to the u-bolts using a doubled-back Figure 8 knot. The u-bolt is barely visible in Figure 20, but the push bar assembly and swing cable are clearly noted.

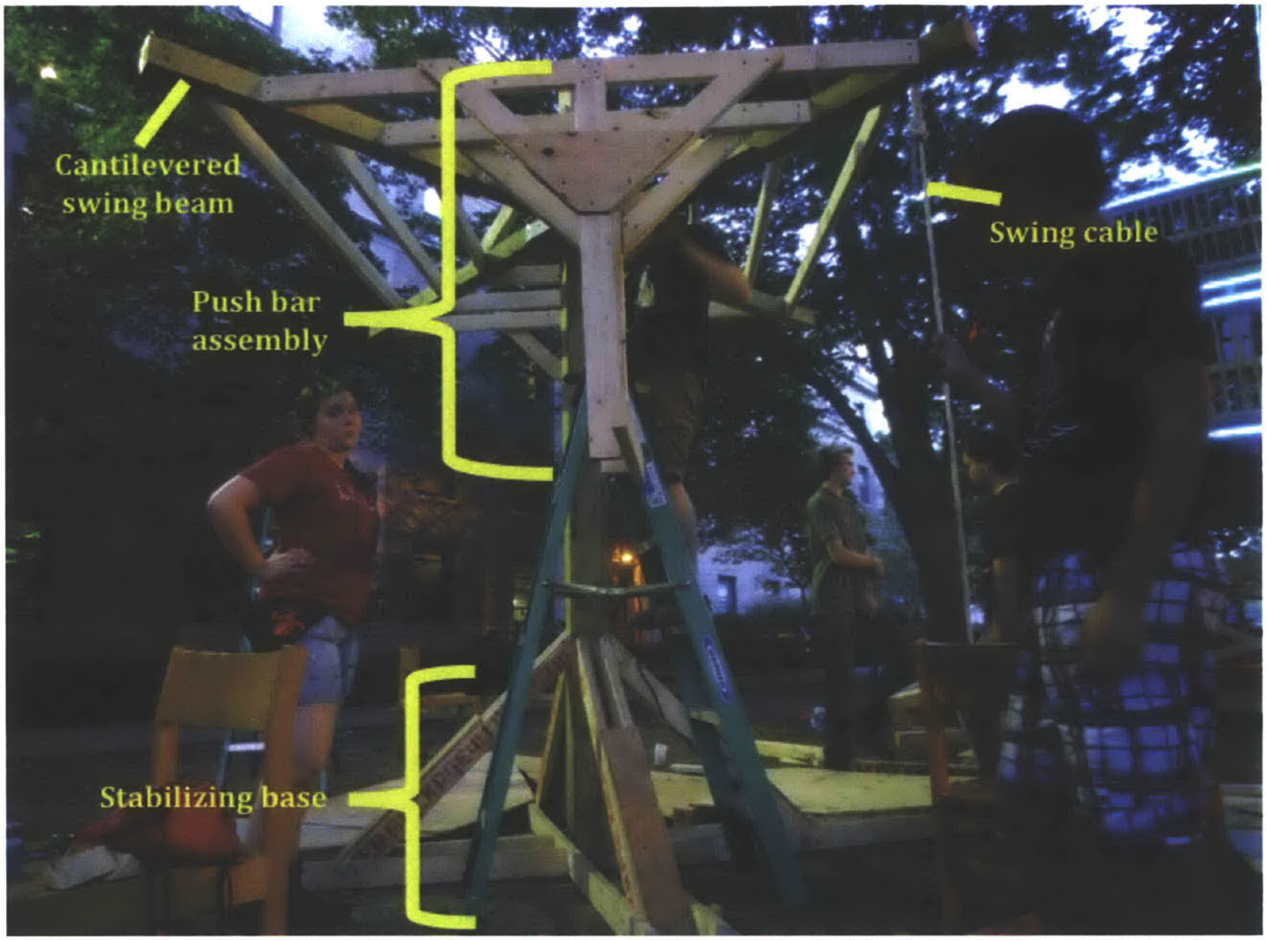

Figure 20: Swing and pusher bar assembly. Pusher bar is directly in the front of the image, nearly completed, with a trapezoidal gusset plate.

Final construction is illustrated in Figure 21:

Figure 21: Final ride assembly.

Testing was performed before people were permitted to ride. Four 100-pound sandbags were attached to the swings with several ropes for redundancy, and the ride was spun up to speed. Observers were required to stand far away from the ride in case one of the sandbags flew off. Careful analysis of potentially hazardous failure from load was performed before riders were permitted. The rotational cage and bolts were examined for bending or fatigue cracking, the cantilevered beams were examined for cracks especially in the area near the cage and the swing bolts, and the swings themselves, including the swing cable, were examined for fraying, tears, or other signs of wear or failure.

Finding none, the ride became operational for the duration of the carnival (see Figure 22). It was paused and checked for signs of failure every 30 minutes during the carnival.

Figure 22: Completed ride in operation. Slightly left and right of center, two pushers are pictured. Despite the clear difference in weight and size of the riders on left and right of the picture, all swings are at the same angle from vertical. A small deflection in the upper cantilevered beam is visible for the left rider; it is less than the maximum predicted 8". Riders sit according to Section 2.2.5.

Teardown took place as scheduled 15 days after the construction was completed, due to constraints on the outdoor space the ride occupied. The ride was disassembled in reverse order of assembly: first, the swings and push bars were removed, using ladders and worker teams. A lifting team of five students (four for lifting, and one for direction) removed the upper section of the ride from the lower section. The upper and lower sections, once separated, were disassembled simultaneously, and the rotational cage, pole, bolts, and other hardware were saved in case of future assemblies.

Chapter 4: Summary and Discussion

This section presents findings post-construction of the swing carousel.

4.1 Operational statistics

The swing carousel ran for the duration of the carnival, with the exception of a fifteen-minute period where a section of plywood on the base was reinforced. Over 200 people rode it over the course of the 4-hour evening event. There were more than 50 runs of 4 people each, approximately every 4 minutes, with 5-minute breaks for safety checks every 30 minutes. A video of the cycle of the ride is available as of Monday, May 18, 2015, at https://youtu.be/45FN6K8-GHY.

Riders at top speed performed about 15 rotations per minute, and maximum angle achieved was approximately 50 degrees (see Figure 23). This was 12 degrees larger than the expected 38 degrees, achieved in operation because pushers pushed at a running speed instead of the expected walking speed. This corresponded to a maximum rider speed of 4.26 m/s, or about 9.5 mph, with a maximum horizontal g-force for riders of 0.68g (well within safe bounds). Due to frictional effects, this speed is close to the maximum calculated for the lower 38-degree angle.

Figure 23: Screen capture from video of one run of the ride, taken immediately after pushers stopped pushing riders. The angle achieved at the moment that pushers stopped pushing was about 50 degrees.

Ride pushers took an average of 15 to 20 seconds to get the ride up to speed. Riders were then given 40 seconds to spin down freely from top speed, after which the pushers used the push bars as leverage to slow the ride to a stop.

4.2 Specific operational considerations

The ride was rebuilt using a similar design the following year, but the hole for the rotational collar drilled by the Forstner bit was not exactly plumb and the aluminum collar omitted, so when the ride was subjected to extreme off-balance loading as part of a test, the main column split, according to the pole-torque mechanism described in Section 2.2.2. An alternative design might include compression rings around the top 6" of the 6x6 column to prevent this splitting behavior.

The lack of braking mechanism on the swing carousel was not a large problem, as friction slowed the ride down to a near-stop within one minute of being spun up to top speed.

There were some safety concerns with the ride design as well: human pushers who were at the center of the ride could put themselves in danger in several ways. First, if the pushers were out-of-sync, one pusher could walk significantly faster than the other, speeding the ride up so that the other pusher might get caught. Additionally, pushers would occasionally run while pushing the pusher bars, speeding the ride up such that it was moving faster than a comfortable walking speed, which felt out-of-control for pushers, who were uncomfortable using the push bars for leverage in the opposite direction for braking at high speed. Finally, pushers were supposed to move to the center of the ride after getting the riders up to speed, but in one instance, a pusher moved to the outside of the ride, through the spinning riders – there was no physical mechanism in place to prevent this behavior. Some of these issues were mitigated through careful instruction, but a redesign could be helpful to limit the number of potential safety failures.

Many riders used the single-point attachment of the swing cable to spin around the axis of the swing cable while they were also spinning around the central axis of the ride. This twisted the swing cable, which was not considered in the calculations for this project and could potentially have damaged the swing cables. A two-point attachment and a seatback would prevent this behavior, but introduces further concerns about swings tipping and structural capacity of the swing seatbacks.

Further analysis could include finite element modeling, which could provide a more precise understanding of the static and dynamic stresses experienced by the structure under a variety of loading and operational conditions. Of particular concern are areas of high stress concentration in the rotational cage and wood where holes were drilled. An additional investigation of frictional forces in the ride would be useful in developing a motorized version of the ride, particularly for sizing the motor and determining necessary lubrication of bearing elements.

4.3 Conclusions

The swing carousel ride designed in this project was far more successful than anticipated. The author took the project from conceptual design plans to a final, operational ride, including all intermittent steps such as component sizing, safety calculations, material choice and subsequent procurement, coordination of construction, participation in construction, performing a safety review, performing safety testing, and finally organizing rides for interested students. Design goals were met: freshmen were instructed in power tool operation, and the ride satisfied over 250 students.

The ride's operational performance was excellent. In addition to performing for 4 hours of continuous operation during the carnival event for which it was designed (minimum operational requirement), the ride also ran smoothly for 14 days post-construction (maximum operational goal). The system was disassembled successfully and stored for the following year, when it was rebuilt. The team in the following year omitted the collar, and the ride broke as expected according to the calculations provided in this document.

Future constructions could benefit from performing safety calculations for a variety of materials for the rotational cage, considering frictional concerns and potentially lubricating the rotational assembly for faster rider rotation, and considering additional safety concerns described in Section 4.2. The construction described in this document confirms that the swing ride is well-suited for the East Campus carnival environment, providing fabrication and organization opportunities for students of all experience levels, and operating consistently with minimal safety issues during the event itself.

Appendix A: Table of Values

Quantity	**Value**
E (Young's modulus) for 4x4 pressure-treated pine beam[22]	8500 MPa
q (density in kg/in) for 4x4 pressure-treated pine beam [22]	0.9557 kg/in
m (mass) of 4x4 pressure-treated beam, length 64"	11.468 kg
I_z (moment of inertia about longitudinal axis of beam) for 4x4 pressure-treated pine beam with cross-section of 3.5" x 3.5"	0.0151 kgm^2
m_{rider} (mass of assumed rider; 2x safety factor)	400 lb
F_{rider} (force from rider with mass m_{rider})	1779 N
v_{rider} (maximum linear velocity of riders on swings)	Designed: 9.5 mph Physical: 15 mph
θ_{max} (maximum angle from vertical of swing riders)	Designed: 38° Physical: 50°
R_{swing} (distance from center rotational axis of ride to swing attachment point); design parameter	Designed: 70"
R_{pusher} (distance from); design parameter	Designed: 50"
L (swing cable length); design parameter	Designed: 48"

Appendix B: Bill of Materials

Lumber

Standard pine 2x4, 8' long	38
Pressure-treated 4x4, 8' long	5
Pressure-treated 6x6, 8' long	1
¾" thick plywood, 4' x 8' sheets	5

Rotational assembly hardware

12x12" aluminum, ¼" thick	4
3/8"-16 high-strength steel bolts, 5" long	8
3/8"-16 nuts	8
3/8" washers	16
Ultra-tough, oil-lubricated bronze thrust bearing, 2" ID	1
Steel sheet (for washer)	1
Ultra-tough, oil-lubricated bronze flanged sleeve bearings, 2" ID	2
2" precision steel pole	1

Swing hardware

3" wood screws	Box
Steel u-bolts	4
1" Bluewater tubular webbing, climb spec (Bluewater)	220'

Assembly tools

2" Forstner bit	1
Chop saw	1
Corded drills	3-5

Additional materials

Gaffer's tape	1 roll
Extension cord for courtyard construction	2

References

1. Second Freshman Conclave To Be At Camp Massapoag, September 23-26. (1927, May 27). *The Tech*. Retrieved from http://tech.mit.edu/V47/PDF/V47-N46.pdf.
2. Frosh Weekend Here Now Definitely Planned. (1950, May 19). *The Tech*. Retrieved from http://tech.mit.edu/V70/PDF/V70-N29.pdf.
3. Lima, Tony. IFC resolution backs joint Residence Week. (1968, April 16). *The Tech*. Retrieved from http://tech.mit.edu/V88/PDF/V88-N19.pdf.
4. Winstein, Keith J. Two Days Reserved for 'REX'. (2003, February 28). *The Tech*. Retrieved from http://tech.mit.edu/V123/N8/8rex.8n.html.
5. Retrieved from http://eastcamp.us/about.
6. The Daily Confusion. (1994, August 28). *The Tech*. Retrieved from http://tech.mit.edu/V114/PDF/V114-N33.pdf.
7. Narendran, Kailas. "The East Campus spinning ride of death." Image. *The Tech*. Retrieved from http://tech.mit.edu/V121/PDF/V121-N36.pdf.
8. Merry-go-rounds. Retrieved from http://www.fairsarefun.net/html/icon.aspx?id=21&p=4.
9. Sticht, Wade R. (2004). Design and Construction Specifications for Nielsen's Grove Swing Carousel (Master's Thesis). Retrieved from https://ceen.et.byu.edu/sites/default/files/snrprojects/492-wade_sticht-2003-wkl.pdf
10. Nielsen's Grove Park – Orem Utah. Retrieved from http://www.orem-utah.us/nielsens-grove-park---orem.html.
11. "Flying Swing & Skating Rink Idora Park Oakland, California" and "Idora Park Swing." Picture postcard. Idora Park, 1910. Retrieved from http://www.alamedainfo.com/.
12. Retrieved from https://www.google.com/patents/DE3327291A1.
13. Wave Swinger. Retrieved from http://www.zierer.com/en/mainmenu/products/wave-swinger/.
14. SkyScreamer. Retrieved from https://www.sixflags.com/greatadventure/attractions/skyscreamer.
15. http://database.saferparks.org/sites/default/files/accident_reports/NY_909366.pdf
16. Family of 5 kids in Calif. ride collapse gets $3.4M. (2010, November 24). Retrieved from http://www.foxnews.com/us/2010/11/24/family-kids-calif-ride-collapse-gets-m/.
17. Mother tells of terror as fairground ride fell apart beneath her. (2013, December 16). Retrieved from http://www.dailymail.co.uk/news/article-2524675/Mother-tells-terror-fairground-ride-fell-apart-200ft-air.html).
18. Nine children injured in swing carousel accident. (2013, March 31). Retrieved from http://www.b92.net/eng/news/society.php?yyyy=2013&mm=03&dd=31&nav_id=85455).
19. Police say 12 kids injured when sing ride malfunctions at Connecticut festival. (2013, Sepember 8). Retrieved from http://www.foxnews.com/us/2013/09/08/police-say-13-children-injured-when-swing-ride-malfunctions-at-conn-festival/.
20. Sky ride carriages out of control at Cardiff Winter Wonderland. (2014, December 8). Retrieved from http://www.telegraph.co.uk/news/uknews/11278155/Sky-ride-carriages-out-of-control-at-Cardiff-Winter-Wonderland.html
21. Product information sheets, McMaster.com.
22. Green, David W., Winandy, Jerrold E., Kretschmann, David E. Mechanical Properties of Wood. Wood Handbook: wood as an engineering material. Madison, WI: USDA Forest Service, Forest Products Laboratory, 1999. Chapter 4. Accessed online at http://www.conradfp.com/pdf/ch4-Mechanical-Properties-of-Wood.pdf.
23. Hibbeler, R.C. "Beam bending." *Mechanics of Materials, 8th Edition.* Boston, MA: Prentice Hall, 2010. Print.

Additional references

Fairground Rides: A Chronological Development. National Fairground Archive. Retrieved from http://www.nfa.dept.shef.ac.uk/history/rides/history.html.