Development and Construction of a Timber Composite Guide Way Beam and Steel Supporting Structure for a Full-Scale Prototype of an Elevated Transportation System

by

Keith A. McKenna

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Special thanks go to my wife Elizabeth D. McKenna for her support and understanding; her encouragement has motivated my persistence for an education at San Jose State University. Also, I would like to thank all my professors at San Jose State University. I appreciate their dedication to promote learning and understanding of their disciplines. Also, I would like to thank my colleagues at San Jose State University. Their collaboration and camaraderie has made my educational experience exceptionally enjoyable.

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Chapter1. Introduction

On February 19, 2014 Sam Ellis and Bryan Burlingame made a presentation to the CE163 Steel Design class at San Jose State University. They informed the students on the subject of a multi disciplinary project that the Mechanical Engineering Department was involved with: a feasibility study of a solar powered elevated Automated Transit Network system (ATN) for urban public transportation. Structural design assistance was requested from the Steel Design class and an invitation to the next ATN group meeting was offered.

The ATN group “Spartan Superway” is a conglomerate of SJSU faculty, designers, urban planners, and students of various disciplines as listed in the Appendix. The academic disciplines represented in the group are: business, computer engineering, mechanical engineering, and now civil engineering. These disciplines were divided into several teams within the group:

- guide way design
- station design
- control systems design
- bogie design
- cabin design
- solar power design
- human centered design
- administrative

The report author, a structural civil engineer student (SCES), accepted the requested structural design role. The civil engineering role included construction management for fabrication and assembly of the full scale guide way prototype. The prototype model was displayed at the Maker Faire event at the San Mateo Convention Center May 17, 2014. Though the SCES participated in many aspects of the project, primary responsibilities included:

- to provide technical assistance to ME team for design of full scale exhibit of an elevated guide way
- to review the structural design and evaluate the constructability of the proposed full scale exhibit of an elevated guide way
- to provide technical expertise and assistance in the fabrication and construction of an elevated guide way
- to assist in the assembly and disassembly of the final full scale elevated guide way exhibit

This report documents the contribution of one structural engineering student into the development and building of the Spartan Superway full-scale prototype model. In Chapter 3, the schematic phase of the full-scale model development is described with reference to initial geometric and material changes. Then, in Chapters 4 through 6, the design development phase is described; the guide way system is modeled, load cases established, and structural analysis presented. Finally, in Chapter 7, construction documentation of the elevated guide way is given which culminates in delivery to the Maker Faire event site. A time line is given in Table 1.

Table 1 Author's Project Time Line

Task	**Date** (2014)
Author’s first attendance of weekly meetings	2/26
Weekly meeting	3/5
Weekly meeting	3/19
Received first schematic representation of ME’s system design	3/19
Suggested reducing weight of column assemblies	3/19
Began technical drawings (initial draft)	3/24
Analyzed strength of plywood box beam column	3/24
Weekly group meeting	3/26
Suggested constructing each column assembly as one steel unit	3/26
Completed technical drawings (initial draft)	3/28
Weekly group meeting	4/2
Suggested using construction adhesive for all connections of timber guide way	4/2
Suggested using continuous 2 x 4 for guide way beam tension chord	4/2
Transported wood construction materials from Santa Cruz to San Jose	4/7
First meeting with Pat Joice (CE Technician) concerning steel fabrication	4/7
Weekly group meeting	4/9
Began assistance with timber guide way beam construction	4/12
Finished assistance with timber guide way beam construction	4/13
Weekly group meeting	4/16
Assigned to build exhibit entrance gate	4/16
Verified steel delivery	4/21
Weekly group meeting	4/23
Cut angles on ends of twelve steel diagonal braces	4/26
Began assistance with constructing steel support structures	4/28
Weekly group meeting	4/30
Positioned column on base plate and support arms (weld preparation)	4/30
Completed assistance with constructing steel support structures	5/3
Assisted transporting steel columns from SJSU to building site	5/3
Assisted with connection of timber beam to steel supports	5/3
Suggested eye bolt on guide way to facilitate lifting method	5/3
Weekly group meeting	5/7
Transported materials for entrance gate	5/10
Completed exhibit entrance gate	5/10
Weekly group meeting	5/14
Installed eye bolt in guide way	5/15
Assisted with disassembly, loading, and transporting guide way from San Jose to San Mateo	5/15
Assisted with exhibit assembly at San Mateo Convention Center	5/16
Assisted with disassembly, loading, and transporting guide way from San Mateo back to San Jose	5/18

Chapter 2. Literature Review

Both global and local stability must be addressed in first-order elastic analysis. According to System Stability Design Requirements (2005), global "Lateral stability shall be provided by . . . lateral load resisting systems . . . ,[and] the overturning effects of *drift* and the destabilizing influence of *gravity loads* shall be considered" (AISC, 16.1-20). Locally, individual structural component and connection strengths must resist internal forces induced by load effect. Consequently, structural stability depends on system geometry, structural component strength, and connection strength.

Structural design requires that certain approximations be made to idealize individual components and their connections. First, the geometry of a structure is assumed and design loads established. Then the load path is determined and traced through an idealized force body diagram of the structure. Resulting forces in structural components can then be calculated using theory of structural analysis (Hibbeler, 2012). Finally, nominal internal demand stresses can be determined using fundamental mechanics of materials (Hibbeler, 2011).

Structural components must be proportioned such that load induced stresses are less than or equal to allowable design stresses. The American Society of Civil Engineers allows two methods "for proportioning elements of particular construction material throughout the structure" (SEI/ASCE 7, 2.1): Load Resistance Factor Design (LRFD), and Allowable Stress Design (ASD). Since 2005, allowable stress design has commonly been referred to as allowable strength design (Geschwindner, 18).

Allowable strength design was used to calculate adequacy of structural components and connections of the guide way structure. Load combinations are calculated according to ASCE 7 Section 2.4, and the most unfavorable factored load combination is compared to the allowable strength (or resistance) of specific component limit states. Allowable strength can be "obtained by using the proper combination of allowable stress and the corresponding section property, such as area or elastic section modulus" (Geschwindner, 18). Allowable stresses are documented according to specific type of construction material and limit state.

Timber construction uses a variety of wood species and products. Structural members can be composed of dimensional boards, timbers, or manufactured products such as plywood or oriented strand board (OSB). Nominal design stresses for timber or plywood materials are available in the *National Design Specification for Wood Construction, American Forest and Paper Association* (AFPA) and the *Plywood Design Specification, APA-The Engineered Wood Association.* The guide way beam was constructed from plywood and dimensional boards. Conservative design strength for the guide way beam was assumed using the allowable stresses of Douglas-Fir Larch No. 2, given below in Table 2.

Table 2 Allowable Stresses for Douglas-Fir Larch No. 2

Bending (Fb)	Tension Parallel To Grain (Ft)	Shear Parallel To Grain (Fv)	Compression Perpendicular To Grain (Fc⊦)	Compression Parallel To Grain (Fc)	Modulus of Elasticity (psi)	
					(E)	(E min)
900 psi	575 psi	180 psi	625 psi	1350 psi	1,600,000	580,000

Steel construction uses a variety of shapes, grades, and sizes. Nominal strengths of steel are defined by the American Standards and Testing of Materials (ASTM). Design specifications for common steel applications are given in the *Manual of Steel Construction, American Institute of Steel Construction* (AISC). Design strengths for the guide way columns were calculated using tabulated properties for HSS4x4x¼ and material properties of ASTM A-500 Grade B. Design strengths for all flat plate steel components were calculated using component geometry and material properties of ASTM A572 Grade 50. These are steel strengths and shapes available from a local steel supplier (PDM Steel Service Supply, Inc). The properties for guide way steel components are listed below in Table 3. The least moment of inertia and smallest radius of gyration was calculated using cross sectional properties of the nominal area for the flat plate components.

Table 3 Guide Way Steel Properties

Steel Component	Steel Type	Nominal Area (in^2)	Moment of Inertia (in^4)	Radius of gyration (in)	Fy min. Yield Stress (ksi)	Fu Tensile Stress (ksi)
HSS 4 x 4 x ¼	ASTM A-500 Grade B	3.37	7.80	1.52	42	58
5/16" x 3" Flat Plate	ASTM A-572 Grade 50	0.94	0.670	0.089	50	65
1/4" x 8" Flat Plate	ASTM A-572 Grade 50	4.00	0.010	0.072	50	65

Design loads are commonly divided into two categories: vertical gravity forces and lateral forces. These forces can be traced through a load path in the structure. Generally, analysis is performed on an idealized structure or structural element "that lies in a plane and is subjected to a force system that lies in the same plane" (Hibbeler, 2011, 33). This method provides a simplified approach for modeling specific structural elements that are part of a larger structure.

Forces induced by gravity or wind loads are established using different methodology. Vertical gravity loads induced by self weight can be approximated using various weights of materials. The weight of the guide way beam was estimated using tabulated values for plywood and wood studs (ASCE7, 399). The weight of steel components was estimated using tabulated values obtained from the steel manufacturer (PDM Steel Service Suppliers, Inc.). The assumed weights of materials for the guide way system are given below in Table 4.

Table 4 Tabulated Weights of Materials

Material	Weight
Plywood (per 1/8-in. thickness)	0.4 psf
Wood Studs, 2 x 4, unplastered	4.0 psf
HSS 4 x 4 x ¼	12.21 plf
5/16" x 3" Flat Plate Steel	3.191 plf
1/4" x 8" Flat Plate Steel	6.806 plf

Wind load can be established using fundamentals of physics. According to Walker (2008), "when there is a relative velocity between a fluid [air] and a body . . . , the body experiences a drag force . . . that opposes the relative motion" (pg. 122). For analysis, this drag force is considered a lateral wind force which can be approximated with the drag force equation (Walker, 122):

$$D = \frac{1}{2} C\rho A v^2 \qquad \text{(EQ 1)}$$

Where:

D = *Drag Force*
C = *Drag coefficient*
ρ = *Air density*
A= *Total Effective Area*
v_w= *Air Velocity*

Fundamental mechanics of materials uses structural models that examine "the internal effects of stress and strain in a solid body that is subjected to an external loading" (Hibbeler, 2011, 3). Several types of stresses can develop under different loading conditions. Load applied parallel to the length of a beam generally results in axial stress. Axial stress can be described as:

$$\sigma = \frac{F}{A} \qquad \text{(EQ 2)}$$

Where:

σ = *axial stress*
F= *applied load*
A= $cross\ sectional\ area\ of\ beam$

In general, shear and bending stresses develop when a load is applied perpendicular to the length of a beam. Maximum bending stresses can be calculated for specific components at their extreme external fibers using the flexure formula (Hibbeler, 2011, 287):

$$\sigma = \frac{Mc}{I} \qquad \text{(EQ 3)}$$

Where:

σ = normal stress in the member
M = resultant internal moment
c = perpendicular distance from neutral axis to extreme fiber
I = moment of inertia of cross section about neutral axis

Average shear stress of a structural element can be calculated using the shear formula (Hibbeler, 2011, 363):

$$\tau = \frac{VQ}{It} \qquad \text{(EQ 4)}$$

Where:

τ = internal shear stress
V = internal resultant shear force (determined from method of sections and equations of equilibrium
Q= $\overline{y}'A'$ where A' is the area above or below where t is measured, and $\overline{y}'$ is the distance between the neutral axis and centroid of A'
I = moment of inertia of cross section about neutral axis
t = width of cross section where τ is measured

The accuracy of the flexure and shear formulas depends on certain criteria. The flexure formula determines "the normal stress in a straight member having a cross section that is symmetrical with respect to an axis, and the moment is applied perpendicular to this axis" (Hibbeler, 2011, 287). Derivation of the shear formula is based on the flexure formula. Therefore, the same criteria must be met when using the shear formula.

Certain components of the guide way system do not meet the flexure or shear formula criteria. Specifically, the guide way beam is a built-up member that does not have a symmetrical cross section about any axis and is not composed of a homogenous isotropic material. Therefore, the bending and shear formulas are used only for rough approximations of demand stresses in order to make design judgments and decisions regarding construction of the guide way system.

Chapter 3. Schematic Phase

3.1 Overview

The author's participation began with attendance of weekly Spartan Superway meetings on February 26, 2014. At this date the schematic phase of the elevated guide way design was progressing and project duration was limited. Eighty days remained until the product delivery deadline. A detailed project log is given in the Appendix.

Initially, the guide way team proposed the schematic shown below in Figure 1. This design included a supporting structure using a box column design. For aesthetics, the supporting columns were designed as four pieces of 16 x 1/4 inch flat plate steel. These plates were to be welded together to form a ten foot tall column. Support arm plates would be welded to the top of the steel columns, and a 16 foot long built-up timber beam would be mounted to a steel back plate.

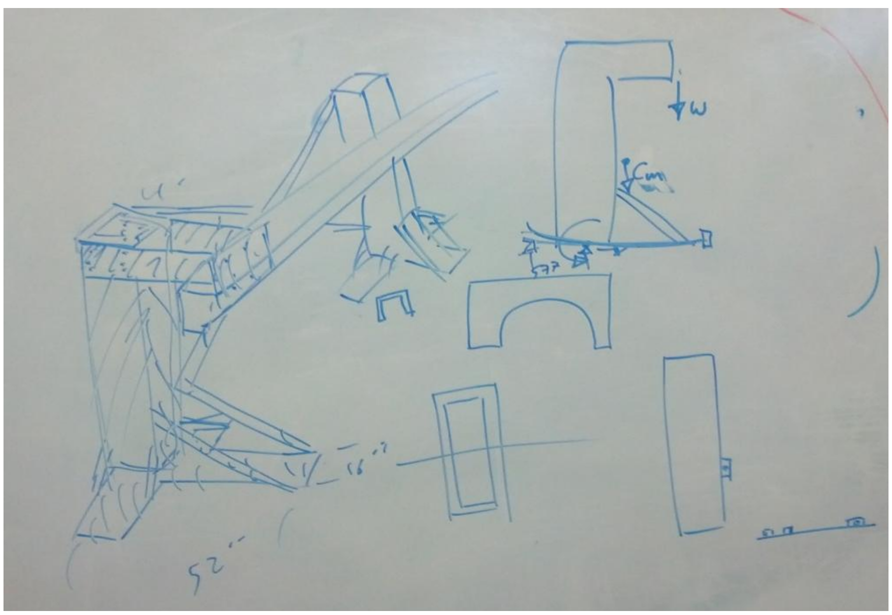


Figure 1 White Board Sketch of Elevated Guide Way Initial Design (Wicklow, 2014).

Design of the structural system evolved from this point with SCES and Spartan Superway Team collaboration. Though technical assistance was provided (see calculation sheets in Appendix) and structural design reviewed by the SCES; the guide way team was responsible for the final design of the guide way and all necessary design decisions.

3.2 Composite Timber Guide Way

Timber guide way beam design information was limited during the schematic phase of the project. An irregular plywood box beam supported by a 2 x 4 frame was proposed by the Spartan Superway Team. The riding surface of the guide way would be capped with steel channel. Geometric cross section assumptions were made by the assisting SCES in accord with the previous design illustration (Figure 1). These were drawn and presented to the guide way team. The technical validity of these drawings was verified by the guide way team after several iterations.

Rigidity of the composite timber guide way was addressed. The assisting SCES questioned the rigidity of the composite timber guide way beam as designed. Gaps would exist between the numerous 2x4 rib blocking joints, and plywood connections. These gaps might allow excessive internal movement when the composite timber beam is loaded; causing excessive beam deflection. The SCES suggested using construction adhesive at all connections and to fill all gaps. This suggestion was implemented in construction of the composite timber guide way.

3.3 Steel Support Assemblies

Reducing the weight of the steel structure was a concern. The initial column assembly design weight was substantial (458 lbs each). The column assemblies would be difficult to transport to the Makers Faire event. SCES analysis of plywood box columns proved that plywood of similar cross section would not have sufficient strength to resist design forces; specifically at connections. After a week of correspondence with the Spartan Superway team the final column design was established. As Dr. Furman had suggested, the columns would be constructed using HSS4x4x1/4 steel tube.

Design of steel column assemblies continued. The initial schematic design of the supporting columns included a hinged connection at the base (see Figure 2). The sono-tube shown in Figure 2 was provided to satisfy initial aesthetic design. The hinged joint design was founded on the premise that a hinged base would facilitate transportation of the assembly and allow it to be easily tipped up. Though this design resolved transportation and set-up concerns; fabricating steel components would be difficult and time consuming.

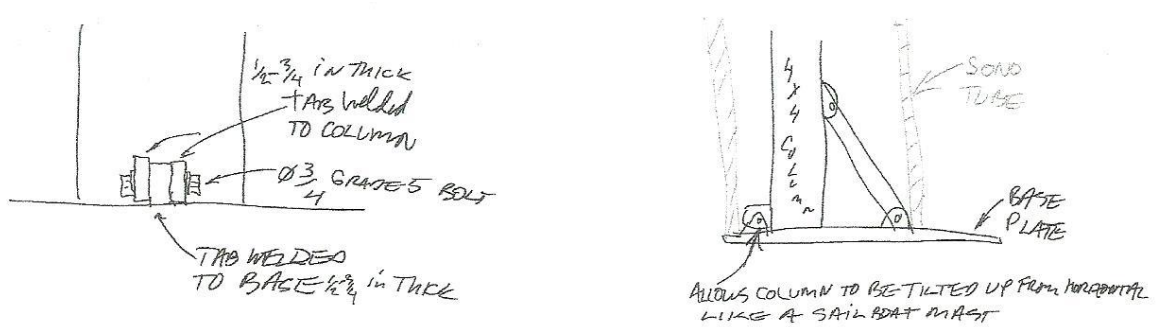


Figure 2 Schematic Phase Column to Base Hinge Connection (Furman 2014)

After the column cross section had been changed, the SCES calculations confirmed that each supporting column assembly would now weigh approximately 260 pounds. It was expected that four people could maneuver the assembly (65 pounds per person). The SCES suggested constructing each steel column assembly as one unit; thus, avoiding the complexity and fabrication time associated with a hinged joint. This suggestion became part of the final design. On March 25, 2014 the guide way design team had concluded that each column assembly would be constructed as a single unit.

Communicating further preliminary design calculations required improved illustrations; therefore, the SCES composed a set of drawings based upon Figure 1 illustration and the free body diagram sketches provided by the guide way team March 24, 2014 (see Appendix). Drawing Set March 28, 2014 was used during the project to convey information to the welding technician for a design-build strategy. The drawings evolved during the period of the project. At project completion, the drawings received final editing and became the detailed shop drawings found in the Appendix. The guide way team presented their drawings to the SCES much later in the design phase: April 21, 2014. The guide way team drawings are also presented in the Appendix.

3.4 Exhibit Assembly

Connecting the composite timber guide way beam to support columns during assembly was identified as a challenge early in the schematic phase. A method was required to lift the estimated 634 pound timber guide way 10 feet to the steel supporting back plates. Several options were identified. Both steel and timber lifting structures were proposed. Each would provide an elevated location to mount a winch. Construction time of a lifting structure was constrained by the impending project delivery date. Therefore, another alternative was required. Fortunately, a fork lift was found available at the work space and destination site. The proposed lifting structure suggestion was abandoned.

Securing lifting straps to the guide way presented difficulties during the initial fit-up of the assembly. The irregular shape of the guide way prevented reliable lifting strap attachment. The assisting SCES proposed a lifting alternative. An eye-bolt mounted at the center of guide way mass could provide an attachment for a chain with S-hook. The guide way could then be lifted in a secure and controllable manner. The Spartan Superway Team was concerned that the guide way structure was insufficient to resist lifting forces induced by one eye-bolt. The SCES calculated that the guide way structure could resist lifting forces with a reasonable factor of safety. Supporting calculations are given in the Appendix.

Chapter 4. Development of Analytical Model

4.1 Prototype Design

A final design was reached after several weeks of collaboration among the SCES and Spartan Superway Teams (see Figure 3). The full scale exhibit prototype consists of two identical steel column assemblies and a built-up composite timber guide way beam. The timber beam section provides a 16 foot long elevated path for the transit vehicle cabin. The steel support structure suspends the timber beam at a height of eighty-six inches. Steel back plates connect to the timber guiderail 32 inches from the guide way ends. A 10'- 8" span remains between the two support arms.

In addition to the vehicle cabin and guide way, solar panels are supported by the steel column assemblies. The solar array has a width of three feet, spans the entire length of the guide way, and is fixed at a 30 degree angle from horizontal. An aluminum frame supports the solar panels and connects to the top of the steel columns.

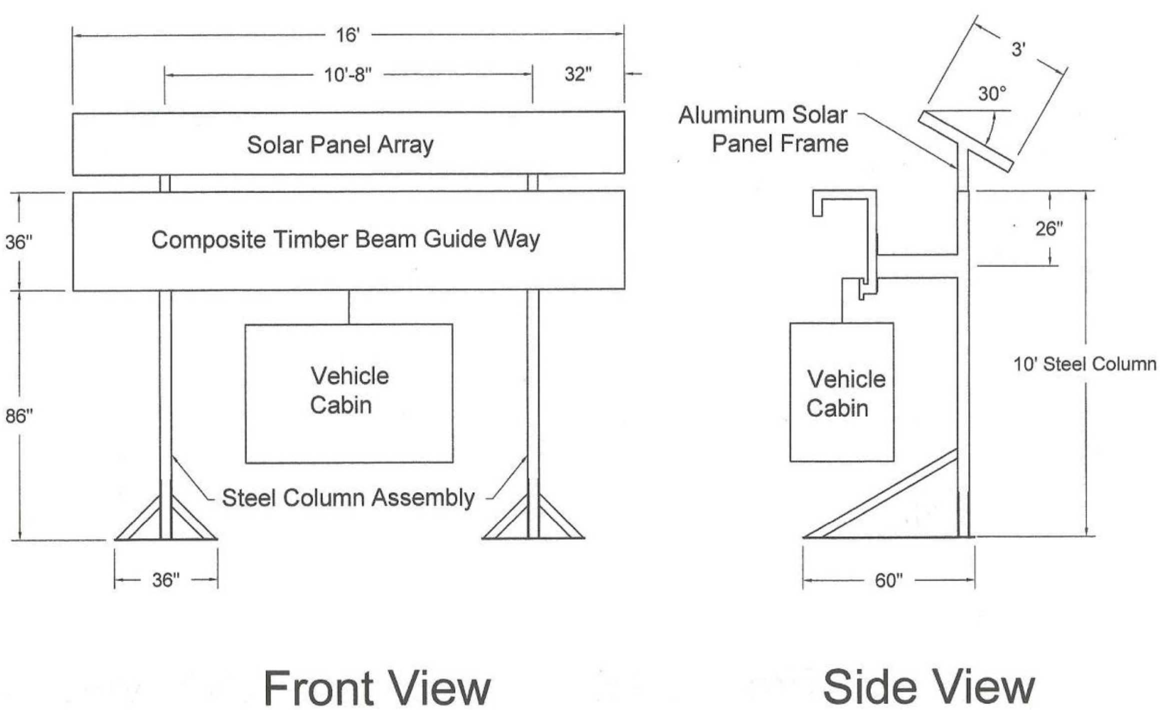


Figure 3 Full Scale Exhibit Guide Way Model

The steel support structures consist of two identical welded assemblies shown below in Figure 4. Each assembly consists of four primary components: the base plate, support column, support-arms, and back plate. The base plate provides vertical and lateral stability for the columns. Steel braces extend at angles from the outermost portions of the base plate to the column. The steel braces provide lateral stability for the guide way system. The steel column extends ten feet from the base plate to the solar array mount. Two support arms extend 32 inches from the rear of the column to the back plate. The back plates connect the steel support arms to the timber guide way beam.

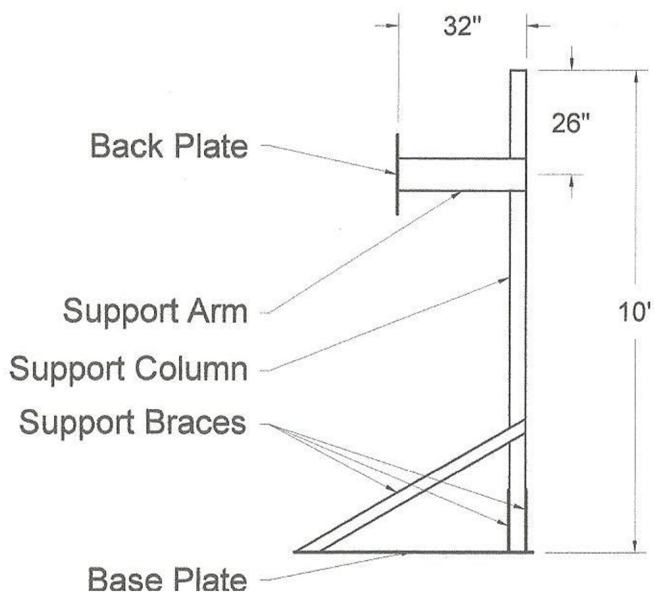


Figure 4 Welded Steel Support Structure Assembly

The timber guide way beam shown in Figure 5 is a composite system. The beam is composed of plywood sheets, wood boards, steel L-brackets, and nails. A frame work of 2x4 ribs provides the core structure. Steel angles are screwed and glued (both sides) at all orthogonal joints of the 2x4 ribs. A 2x4 tension chord runs the bottom length of the beam and secures the bottom end of the rib components. Horizontal blocking is placed between the 2x4 ribs along the two upper corner lengths. The blocking serves as both a compression chord and plywood backing. This frame work is sandwiched by a ¾ inch glued plywood shell. The vehicle guide rail is fastened to the core structure with construction adhesive and steel bolts.

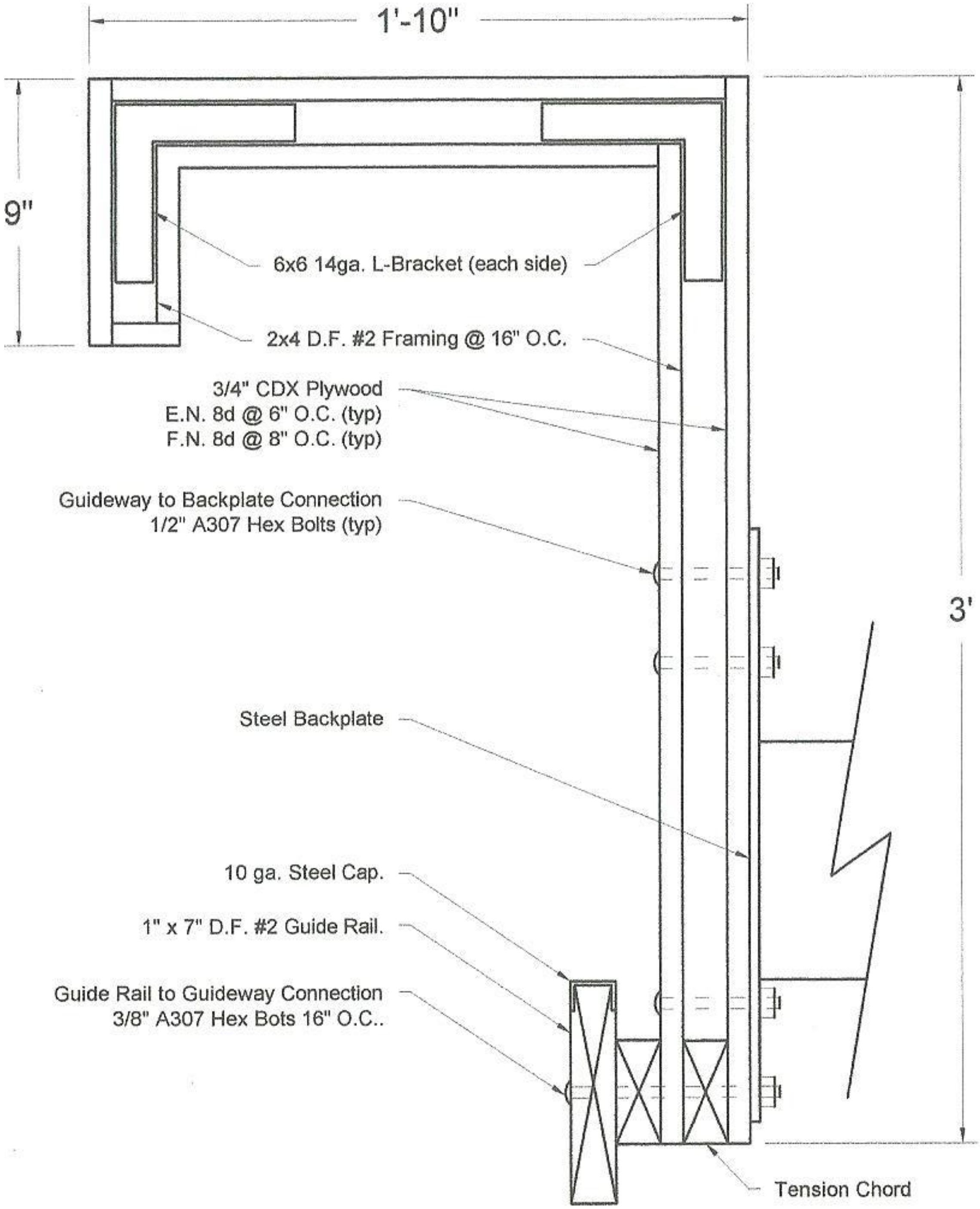


Figure 5 Plywood Timber Guide Way Beam Cross Section

4.2 Structural Model

Several assumptions were made during the design development phase of the guide way system:

General Assumptions:

- Material behavior is linear elastic
- Cross sections are prismatic
- Cross sections behave as homogenous isotropic material
- Plane cross sections remain plane after deformation
- Material warping does not occur after deformation

Composite Timber Beam:

- Framing Timber is Douglas Fir No. 2
- Plywood edge nailing is 10d common nails at 6” O.C.
- All joints are rigid connections

Steel Column Assemblies:

- Column steel is ASTM A-500 Gr. B
- Plate steel is ASTM A-572 Gr. 50
- Welding electrode is E70
- Base plates provide resistance to rotation and translation

Connections:

- Bolts are grade A307-N
- All welds are ¼ inch fillet

4.3 Gravity Load

Gravity load demands resisted by specific structural components were verified by the SCES. Figure 6 shows component positions and locations of center of mass. Component descriptions, item numbers, and weights are given in Table 5.

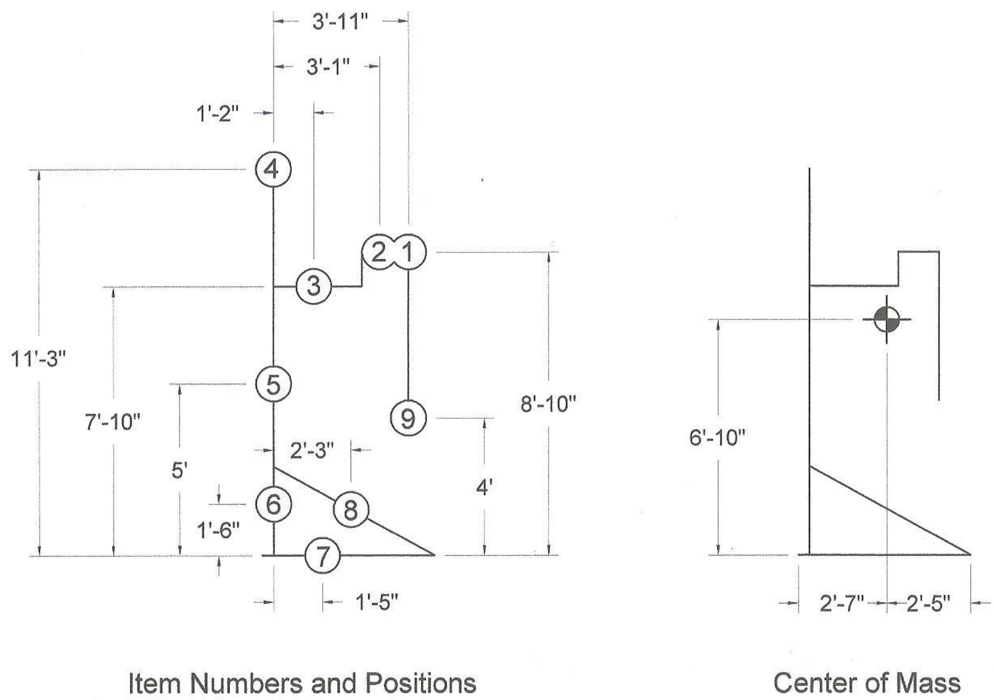


Figure 6 Component Positions and Locations of Center of Mass

Table 5 Component Descriptions and Weights

Item	Item ID	Number of Items	Item Weight (lb)	Total Weight (lb)
Bogey	1	2	250	500
Guide way	2	1	634	634
Support Arm	3	4	20	80
Solar	4	1	200	200
Column	5	2	122	244
45° Brace	6	8	7	56
Base Plate	7	2	119	238
30° Brace	8	4	17	68
Vehicle Cabin	9	1	150	150
			Total Assembly Weight	2170 lb

4.4 Lateral Load

Analysis of longitudinal overturning due to lateral forces was evaluated qualitatively. The weight of each column assembly opposes the overturning moment in the longitudinal direction. The vehicle cabin will remain essentially stationary during the exhibition and the effective area subjected to wind force is relatively small; therefore, longitudinal lateral forces are assumed to be minimal. Analysis of the transverse direction of loading was conducted in a more quantitative manner.

Wind forces were analyzed by the SCES using the assumed distribution shown in Figure 7 below. Wind load is resisted by two effective areas: the guide way/vehicle cabin (Af1), and solar panel (Af2). The two resulting wind load forces (Fw1 and Fw2) are modeled at the centroid of their respective areas. The total wind force is then considered as a single point load (Fwr) acting horizontally on the structure. Maximum wind load is considered at the wind velocity required to overturn the structure. Global structural stability limits the extent of the induced wind force.

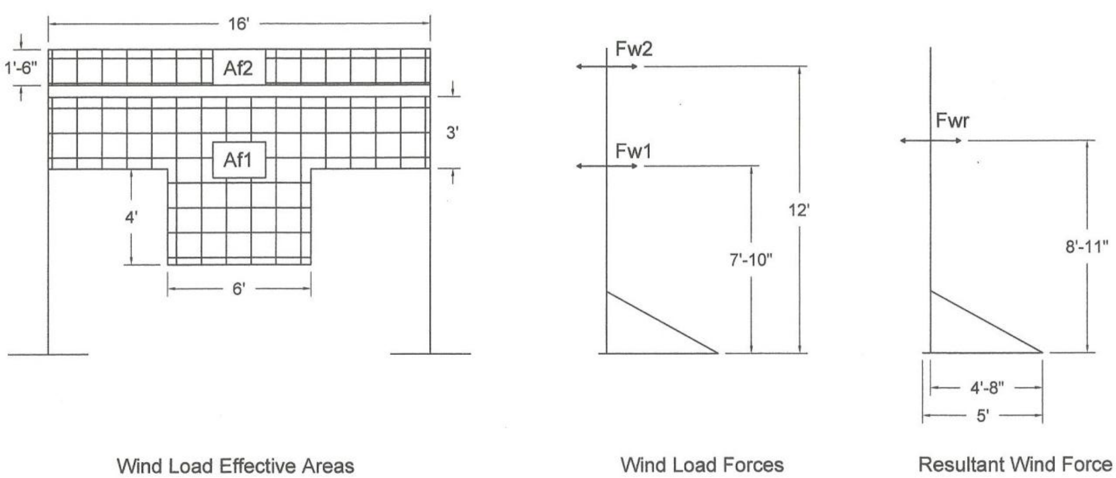


Figure 7 Assumed Effective Areas and Resultant Wind Force

Chapter 5 Analysis Results

5.1 Structure Overturning

Structure overturning could occur if the wind load generates a demand moment greater than the structure's overturning resistance. Since the structure's center of mass is one inch eccentric toward the front, the structure is more likely to tip forward than rearward. However, both forward and rearward overturning was analyzed. The structural system is in equilibrium for overturning when the moments are equal, or when:

$$M_m = M_w$$

Where:

M_m = resistive moment due to mass
M_w = overturning moment induced by wind

From Figure 8, the statement for forward overturning can be written:

$$M_m = (2170lb)(29in.) = M_w = F_w(107in.);\ \ which\ correspondes\ to:$$

$$\boldsymbol{F_w = 588\ lb\ or\ 0.0425\ psi}$$

Likewise, for rearward over turning, a similar statement can be written as:

$$M_m = (2170lb)(31in.) = M_w = F_w(107in.);\ \ which\ correspondes\ to:$$

$$\boldsymbol{F_w = 629\ lb\ or\ 0.0455\ psi}$$

Therefore, the calculated overturning capacity of the structure is 5.24 kip·ft. forward and 5.61 kip·ft rearward. Using Equation 1, the calculated minimum wind speed (before tipping) results in forward air velocity $\boldsymbol{v_w}$**= 50 mph**. This indicates that a minimum 50 mph wind would generate a resultant 588 pounds of lateral force at a height of 107 inches, and cause potential forward overturning of the structure.

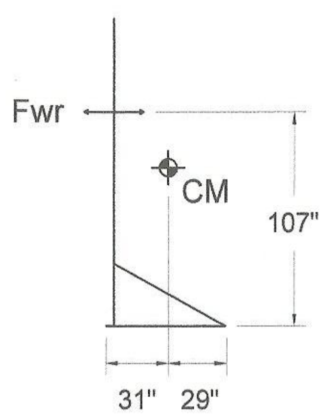


Figure 8 Overturning Analysis Model

5.2 Guide Way

Internal forces associated with specific structural elements can be determined once vertical and horizontal loading has been established and support conditions idealized. Induced internal forces depend on the location and orientation of loading with respect to a structural element   Planar loading can result in axial, transverse, and longitudinal internal forces.

For analysis, the composite timber guide way is modeled as a continuous beam with continuity over both supports as shown in Figure 9. Quantitative values of estimated weights for solar panels, bogie, and cabin were received from respective group managers. Self-weight of the guide way was determined by the SCES while providing technical assistance to the guide way team. Estimated self weight of the composite guide way beam was based on documented minimum weights of materials (ASCE 7) which resulted in a uniformly distributed load of 39.6 lb/ft.

The vehicle cabin is a simulated passenger car that is suspended from two bogies. The bogies are steel mechanisms that guide the vehicle cabin along the guide way path. The weight of vehicle cabin and two bogies results in two point loads (F1 and F2) on the guide way. The combined guide way, bogies, and vehicle cabin loading results in two gravity loads (R1 and R2) acting at the exterior end of each support arm assembly. The solar array results in point loads at the top of the columns since it is not directly attached to the guide way.

Shear and moment diagrams were calculated according to guide way loading. Internal guide way shear forces were determined using method of sections and equations of equilibrium. A maximum shear force of 536 lb was found to occur at each support (V1 and V2). Internal bending moment forces in the guide way were deduced as the sum of areas given in the shear diagram. A maximum bending moment of 1.68 kip·ft was calculated at the center of the guide way span (M1).

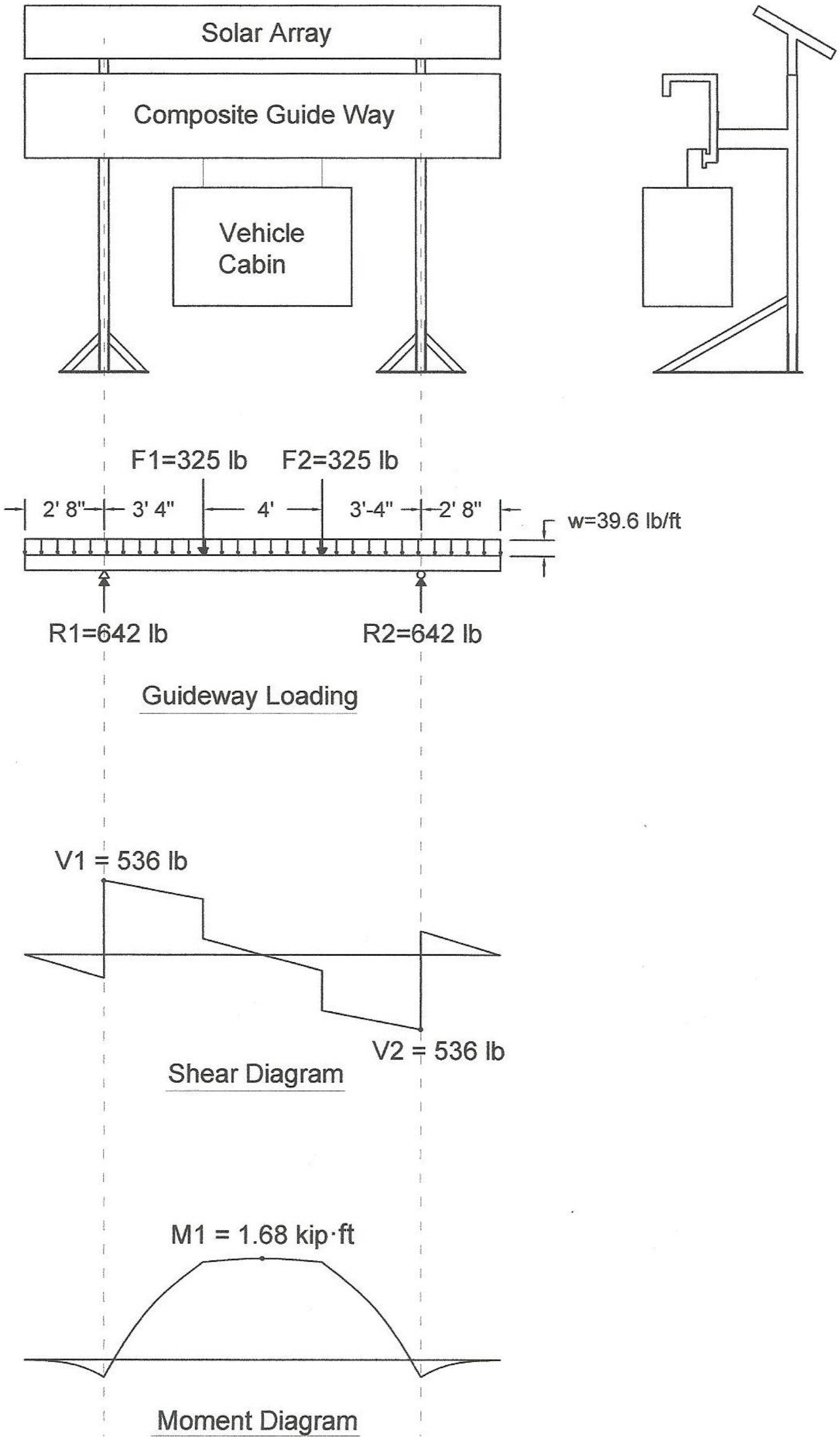


Figure 9 Geometry and Loading of Composite Timber Guide Way Beam, Shear Diagram, and Moment Diagram

5.3 Steel Support Assemblies

The steel support assemblies are modeled as braced columns to allow for structural analysis as shown in Figure 10. The support arms and column are assumed to form a rigid bent. Pin connections are assumed between the composite timber guide way beam and support arms. Pinned connections are assumed at all diagonal brace connections. Gravity load of cabin, bogies, and guide way is modeled as a single force resultant for column stress analysis. Self weight of the steel components was attained from manufacturer specifications (PDM).

Demand stresses were calculated according to allowable strength design load combinations. Column shear forces were determined using method of sections and equations of equilibrium. A maximum shear force of 2.84 kip was found to occur in the column section below the diagonal brace (V4). Internal bending moment demand forces in the columns were deduced as the sum of areas given in the shear diagram. A maximum bending moment demand of 7.3 kip·ft was calculated at a height of 31 inches at the diagonal brace connection (M4).

Several smaller analytical models were developed to calculate internal demand forces on individual structural components. These models are described and illustrated in the following chapter.

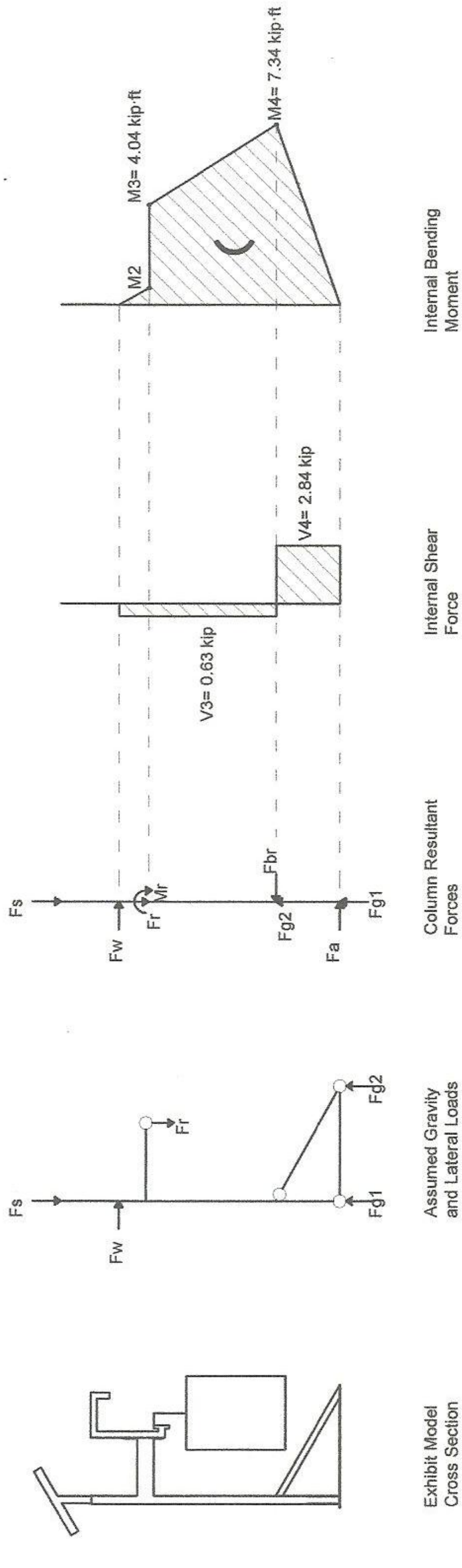


Figure 10 Steel Support Assembly Structural Model

Chapter 6 Stress Analysis

6.1 Overview

Several iterative models were required for the structural analysis during design development of the guide way exhibit. Since the project was a prototype done under time constraints, structural analysis was done on components only for assumed critical limit states. Time constraints did not allow a detailed evaluation of every structural force aspect. Load combinations were assumed according to allowable strength design specifications (SEI/ASCE7, Section 2.4) and fundamental mechanics of materials were used to calculate specific demand stresses. Resulting critical demand stresses were verified to be less than the ASD specified allowable internal capacity stresses. Efficiency of the design is expressed as a demand/capacity ratio.

6.2 Composite Timber Guide Way Beam

Two load combinations were assumed to apply to the timber guide way beam: load combination 1 (dead load alone), and load combination 2 (dead load + wind load); no amplification factors apply to load combinations. All timber strength adjustment factors are assumed to be equal to one; except the load duration factor. For load combination 1 the load duration factor is 0.9, and for load combination 2 the load duration factor is 1.6 (Breyer et al, 4.39). Maximum demand shear stress due to gravity load is assumed to occur at the horizontal neutral axis of the beam cross section as shown in Figure 11. Maximum demand stresses due to bending are evaluated at the tensile and compressive extreme fibers of the composite beam. The calculated values for the stress analysis of the timber guide way beam way is shown in Table 6. Sample calculations are given in the Appendix.

Similarly, the lateral wind load induced stresses are evaluated relative to the vertical neutral axis of the beam cross section. However, only the lower half of the guide way beam is considered. This is due to the fact that the vehicle cabin is suspended from the bottom rail of the guide way. Wind load generated from the vehicle cabin is assumed to act only at the bottom portion of the guide way as two point loads located at each bogie/guide rail attachment.

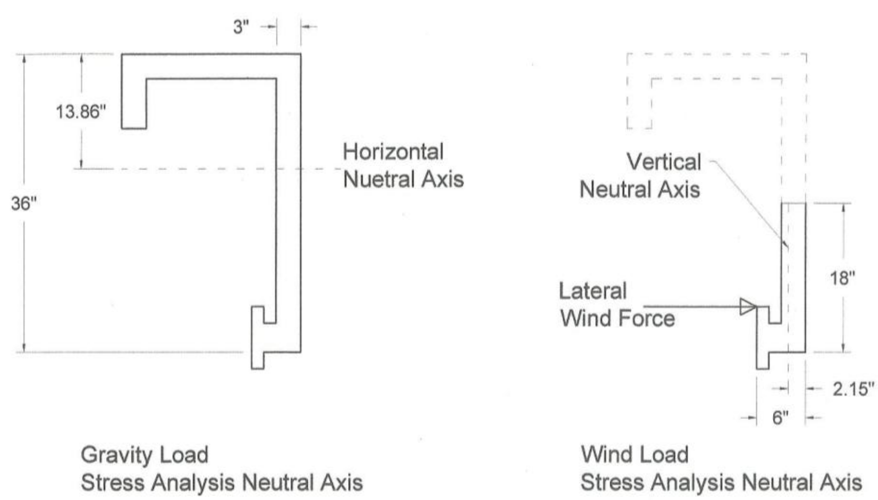


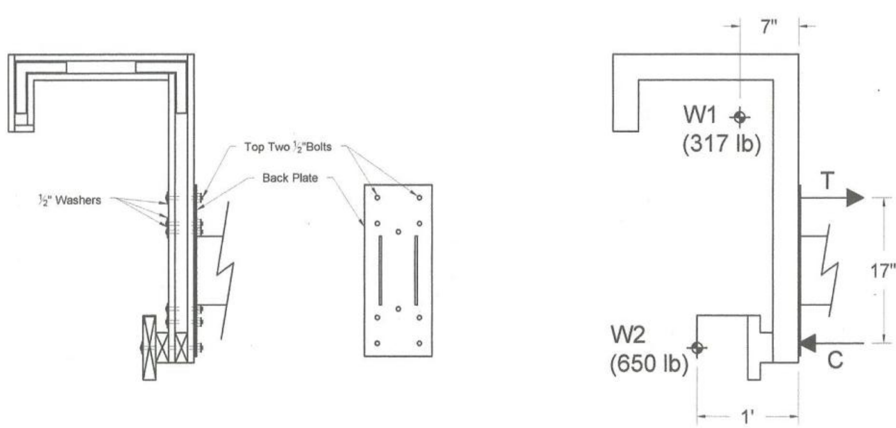
Figure 11 Horizontal and Vertical Neutral Axis

Table 6 Composite Timber Guide Way Stress Analysis

Stress Parameter	Capacity (psi) F	Load Combination Capacity* (psi)		Service Level Demand (psi)		Load Combination Demand (psi)		Critical D/C Ratio	
		F_1'	F_2'	Dead	Wind	f_1	f_2	Combo	Value
Shear Stress	180	162	288	12.5	2.2	12.5	14.7	1	0.08
Bending (tension)	575	518	920	8.64	73.6	8.64	82.2	2	0.09
Bending (Compression)	900	810	1440	13.8	114.7	13.8	128.5	2	0.08

*Load combination 1 is (dead load alone); $C_d = 0.9$
Load combination 2 is (1 x dead load + 1 x wind load); $C_d = 1.6$

The guide way is connected to the back plates using ten ½" bolts at each connection. The shear force R1 and R2 (Fig. 8) is assumed to be evenly distributed through the bolts at each respective connection. Torque from the guide way, vehicle cabin, and bogies induce a bending moment on the back plates. The torque induces a couple with a maximum tension force (T = 587 lb) assumed to be distributed to the top two bolts which in turn induces compressive forces between the inside of the guide way and bolt washers. Crushing of the plywood guide way is analyzed at this location using the area of the two ½" washers (see Appendix). The calculated values for the stress analysis of the timber guide way beam to steel back plate are given in Table 7. The distance from edge of bolt hole to edge of back plate is greater than two bolt diameters; therefore, shear tear-out will not control (Geschwindner, 369).



Guide Way/Back Plate
Bolt Connections

Force Body Diagram

Figure 12 Guide Way to Back Plate Connection

Table 7 Guide Way to Back Plate Bolt Connections Stress Analysis

Strength Parameter	Item	No. of Items	Item Capacity	Total Capacity	Demand	D/C
Bolt Tension (kip)	½” A307-N Bolt	2	4.42	8.84	0.616	0.07
Bolt Shear (kip)	½” A307-N Bolt	10	2.65	26.5	0.642	0.02
Bolt Bearing (kip)	½” A307-N Bolt	10	8.70	174	0.642	0.003

Stress Parameter	Capacity (psi) $F_{c\perp}$	Load Combination Capacity* (psi)		Service Level Demand (psi)		Load Combination Demand (psi)		Critical D/C Ratio	
		F_1'	F_2'	Dead	Wind	f_1	f_2	Combo	Value
Plywood Crushing (psi)	625	563	1000	488	12.2	488	500.2	1	0.87

Vertical and lateral loads are assumed to bear on the guiderail as shown in Figure 13. The vertical gravity load of cabin and bogies (650 lb) bears on the top of the guiderail. Eccentricity of gravity load induces a lateral force (176 lb) on the bottom of the guiderail. The gravity and lateral loads are equally divided into point loads 4 feet apart; the distance between centers of bogies. This load combination is transferred from the guiderail to the guide way through a glued and bolted connection. The connection is glued with construction adhesive and uses ¼” bolts spaced at 14 inches on center. The faying surfaces of the glued connections are neglected for bolt stress analysis.

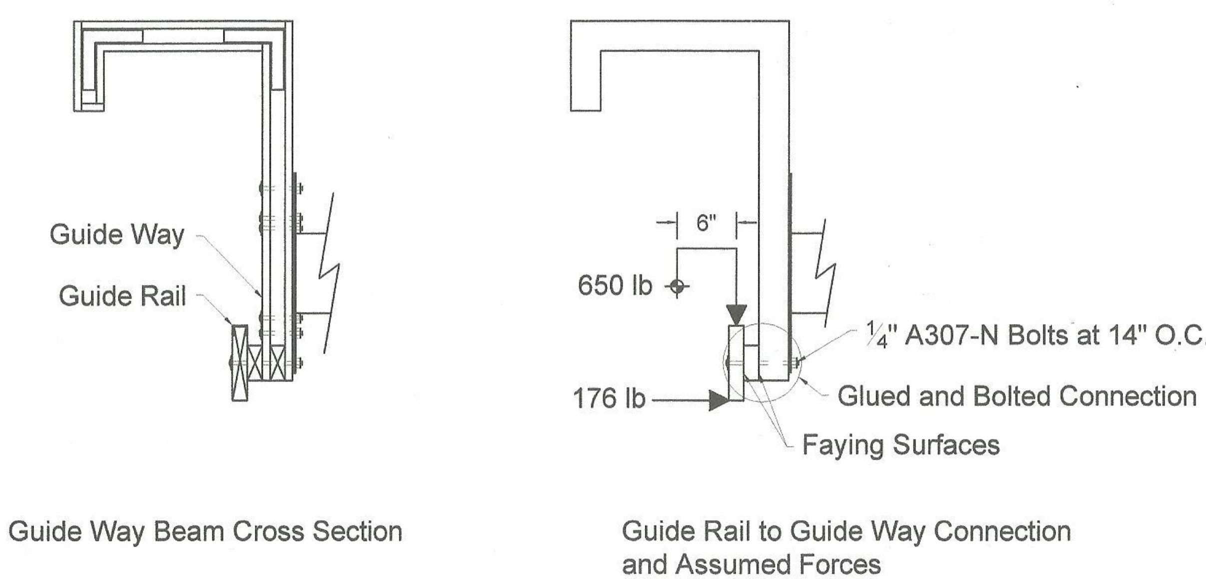


Figure 13 Guide Rail to Guide Way Bolted Connection

Table 8 Guiderail to Guide Way Bolt Connections Stress Analysis

Strength Parameter	Item	Capacity	Demand	D/C
Tension (kip)	¼" A307-N Bolt	1.10	0.088	0.08
Shear (kip)	¼" A307-N Bolt	0.66	0.325	0.49
Plywood Crushing (psi)	¼" Washer on D.F. #2 Plywood	563	474	0.84

6.3 Steel Support Column Assemblies

The HSS4x4x1/4 steel columns resist axial, shear, and bending forces as shown in Figure 10. Axial compressive stresses are induced by gravity load of cabin, bogies, guide way, and solar panels. Shear stresses are induced by the wind load; however, the associated shear stress is assumed to be minimal relative to the shear limit state of the column. Bending stresses are induced by the wind force and the torque produced by the support arms. The bending demand is calculated at the extreme fiber of the column cross section. Bending capacity is considered as the elastic yield stress of ASTM A-572 Gr. 50 steel. Calculated values for the column analysis are given in Table 9. Supporting calculations are given in the Appendix.

Beam-column analysis was not addressed for two reasons: one, bending demand is significantly lower than bending capacity; and two, time constraints limited the depth of analysis.

Table 9 Column Bending and Yielding Analysis Values

Strength Parameter	Capacity	Demand	D/C
Yielding (kip)	101	1.23	0.01
Buckling (kip)	55.5	1.23	0.02
Bending (ksi)	29.9	22.6	0.75

The diagonal braces were modeled as pin connected rods. Basic principles of structural analysis indicate that the diagonal braces resist 2.3 kip of compressive force; 1.15 kip each. The effective length of each diagonal brace is reduced to 19.5 inches by placement of a 4 x 2 x 1/8 steel tube web stiffener shown in Figure 14. Since the stiffener is not continuous through the entire length of the braces, the braces are analyzed using two different scenarios: case one, as a solid doubled brace running the full length resisting the full 2.3 kip; and case two, as a single brace with 19.5 inch effective length resisting half the induced load (1.15 kip). Calculated values for the diagonal brace analysis are given in Table 10.

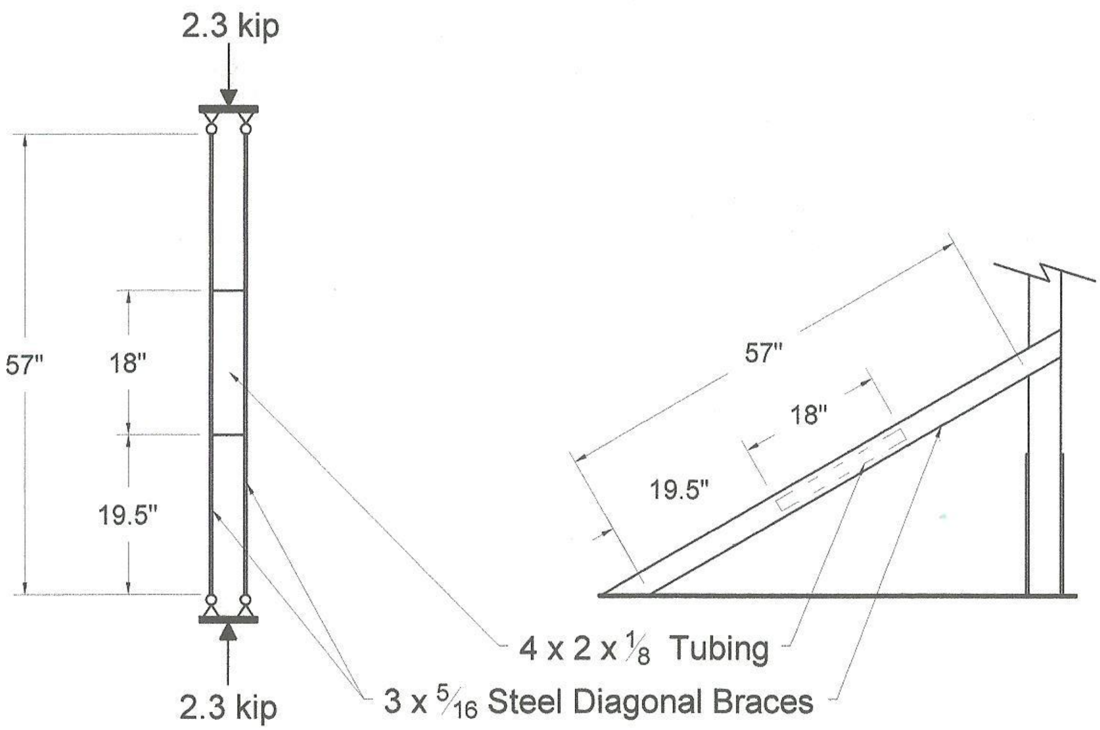


Figure 14 Diagonal Braces Analytical Model

Table 10 Diagonal Braces Analysis Values

Diagonal Braces	**Capacity (kip)**	**Demand (kip)**	**D/C**
Yielding	28.1	2.30	0.08
Buckling Case 1	2.78	2.30	0.83
Buckling Case 2	3.01	1.15	0.38
Welds			
Brace to Base Plate	44	1.15	0.03
Brace to Column	34	1.15	0.03

The horizontal support arms resist the vertical gravity force of the guide way, bogies, and vehicle cabin. A lateral wind load is also resisted by the support arm; however, the wind load is assumed to induce minimal axial force. There are two support arms per column assembly; one welded to each side of the column. For analysis, vertical force induced stresses from the bogies, vehicle cabin, and half the guide way is assumed to be equally divided between the two support arms of one column. The combined weights are modeled as a resultant vertical force (1007 lb) as shown in Figure 15. This model is also used to determine demand on support arm to column weld connections (F1 and F2). Calculated values for the support arm analysis are given in Table 11.

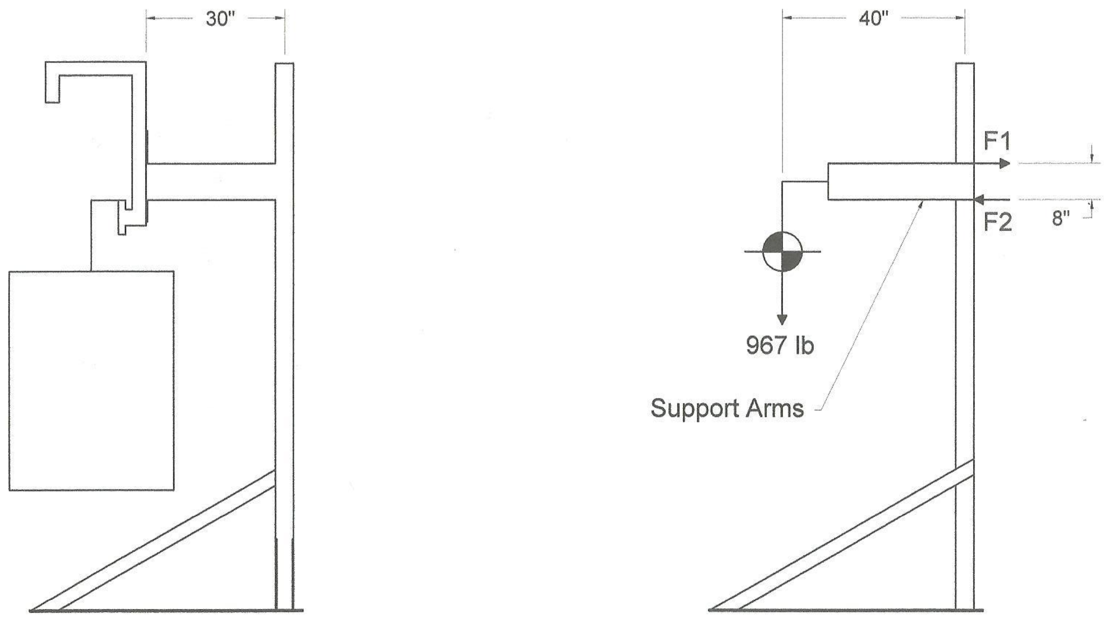


Figure 15 Support Arms Analytical Model

Table 11 Support Arms Analysis Values

Strength Parameter	Capacity	Demand	D/C
Bending (ksi)	22.9	13.8	0.60
Weld Location			
Support Arm to Column Shear (kip)	29.6	5.04	0.17
Support Arm to Back Plate Shear (kip)	59.2	0.967	0.02

The back plate that connects the timber guide way to the steel support structure is subjected to a combination of forces. Gravity load from the guide way, bogies, and vehicle cabin is transferred through the back plate and bolt connections as a shear force. The dominant force is assumed to be torque on the back plate that is produced from the eccentricity of the guide way, bogies and vehicle cabin. The load applied to the back plate to support arms connection is eccentric to the plane of the weld. Vector mechanics was employed to calculate maximum demand on the weld at the extreme fiber on a force per length basis. This value was compared to the calculated longitudinal strength of weld. Calculated values for the weld analysis are given in Table12. Supporting calculations are given in the Appendix. Further analysis is required to verify accuracy of this method.

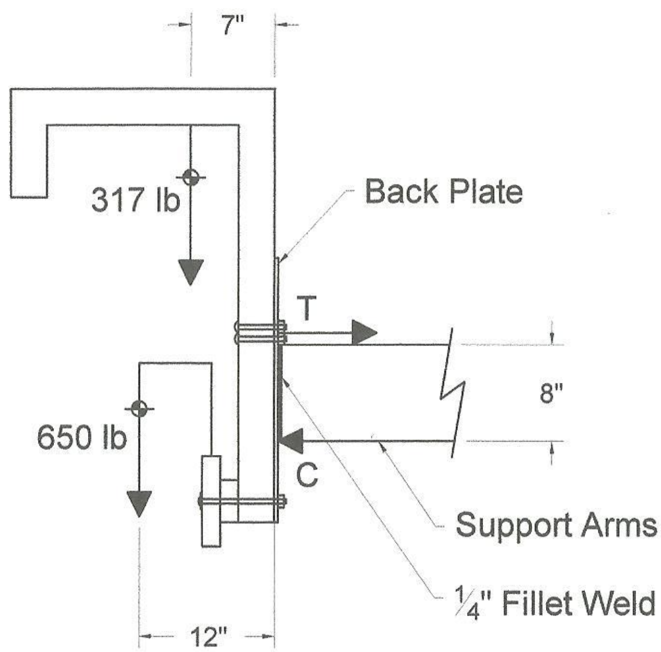


Figure 16 Back Plate Analysis Model

Table 12 Back Plate Analysis Values

Weld Strength Parameter	Capacity	Demand	D/C
In-Plane Shear (kip)	59.2	0.967	0.02
Combined Shear and Torsion (kip/in.)	3.71	0.47	0.13

Chapter 7 Full-Scale Model Construction

7.1 Guide Way Construction

Acquisition of building materials for the composite timber guide way required a group effort. The guide way team was responsible for initial acquisition of composite timber guide way building materials. These materials were mostly donated by the Santa Cruz location Big Creek Lumber Company. However, before construction could begin the donated building materials at the Santa Cruz Big Creek Lumber Co. required delivery to the San Jose building site. Big Creek Lumber Co. offers transportation of their building materials for a fee. As a time and cost saving measure the author volunteered to supply transportation for the building materials. Additional materials were needed during guide way construction. These were purchased and transported by the author and the cost was later reimbursed.

Fabrication and construction of the composite timber guide way proceeded efficiently. Assembly of the timber guide way structure began April 12, 2014 at 1555 South 7th Street. The composite timber guide way was completed the following day. A detailed work log is given in the Appendix.

The assisting SCES provided technical expertise and several construction tools. The guide way team was divided and delegated separate tasks. Plywood sections and 2 x 4 pieces were cut simultaneously using a parts list which had been prepared the previous day. Another guide way team member began assembling the 2 x 4 ribs once a few pieces were cut. The fabrication and construction of the composite beam proceeded smoothly. By the end of the first day of guide way construction the 2 x 4 structural ribs were completed and installation of the plywood shell had begun (Figures 10 and 11).

The guide way team leader and author continued construction the following day and completed the composite timber beam. Only attachment of the bogie guide rail remained for completion of the timber assembly.

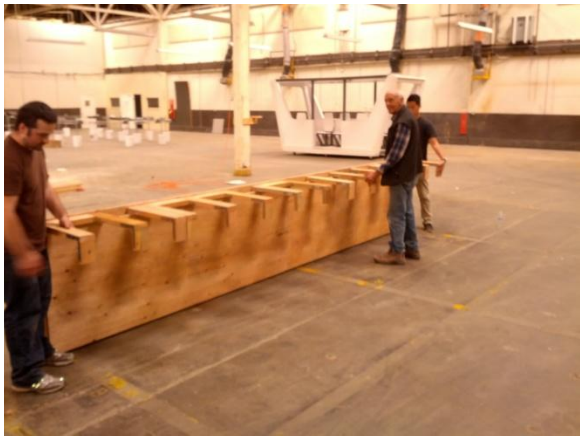


Figure 17 Guide Way Construction 1

Figure 18 Guide Way Construction 2

7.2 Steel Support Construction

Scheduling fabrication and construction time for steel column assemblies was difficult. Conflicting schedules and lack of access to steel machine tools delayed construction progress. Final design details were established during construction. Personal correspondence with Pat Joice, (the welding technician) began April 9, 2014. The two steel column assemblies were completed May 2, 2014.

During this time period, actual steel fabrication and assembly was intermittent. The design of the steel support assemblies evolved and construction related obstacles were overcome. Every opportunity was exhausted to insure that the steel column construction progressed in a timely manner. A detailed construction time estimate and actual work log is given in the Appendix.

Twenty-four and a half hours of work was estimated for steel fabrication and welding of each column assembly. The project log denotes 58.5 work hours involved for construction of both steel column assemblies. Actual fabrication and welding time of steel column assemblies was under estimated by 16%. This miscalculation was partly due to unfamiliarity with steel fabrication and construction. Positioning components for welding took longer than expected and standby time was not considered.

The 8x1/4 inch flat plate components and HSS4x4x1/4 square tube were cut to size by PDM Steel Supply. Angles remained to be cut at the ends of the twelve 3x5/16 diagonal brace pieces. Acquisition of use to the university machine shop was delayed and the guide way team did not have the means to cut angles in steel. Therefore, the SCES volunteered for the task.

Cutting angles into the brace pieces was time consuming. Mitered angles were cut on the steel plate stock at the author's carpentry shop using his tools and labor. A 10 inch metal cutting blade was fitted to a compound miter saw. The length and end angles were marked on each of the 12 steel plates. Then in succession, each end was clamped to the miter saw table and cut. The compound miter saw was not fit to cut a 60 degree angle of six inch length. Clamping was necessary to improve cutting accuracy and to perform required cuts.

Construction proceeded at a rapid pace after the above transportation and fabrication delays were overcome. Assembly of support columns began with the base plate components. The 8x1/4 inch steel base components and the 3x5/16 inch brace components are shown in Figure 13. A four inch grinding wheel was used to prepare steel surfaces for welding. Contaminants were

Figure 19 Base Plate Components for Steel Column Assembly

ground from the steel surface at all joints prior to welding.

Welding of steel components took place at the SJSU Engineering Building in room 127. Pat Joice is shown welding a base plate connection in Figure 14. This illustration also shows Cormac Wicklow in the background. Cormac is drilling holes in the back plate component for the timber guide way to steel support structure bolt connections. A drill press was purchased specifically for drilling these holes.

Meeting design tolerances during construction of the column structures was difficult due to the size and weight of the components. Special accommodations were made to insure the column was square to the base plate before welding. The top of the ten foot steel columns were clamped to a steel beam at ceiling level. This provided the necessary stability to make fine adjustments before welding. The flat plate base exhibited flexible characteristics. Special attention assured proper geometry of assembly at points of welds.

The guide way team, CE technician, and assisting structural civil engineering student constructed the two column assemblies in approximately two days. Finally, the two welded column assemblies were completed May 2, 2014 (shown in Figure 15) and transported to the 7th Street worksite the following day.

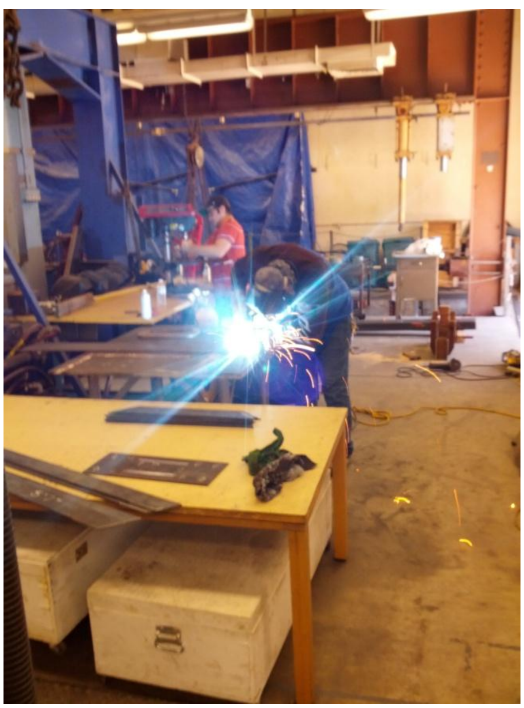


Figure 20 Beginning of Steel Column Construction. Pat Joice is shown welding base plate and Cormac Wicklow is shown drilling holes in back plate.

Figure 21 Completed Steel Support Column Assemblies. Daniel Conroy and Author are shown standing in background (Wicklow).

7.3 Assembly

Initial fit-up of the guide way to the support structures occurred May 3, 2014 during a Saturday workshop. A neighboring company to the workspace (Amberwood) supplied their forklift for the lifting procedure. The guideway was connected to the support columns without incident. The bogey, cabin, and solar teams now had 17 days (until the Maker Faire) to finalize and connect their components. The following are six illustrations show placement of the final components.

Figure 22 Initial Guide Way to Support Columns Connection (Furman).

Figure 23 Initial Bolting of Guide Way to Support Columns.

Figure 24 Completed Guide Way System.

Figure 25 Initial Bogie into Guide Way Placement

Figure 26 Bogie and Guide Way Side View

Figure 27 Completed Personal Rapid Transit (PRT) Protoype

7.4 Makers Faire

Transportation of the ATN model exhibit occurred Thursday, May 15, 2014. The guide way assembly was loaded onto a SJSU owned flat-bed truck and transported to the San Mateo Convention Center. A few ATN team members and the author used personal vehicles to transport other various exhibit items.

Reassembly of the full-scale prototype occurred with use of a forklift provided by personnel from the San Mateo Convention Center. The forklift was used to facilitate attachment of the guide way to the support columns, slide bogies into the guide way, and install the solar array above the guide way. Lifting and attaching the vehicle cabin was done manually.

Figure 28 Guideway Delivery at San Mateo Convention Center and Several Spartan Superway Team Participants.

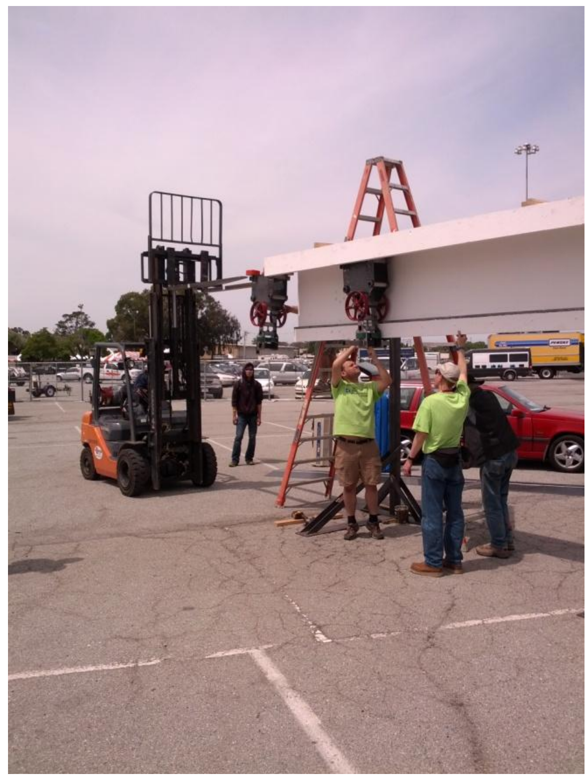


Figure 29 Bogie Installation at San Mateo Convention Center.

Work began on the remaining portion of the exhibit after the full scale prototype had been assembled (Figures 31 and 32). The exhibit entry structure and Spartan Superway banner was raised (Figure 30). On following day (Friday, May 16) Spartan Superway members set-up a 1/12th scale PRT model, a 25th scale model PRT model, posters, and various informative literature. The exhibit was complete for the Makers Faire Event.

Figure 30 Exhibit Entry Structure and Guide Way Assembly at San Mateo

Figure 31 Personal Rapid Transit (PRT) Exhibit at San Mateo Convention Center Convention Center (front view)

Figure 32 Personal Rapid Transit (PRT) Exhibit at San Mateo Convention Center (rear view)

Chapter 8. Deformation

Structural deformation was measured using general carpentry tools: level, straight edge, string line, etc. These tools provided accuracy to one sixteenth inch. Measurements were taken before and after application of service loads. Lateral wind load was simulated by cyclic loading applied manually.

Perpendicular and longitudinal cyclic lateral loading was applied to the support columns at a height of six feet. Force was applied approximately in time with the structures natural frequency in each orthogonal direction. Even though longitudinal lateral service loads were neglected during design development, longitudinal lateral structural stability was tested at the end of the guide way.

Steel

- Lateral deflection at the top of the steel columns was negligible upon application of constant working load. A four foot carpenter's level was employed to measure lateral deflection of the steel columns. The bubbles in the carpenters indicated that columns were plumb before and after application of load
- The 66.40 inch long braces exhibited insignificant horizontal deformation about their weak axis. Deformation occurred mid-span upon rapid change of loading conditions (cyclic loading perpendicular and longitudinal to the guide way). This deformation was considered acceptable by the guide way team because the deformation was almost unobservable.
- The support arms exhibited lateral deflection during system testing. Cyclic loading was applied by hand longitudinal to the guide way. The resulting cyclic horizontal translation of the support arms was approximately 0.5 inches from crest to trough and was visibly observable at the guide way side of the support arms. Lateral translation of the supporting columns was not observable.
- Vertical translation of the support column bases was not observable; however, sound was generated at the base plate/ground interface during cyclic testing (force applied to guide way). The sound was assumed to indicate rocking of the column support bases.

Timber

- Horizontal deflection of the guide way due to constant working load was not observed.
- Lateral deflection of the guide way due to constant working load or cyclic wind load was not observed.
- Twist deflection of the guide way due to working load was not observed.

Connections

- The bolt and weld connections were visually inspected. No deformation was observed.

Chapter 9. Conclusions and Recommendations

9.1 Conclusions

Development and construction of the full-scale prototype model of an elevated transportation system benefits several interests. First, the project organized students from diverse disciplines. Each student brought their own perspective which ultimately motivated evolution of the project to a final design. These students learned valuable team working skills and enjoyed the satisfaction of accomplishing a goal which could not be achieved individually. The project demonstrated the speed at which a small group can accomplish a large goal. Only four months were required for a portion of the Spartan Superway Team to design and build the full-scale personal rapid transit exhibit prototype.

Second, the full-scale model was and can be used to educate the public. The model serves as a show piece that draws attention. To date, the model has been showcased at two events: the Makers Faire at the San Mateo Convention Center (May 17, 2014), and the Intersolar Conference at the Moscone Convention Center in San Francisco (July 8 to July 10, 2014). The curiosity of people at both events was provoked by the size and peculiarity of the full-scale exhibit model. Interested people approached the model in wonder. Generally, this initiated an informative conversation with an ATN project representative.

Most conversations led to the conclusion that something must be done to make public transportation a sustainable system. The American Society of Civil Engineers 2013 Report Card for America's Infrastructure gave roads a (D), Energy a (D+), and rail a (C+), (ASCE). A solution to bring the grade up may just involve automated transportation systems. Personal rapid transit could utilize the benefits of rail; derive its own solar energy, while decreasing use and deterioration of conventional asphalt roadways.

Automated transportation networks could complete an unfinished transportation network. Main arterial transportation networks have been partially completed with systems such as Cal Train. Transportation veins are in place with light rail and other systems provided by organizations such as the Santa Clara Valley Transportation Authority (VTA). Public transportation could be made more efficient with the capillary function that automated transportation networks and personal rapid transportation systems could provide.

9.2 Recommendations for Future Work

Modeling of column support conditions was based on the assumption that the base plates provide sufficient resistance to rotation and lateral translation. Rotation of column base connection could occur given sufficient lateral wind speed (50 mph). Any alteration to the existing structure could change the stability of the prototype.

Significant guide way translation was observed when cyclic force was applied longitudinally to the end of the guide way. This implies that rigidity of the horizontal support arms may not be sufficient to resist braking or other forces applied axially to the guide way. Continued attention should be given to the support arm segment of the prototype should future exhibits include a moving cabin.

Composite timber guide way stresses were analyzed using a simplified model. Second order effects were neglected. The stresses induced by secondary effects may be significant in a guide way of greater length. Therefore, secondary effects should be analyzed for an operational guide way system.

Mid-span twist of the guide way due to eccentric loading was relatively small in the full-scale prototype of an elevated guiderail. However, this may not be the case in a system designed for larger spans or loads. Two methods can be employed to counter mid-span twist. One, the rigid frame connection between guide way and cabin can be constructed using a modified geometry. That geometry would locate the mass centroid of the vehicle cabin and bogie in line with the center of the guide way. Two, bogie mounted flywheels can be employed. Angular momentum could be used to counter the torque induced by the eccentric loading.

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Appendix (Spartan Superway 2014 Personnel)

Mineta Transportation Institute (MTI)
Automated Transit Networks (ATN): A Review of the State of the Industry and Prospects for the Future, Project Number: 1227

Principle Investigator:
Dr. Burford Furman, Ph.D., PE, Professor, SJSU Department of Engineering

Team Members
Ron Swenson, President, International Institute of Sustainable Transportation
Sam Ellis, Program Director, International Institute of Sustainable Transportation
Lawrence Fabian, Director, Trans.21
Grant Kleinman, Sales Engineer, Trane Corp.
Peter Muller, President, PRT Consultanting, Inc.

Student Assistance
Christian Jorgenson, Student Research Assistant, San Jose State University
Cynthia Lee, Student Research Assistant, San Jose State University

Guideway Design Team
Cormac Wicklow, BSME
Daniel Conroy, BSME

Station Design
Cormac Wicklow, BSME

Controls System
Corey Osterman, BSME
Elizabeth Poche, Computer Engineering
Marjo Mallari, Computer Engineering
Eriberto Velazquez, Computer Engineering
Trent Smith, Computer Engineering
Randall Morioka, BSME
Man Ho, BSME

Bogie Design
Max Goldberg, BSME
Paolo Mercado, BSME
David Lohtak, BSME
Carlos Guerrero,BSME

Cabin Design
Ken Ho, BSME

Solar Power Design
Francisco Martinez, BSME
Henry Tran, BSME
Tim Santiago, BSME
Jaston Rivera, BSME

Human Centered Design
Maria Blum-Sullivan, SJSU Alumni

Business Plan
Laisz Lam, SJSU College of Business

Other
Pete Christiansen

Additional Support (SJSU Civil Engineering Dept.)

Dr. Kurt McMullin, PH.D., PE, Professor,
SJSU Department of Engineering

Pat Joice, SJSU Civil Engineering Technician

CE Student Assistance
Keith A. McKenna, BSCE
Eugenia Tai, BSCE

Sponsors
INIST, International Institute of Sustainable Transportation
Beamways
Microsoft
Big Creek Lumber and Building Materials
PDM Steel Service Centers, Inc.
Atra, Advanced Transit Association
Swenson Solar
Barry Swenson Builder
Coast Aluminum and Architectural
Genentech

Appendix (Author's Project Log)

02/26/14 First participation in weekly group meeting (1hr)

- Met with several team members:
  - Principal Investigator Dr. Burford Furman, Ph.D., PE, Professor, Department of Mechanical Engineering
  - Sam Ellis, Program Director, International Institute of Sustainable Transportation
- People of Interest:
  - Lawrence Fabian, Director, Trans.21
  - Grant Kleinman, Sales Engineer, Trane Corp.
  - Peter Muller, President, PRT Consulting, Inc.
- Discussed overview of ATN system concepts:
  - Fully automated 6 person vehicles
  - Elevated guide way
  - Mostly non-stop, origin to destination service
- Additional Research:
  - International Institute of Sustainable Transportation (INIST) is an organization that establishes partnerships to promote sustainable transportation systems. See web site for more info: https://www.inist.org/About.aspx
  - Trans.21 is an informative clearinghouse on worldwide developments in automated people movers (APMs), publishes bimonthly electronic newsletter "Transit Pulse" See web site for more info: http://faculty.washington.edu/jbs/itrans/trans21.htm
  - PRT Consulting, Inc. monitors and participates in the implementation of Personal Rapid Transit around the world. Web site http://www.prtconsulting.com/news.html provides information data base.

03/05/14 Participated in weekly group meeting (1hr)

- Met with additional team members:
  - Ron Swenson, President, International Institute of Sustainable Transportation
  - Christian Jorgenson, Student Research Assistant, San Jose State University
  - Cynthia Lee, Student Research Assistant, San Jose State University
  - Cormak Wicklow, Guide Way Team Leader
- Discussed with Cormak Wicklow tools that I have available to facilitate guide way construction
- Discussed with Sam Ellis uni-directional vs. bi-directional guide way system
  - Bi-directional guide way advantages
    - Supports higher volume of traffic in high flow corridors
  - Bi-directional guide way disadvantages
    - Requires more space for guide way corridor (side by side vs. stacked vehicle path)
    - Higher cost for railway corridor
  - Conclusion: Detailed investigation of probable traffic density in specific regions would be required to justify either alternative. A cost/benefit analysis would determine the proper guide way system for a specific corridor. That analysis should also consider the integration of the specific corridor into the system as a whole.
  - Additional Research:
    - Wikipedia http://en.wikipedia.org/wiki/Personal_rapid_transit

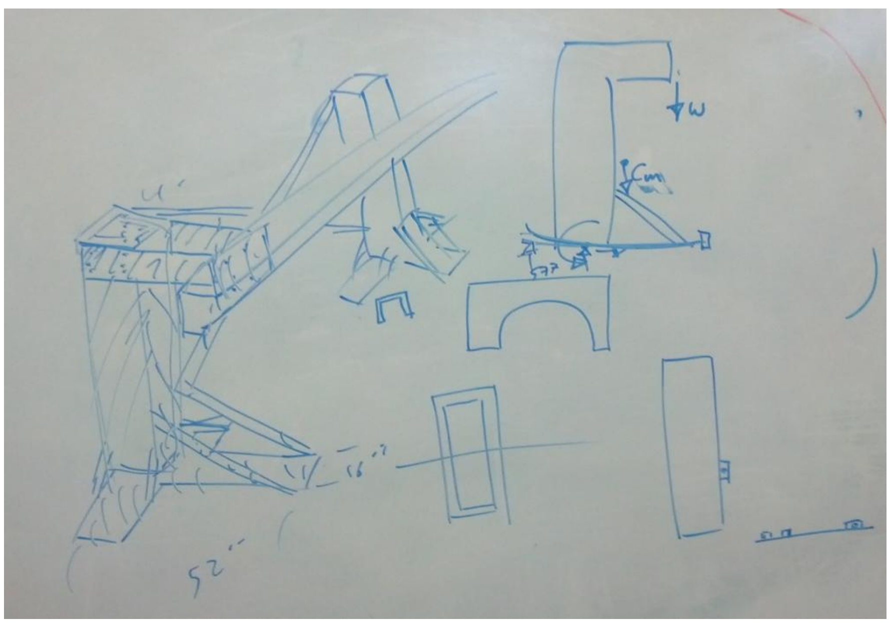
Appendix (Author's Project Log)

03/12/14 Weekly group meeting cancelled

- Met with Ron Swenson and Sam Ellis
  - Discussed my possible participation in guide way rail design
- Additional Research
  - Spartan Superway http://www.engr.sjsu.edu/smssv/

03/19/14 Weekly group meeting (1hr)

- Discussed full scale exhibit guideway with Cormac Wicklow (see illustration below)
  - Columns 3/16" steel 18"X18"X10' tall. Upper horizontal members extend 4' to guide rail, parallel base member extends 52". Guiderail is 16' long. The exhibit must be transported in sections and connected in field; components are: (2) columns with base plates, upper horizontal supports, and guiderail. Estimated pod weight (including bogey)= 500 pounds.
  - Because the pod weight is only 500 pounds, I suggested to Dr Furman, Alex (), and Cormac Wicklow, that the columns could be built out of ply-wood instead of steel. This would reduce the construction cost and lighten the structure, making transportation easier. This was met with neutral response, probably because time has been spent designing and calculating steel columns. Also, the structure must be built in 58 days. Re-designing columns could extend project completion past the dead line.



- Met with Dr. Kurt McMullin after group meeting
  - Discussed my participation as construction management of full scale guide way model for Maker Faire exhibit, transportation logistics of guiderail to exhibit and back , and construction of exhibit guide way and supports.
  - Plywood columns were discussed. One advantage of steel columns is that their weight will help stabilize the guide rails against the dynamic load of the moving pod car.
  - Assigned to constructing a time line for the construction of the guide rails and support structure.

Appendix (Author's Project Log)

  - The guide way team leader is under the impression that only the CE Technician Pat Joice and I will be working on construction.
- Additional Research
  - Welding and fabrication times: http://www.esabna.com/EUWeb/AWTC/Lesson9_3.htm
  - Sustainable Mobility System Silicon Valley (SMSSV)
  - Personal Rapid Transit (PRT)

03/24/14 (3hrs)

- Researched strength of plywood for use on column construction, calculations, determined strength of plywood box-beam construction for supporting columns would not be sufficient to support demand load.

The complete set of welding symbols is given in a standard published by the American National Standards Institute and the American Welding Society

- Weld Symbols tutorial http://www.structuralsteeldetailer.us/weld_symbols.html

03/26/14 E-mail correspondence with PI and guiderail team leader, sketch guiderail transportation alternatives (3hrs)
03/28/14 E-mail correspondence with PI and guiderail team leader, sketch guiderail transportation alternatives (3hrs)
03/29/14 Begin CAD drawings for support structure (4 hrs)
03/30/14 Continue CAD drawings for support structure, research and edit contact info (8hrs)
04/02/14
Questions for 04/02/2014 Group Meeting:

1. Base lengths in direction parallel to guiderail should be increased to resist overturning moment induced by acceleration/deceleration of bogie and cabin.
2. Also, a torsion moment on the guiderail system will be induced by acceleration/deceleration of bogie and cabin.
3. What are the specifications of the guiderail, bogie, and cabin (dimensions & weight)?(back plate bolt hole pattern)?
4. The vertical distance between the back plate and end of the base stem is 10 inches. How much further does the guiderail put the center of mass of cabin and bogie?
5. Can I access Share Point. How do I get on any information sharing lists?
6. Do brace welds need to be continuous. Bottom of braces are 6" can they be 2-2" welds at either end; same question for support arm welds.
7. What is the ground surface where the structure will in operation?

04/07/14 Meeting with Dr. McMullin and CE ATN student research assistants. Discussed expectations as student researchers (action items). Meeting focused on guide way system design methodology.
04/09/14

- Delivered wood guide beam materials to building site. Drive from Big Creek Lumber in Santa Cruz over Highway 17 to San Jose construction site (3 hrs)

Meeting with Dr. McMullin and CE Technician Pat Joice to discuss steel support construction. Possible instability of the structure due to lateral forces was recognized. Pat Joice brought to our attention that welding of the base plate will induce unwanted stress into the steel plate. This will result in curvature of the finished base assembly. After meeting I figured solution that will make this effect work to add stability to the structure. The convex shape of the finished base

- will be face down. This will provide 3 point bearing of the base and reduce chance of rocking. Pat Joice provided options for cutting steel material to proper size and shapes using university shop machines. (Due to un-availability this never happened).
- Attended ATN group meeting. Conveyed information from earlier construction meeting to guide way team leader.

04/12/14 (8 hrs)

- Attended group meeting at building site 9:00am to 3:30 pm. Worked with guide way team, provided tools, construction expertise in wood building technique, and 8hrs labor. Constructed rib framing and started installation of plywood shell. Started rib blocking

04/14/14 (4.5 hrs)

- Met with Cormac at building site 10:00am to 2:30. Finished construction of wood guide way (everything but guiderail). Amberwood is shaping guiderail (dimensions and dado to receive metal cap). Tested strength of beam applying force to beam perpendicular to length; no deformation was observed. Tested torsional strength laying beam flat on floor, placing a 4" block under on corner of the beam. This lifted one edge of the beam along its length. The other corner was lifted approximately 3". This implies a twisting deformation of approximately 1". Then approximately 190 pounds was placed at opposing corners. This resulted in approximately 1 more inch of twist along the 16 foot length of the beam. Cormac and I are optimistic that the forces we applied are far higher than the design load and working stresses; Therefore, working deflections are assumed to be tolerable.
- I suggested method for lifting guide rail: steel brackets at center of mass where forklift forks could slide in and lift. Also need eye bolt for alternative cable lifting.
- Met with Kurt 4:30 for CE298 meeting. Discussed present state of project. Static based calculations show stable structure, but details (such as the many wood connections) cannot be modeled accurately) Stability of structure as a whole is still a concern. The timeline for the project does not allow detailed analysis of the structure that would cover every aspect that could lead to instability. Test prototype must be built for analysis. Steel fabrication discussed.

04/16/14 (1 hr)

- Group Meeting present status and time line of project discussed. Dr. Furman requested that I design and build entrance banner stand 12 feet wide and 14 feet tall using base stand he will provide.

04/21/14 (1 hr)

- Met Cormac at campus 9:00am. Verified steel delivery from PDM. Began bureaucratic process to attain door code for ME machine shop. Not likely code will be attained in time to stay on construction schedule.

04/23/14 (1 hr)

- Group Meeting present status and time line of project discussed. Guide way team has not acquired door code for machine shop. Need pieces cut by Monday so that steel construction can begin and schedule can be met.

04/26/14 (8 hrs)

- Picked up steel pieces at campus, cutting and grinding blade at home depot, and cut steel braces to size and shape at my carpentry shop.

04/28/14 (8 hrs)

Appendix (Author's Project Log)

- Monday worked from 8:30 to 4:30 at the Engineering Building with Pat, Cormac, and Daniel. Constructed one of the steel guide way columns, drilled bolt holes in back plate, prepped pieces for second column section (grinding locations for welds).

04/30/14 (2.5 hrs)

- Pat could not attend scheduled workshop. I positioned column on base plate and positioned support arms so they are ready to weld (1.5 hrs).
- Group Meeting: Layout of exhibit at Maker faire and exhibit component transportation discussed. Also, means of transporting column assemblies from SJSU campus to 7th Street worksite on Saturday (May 3) discussed (access to engineering building inner courtyard and use of university vehicle).

05/03/14 (8 hrs)

- Group workshop at building site
  - transported steel column assemblies from SJSU campus to building site
  - connected timber guide way to steel column assemblies
  - fabricated guide rail
  - attached guide rail to guide way

05/07/14 (1hr)

- Group Meeting
  - Discussed agenda for next Saturday workshop
    - Bogies have been placed on guiderail
    - Paint guide rail
    - Hang cabin from bogies
    - Build entrance gate for Maker Faire space

05/10/14 (6hrs)

- Materials run with Sam Ellis and Ron Swensen. Built entrance gate. Loaned various tools to ATN groups.

05/15/14 8hrs

- Disassemble exhibit at workspace, load on trucks, transport () miles to San Mateo Convention Center. Then reassembled exhibit.

05/18/14 (6 hrs)

- Disassembled guide way assembly, loaded up, and transported back to SJ workspace. Helped transport some of the 1/12th scale model to SJ workspace and entrance gate.

Addendum

06/12/14 (2 hrs)

- Group meeting
  - Discussed preparation tasks for July 6th exhibit at Moscone Convention Center.
    - Assigned to build cover for ½ of guide way. Cover will give better representation of actual guide way and provide space for donor advertising
    - Assigned to build crates for 1/12th scale plexi-glass component transportation.

06/14/14 (5 hrs)

- Built 2 crates for transportation of 1/12th scale plexi-glass components.

Appendix (Author's Project Log)

06/21/14 (4hrs)
- Disassembled partition walls at workspace, reconfigured, and prepared for Moscone Event.

06/28/14 (4hrs)
- Repaired broken swivel wheels on full-scale vehicle cabin (Bryan's model)
- Attached solar panels to aluminum frame which connects to guide way.

07/01/14 (2 hrs)
- Transported 3three solar panels from Santa Cruz to San Jose workspace
- Transported my 14 ft ladder from my shop to San Jose workspace

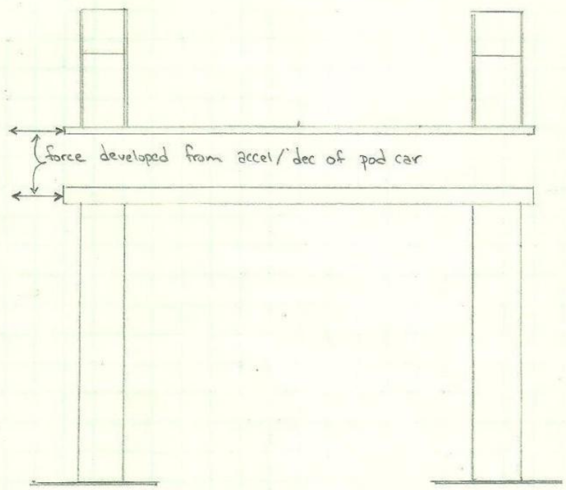
07/07/14 (8 hrs)
- Assisted with set-up of full-scale elevated transportation module exhibit at Moscone Convention Center in San Francisco.
- Assisted with set-up of 1/12th scale elevated transportation module exhibit at Moscone Convention Center in San Francisco.
- General assistance with exhibit set-up

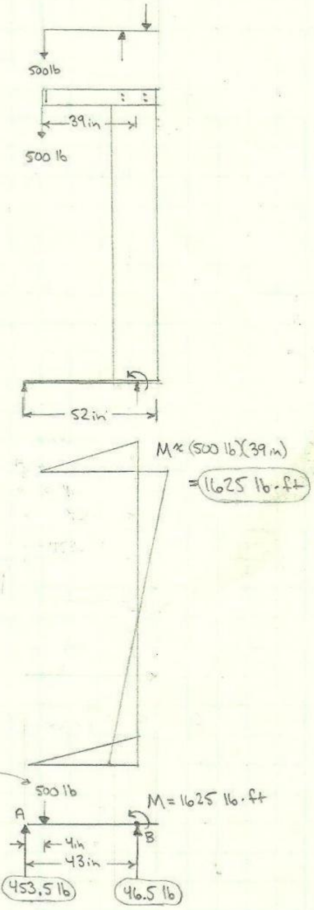
07/08/14 (8 hrs)
- ATN Spartan Superway representative at InterSolar Event at Moscone Convention Center in San Francisco.

07/10/14 (8hrs)
- Break-down exhibit at Moscone Convention Center in San Francisco.

Appendix (Author's Technical Assistance)

3/22/14 (KM) Guide Rail Support Structure





column weight $= 4\left(0.283\frac{lb}{in^3}\right)\left(\frac{3}{16}in\right)(18\,in)(120\,in) \Rightarrow$ columns: 458.5 lb each

Base Reaction

$\circlearrowleft + \Sigma M_A = 0 \rightarrow -500\,lb(4\,in) + B_y(43\,in) = 0 \rightarrow B_y = \frac{(500)(4)}{43} = 46.5\,lb$

$A_y = 453.5\,lb$

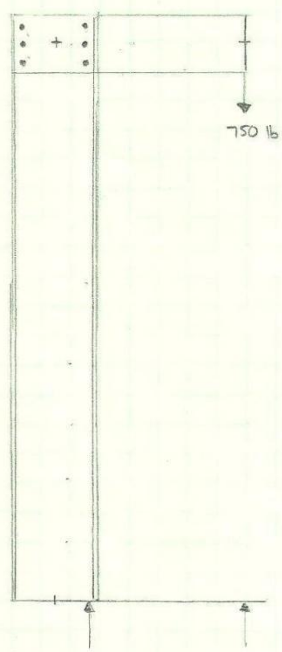
Appendix (Author's Technical Assistance)

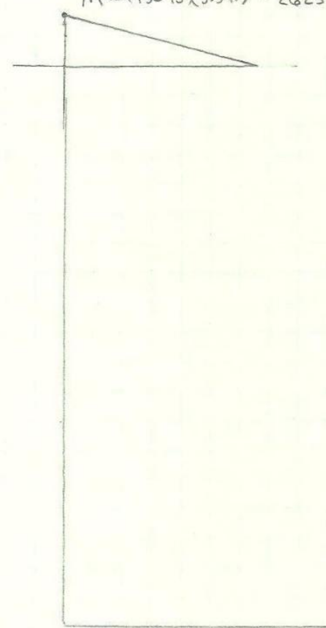
3/24/14

Dr. Furman suggests using 4×4×1/4" steel for columns
Cormack Wicklow suggests truss system (he wants a wide column (16") for aesthetic reasons

KM (alternative) - 1/2" STR I Plywood box
plywood available at Lowe's

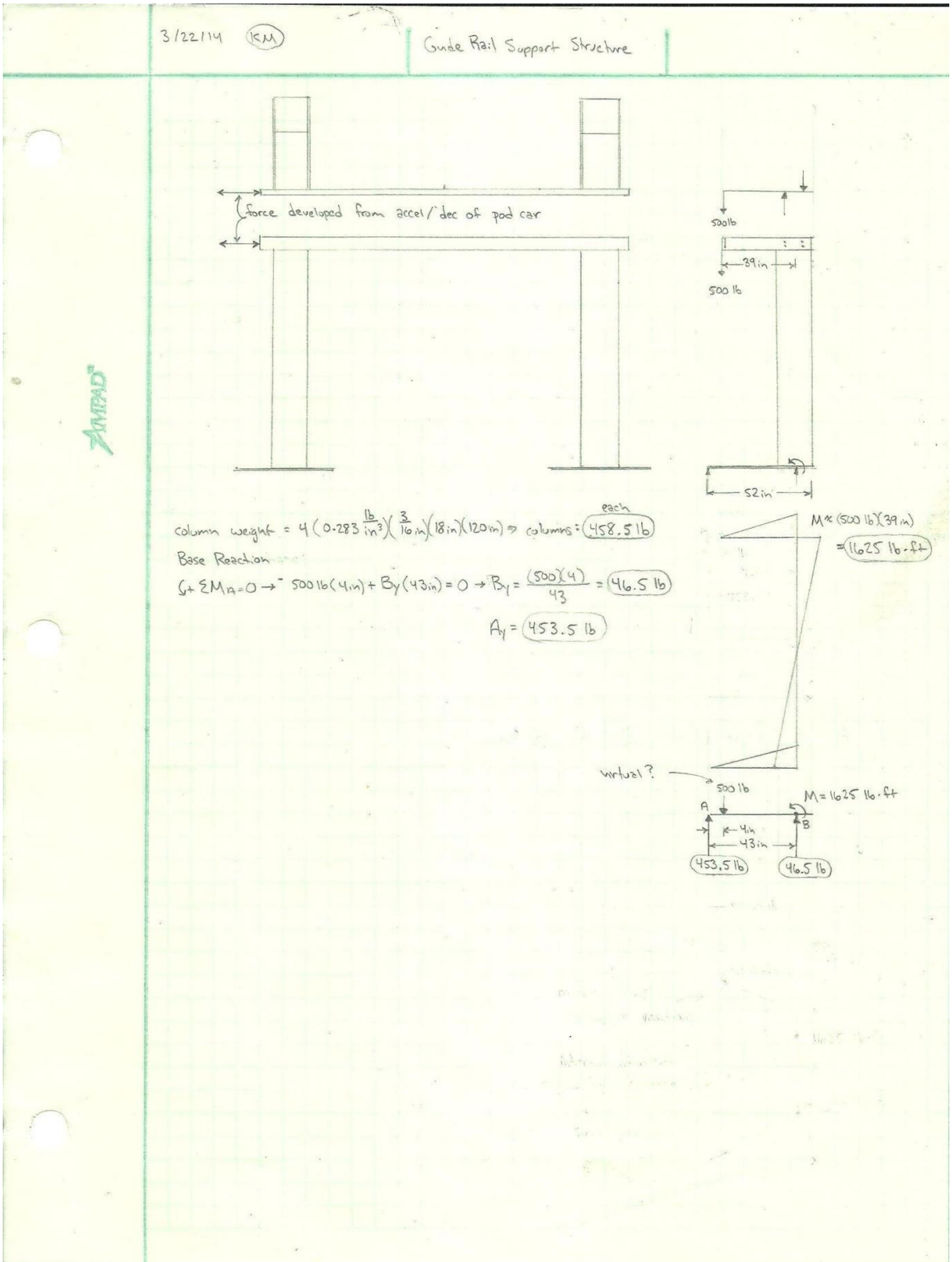
$M \approx (750\text{ lb})(3.5\text{ ft}) = 2625\text{ lb}\cdot\text{ft} = 31{,}500\text{ lb}\cdot\text{in}$



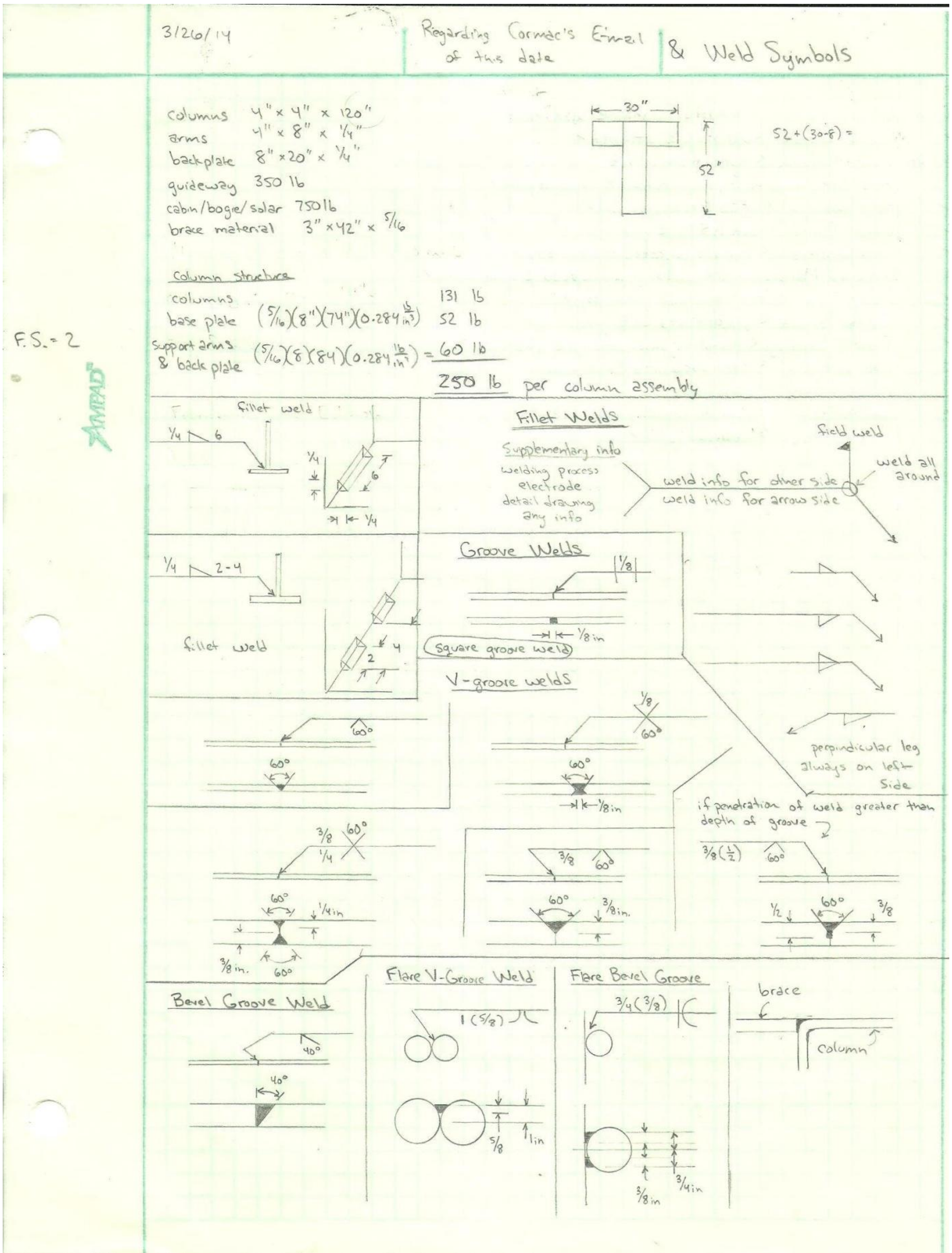


Plywood bending strength $[\,500 \rightarrow \underbrace{1{,}000}_{5\text{ ply}}\,]$ lb·in / ft of width

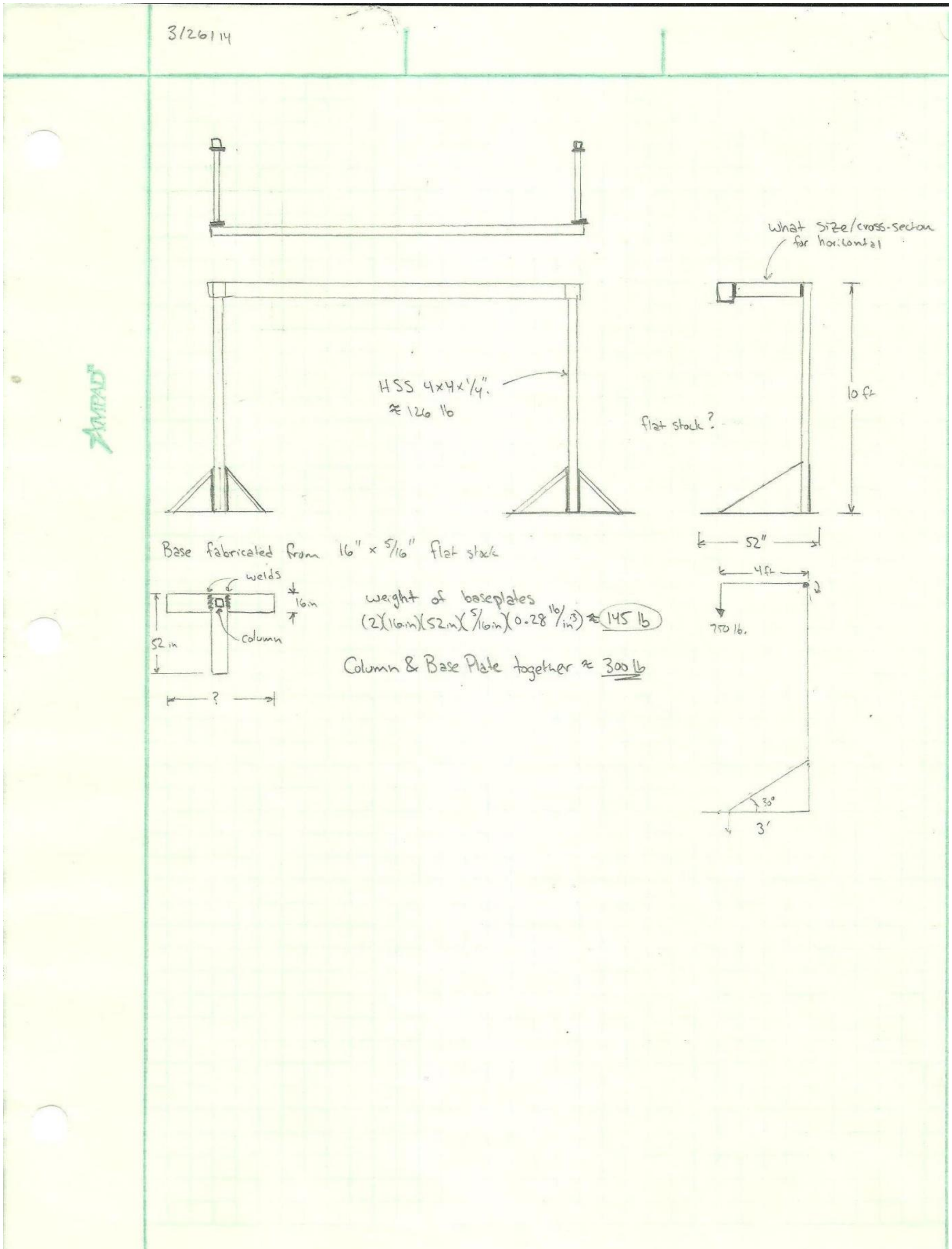
Appendix (Author's Technical Assistance)



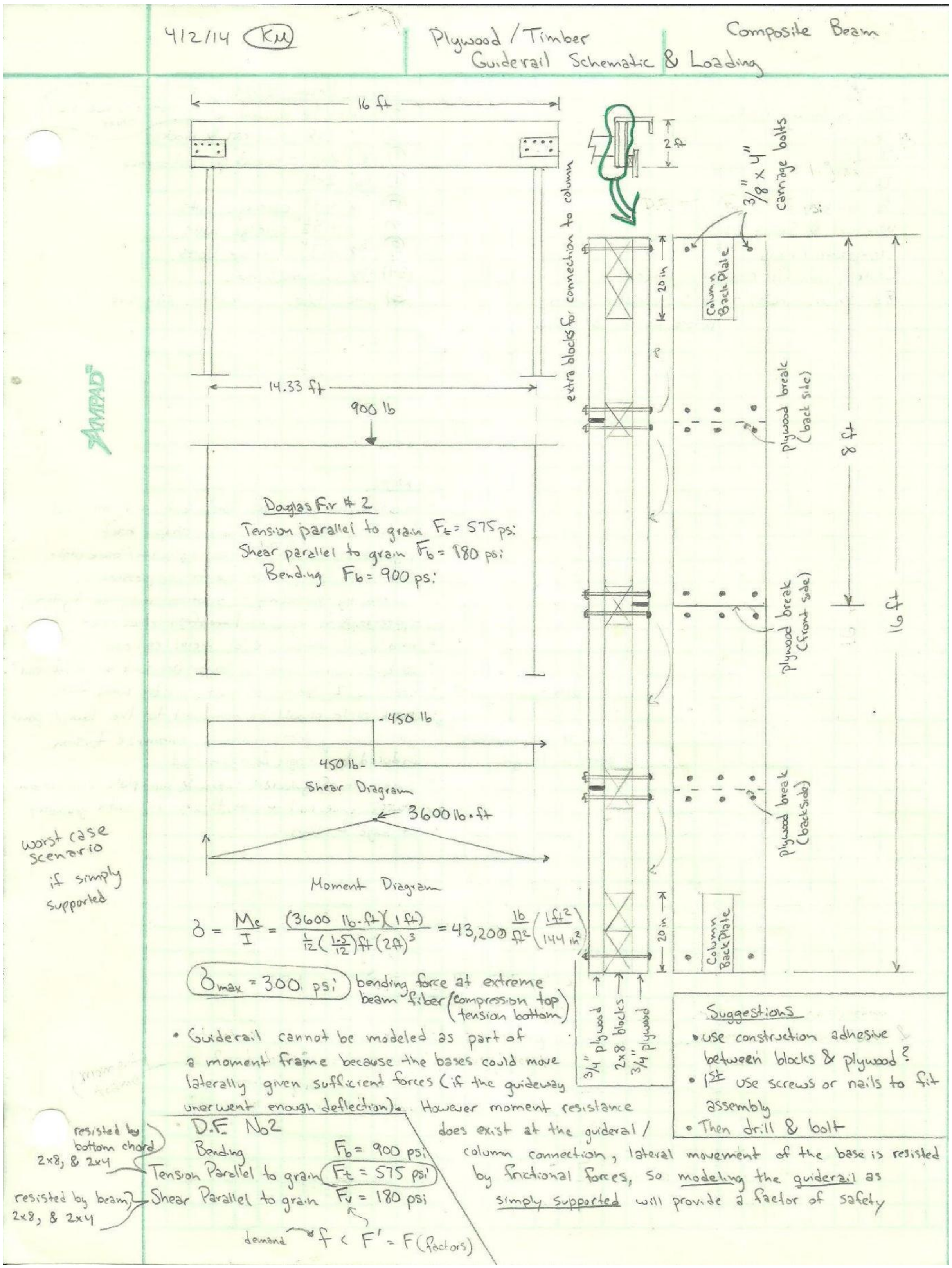
Appendix (Author's Technical Assistance)



Appendix (Author's Technical Assistance)



Appendix (Author's Technical Assistance)



Appendix (Author's Tactical Assistance)

7.5

I will

Tools to bring Wednesday

- Skillsaw
- Power Cord
- Drill
- 3/8 Drill bit
- Wrenches & Socket Set
- String Line / nails
- Caulking Gun (for construction adhesive)
- 8d sinkers (nails) → to prefabricate beam before drilling & bolting

Guidrail Beam BOM (does not include rail cover)

- (2) sheets 3/4" plywood
- (2) 16' 2x8 - guide rail & blocks
- (1) 8' 2x8 - blocks & contingency
- (1) 16' 2x4
- (17) 3/8" x 4" carriage bolts
- (8) 3/8 x 4½" carriage bolts
- (9) 3/8 x 7" carriage bolts
- (34) 3/8 washers & nuts
- (4) small tubes construction adhesive

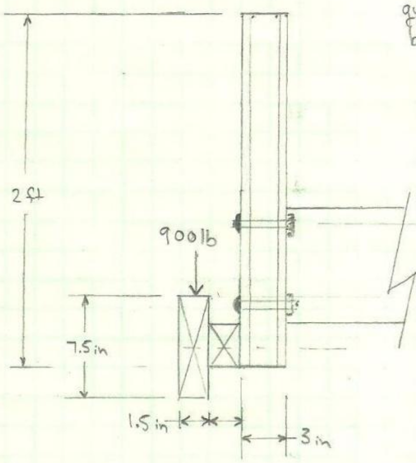
Notes

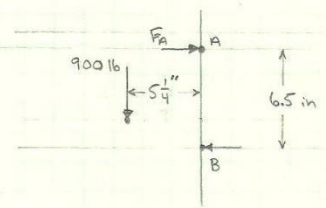
- Sono tube may deflect when cut and may not be possible to get original shape back
- ~~plywood at bottom of guiderail beam / back plate connection may crush due to compression forces induced by moment — solution may be tightening upper bolts to equalize forces (rail to back plate)~~
- need exact dimensions of metal rail cap
- do bolt locations need to be counter-sunk on front rail?
- overturning → beam is 2' height — must consider wind force
- back plate should be connected to the lowest point possible on guiderail beam to minimize torsion induced by bogie & cabin load (need to get backplate bolts in though)
- placement of guiderail beam & backplate connection lowers guide rail → does this work with geometry of bogie & cabin

4/13/14 (KM) Quantify number of bolts for rail to backplate connection

weight
2 x bogie = 500 lb
cabin = 150 lb
½ guiderail = 175 lb
Total = 825 ≈ 900 lb

Determine tension force in one bolt in order to quantify quantity of bolts for upper guiderail to back plate connection





$\circlearrowleft + \Sigma M_B = 0 \rightarrow 900\,lb(5.25\,in) - F_A(6.5\,in) = 0$

$F_A = 728\ lb$

Area of 3/8 washer
Diameter = 1 in $A = 0.78\ in^2$

Demand stress on guiderail beam induced by load x one washer → $\sigma = \frac{F_A}{A} = \frac{728\ lb}{0.78\ in^2} = 932\ psi$ (f_c?)

Design Adjustment Factors

does not apply to compression ⊥ to grain →	Load Duration factor	$C_D = 1$
	wet service factor	$C_m = 1$
applies only to parallel to grain →	Size factor	$C_F = 1$
	flat use factor	$C_{fu} = 1$
	form factor	$C_f = 1$
	incising factor	$C_i = 1$
	temperature factor	$C_t = 1$
only for F_b →	repetetitive member factor	$C_r = 1$

Might need to consider

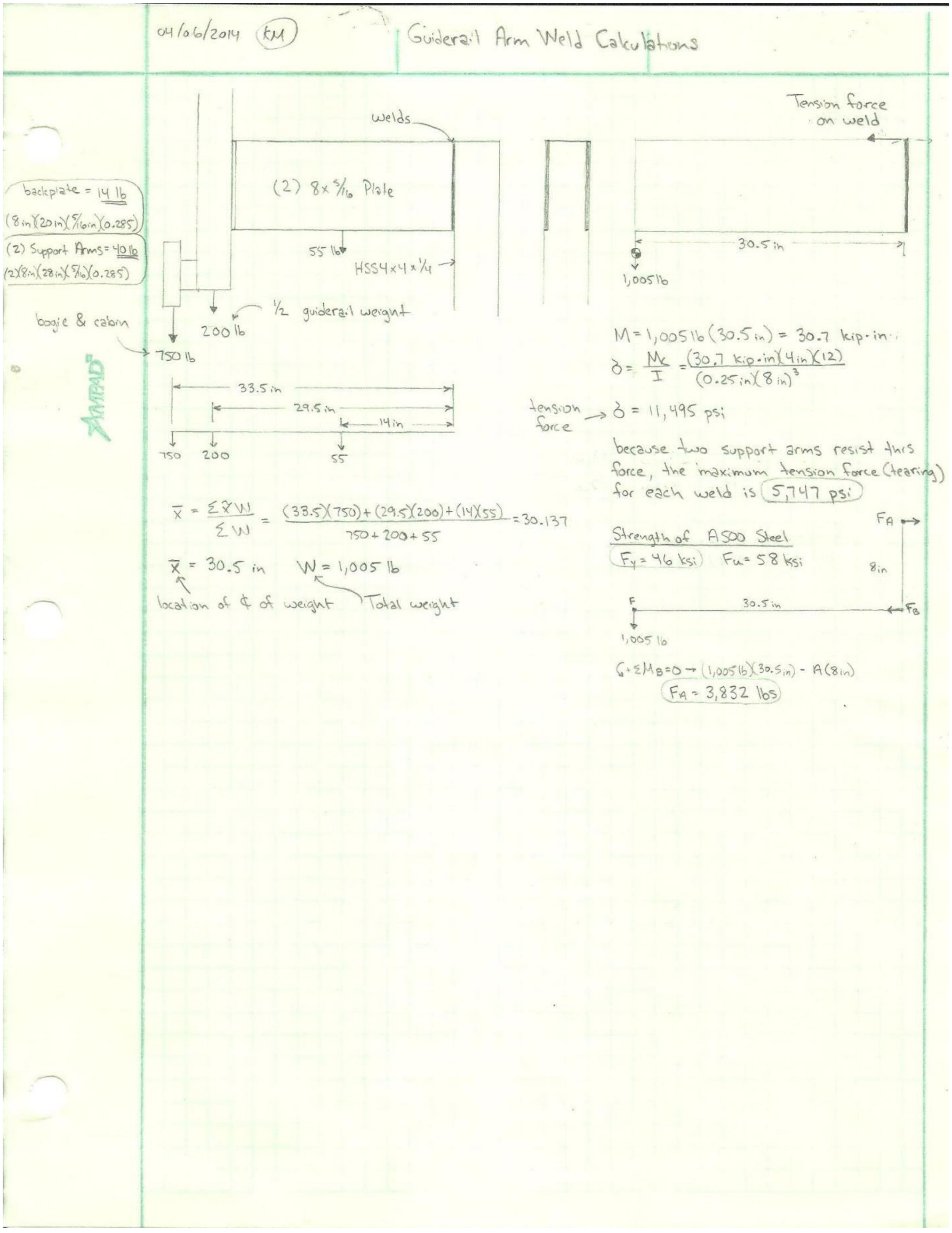
for design $f_c \le F_c' = F_c$ (adjustment factors)

Compression strength of D.F #2 ⇒ $F_c = 625\ psi = F_c'$

$f_c = 932 \le (2)F_c' = 1250$

(2) 3/8 bolts is sufficient

Appendix (Author's Technical Assistance)`


04/06/2014 (KM) Guiderail Arm Weld Calculations

welds

(2) 8 × 5/16 Plate

backplate = 14 lb
(8 in)(20 in)(5/16 in)(0.285)

(2) Support Arms = 40 lb
(2)(8 in)(28 in)(5/16)(0.285)

55 lb

HSS4×4×1/4

1/2 guiderail weight

bogie & cabin

200 lb

750 lb

33.5 in

29.5 in

14 in

750 200 55

$\bar{x} = \frac{\Sigma \bar{x} W}{\Sigma W} = \frac{(33.5)(750) + (29.5)(200) + (14)(55)}{750 + 200 + 55} = 30.137$

$\bar{x} = 30.5$ in $W = 1{,}005$ lb

location of ℄ of weight Total weight

Tension force on weld

30.5 in

1,005 lb

$M = 1{,}005 \text{ lb} (30.5 \text{ in}) = 30.7 \text{ kip·in}$

$\sigma = \frac{Mc}{I} = \frac{(30.7 \text{ kip·in})(4 \text{ in})(12)}{(0.25 \text{ in})(8 \text{ in})^3}$

tension force → $\sigma = 11{,}495$ psi

because two support arms resist this force, the maximum tension force (tearing) for each weld is (5,747 psi)

Strength of A500 Steel

($F_y = 46$ ksi) $F_u = 58$ ksi

F_A

8 in

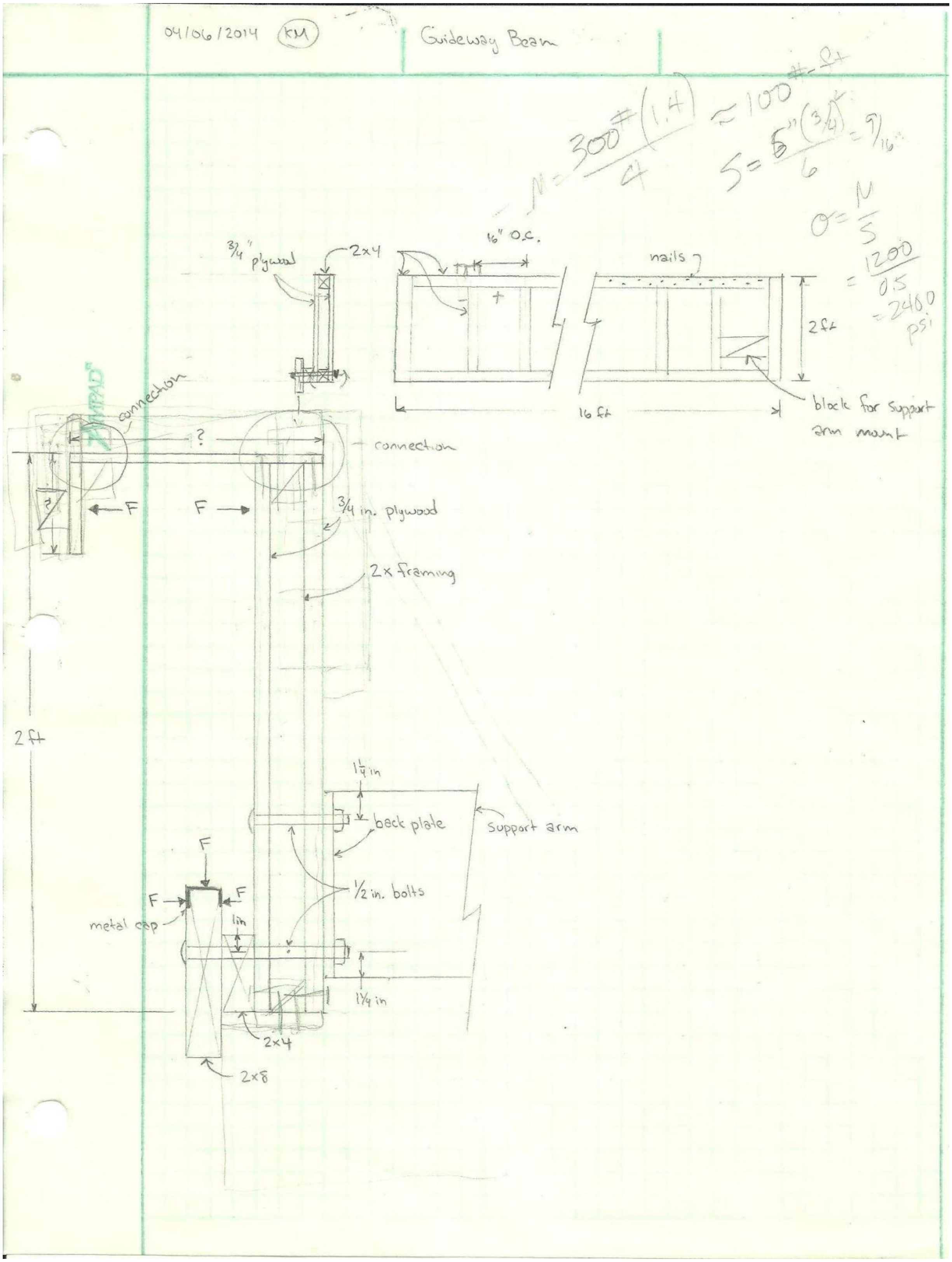
F 30.5 in F_B

1,005 lb

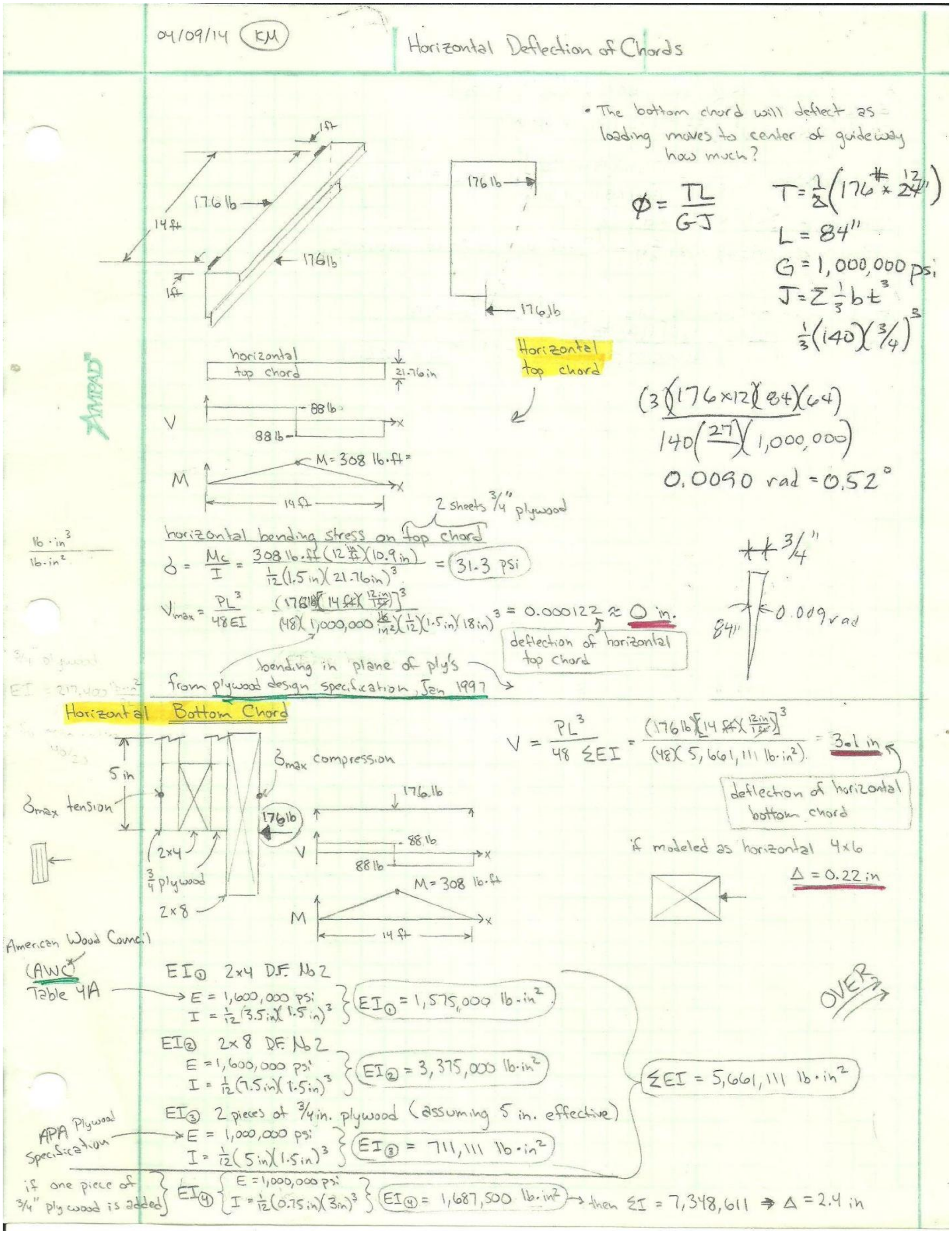
$\circlearrowleft + \Sigma M_B = 0 \rightarrow (1{,}005 \text{ lb})(30.5 \text{ in}) - A(8 \text{ in})$

($F_A = 3{,}832$ lbs)

Appendix (Author's Technical Assistance)



Appendix (Author's Technical Assistance)



Appendix (Author's Technical Assistance)

if one piece of 3x 1/8 steel plate is added to bottom

$E = 29{,}000{,}000$

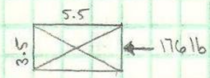
$I = \frac{1}{12}(0.125\,in)(3\,in)^3$ } $EI = 103{,}111{,}111\ lb \cdot in^2$

Then deflection $= \dfrac{PL^3}{48EI} = \dfrac{176\,lb\left[(14\,ft)\left(\frac{12\,in}{1\,ft}\right)\right]^3}{(48)(103{,}111{,}111\ lb \cdot in^2)} \Rightarrow \boxed{\Delta = 0.168\ in}$

Weight of $3'' \times \frac{1}{8}'' \times 16'$ steel plate

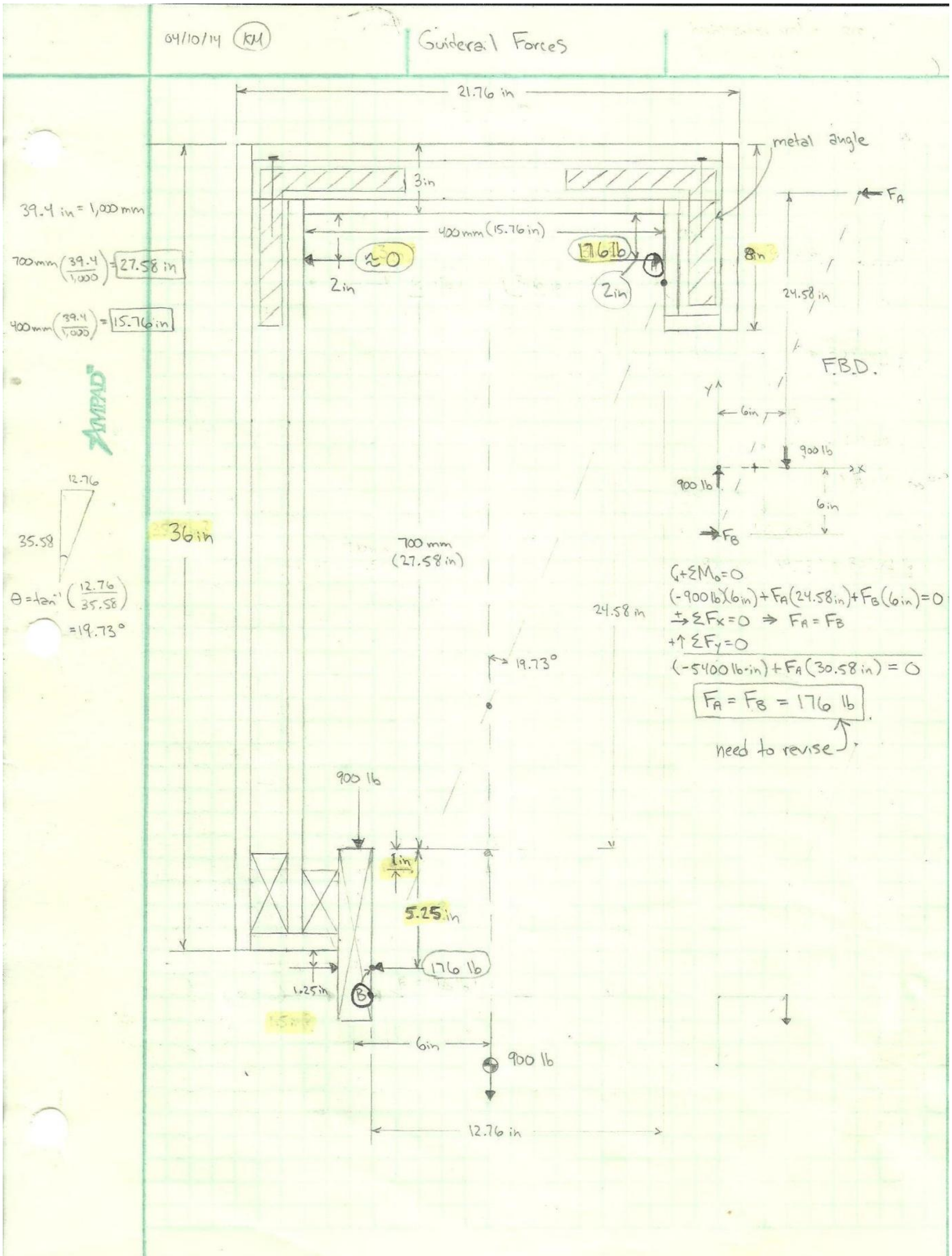
$(3\,in)(0.125\,in)(192\,in)(0.284\,\frac{lb}{in^3}) =$ 20.5 lb + weight of hardware

If section is considered as solid 4x6

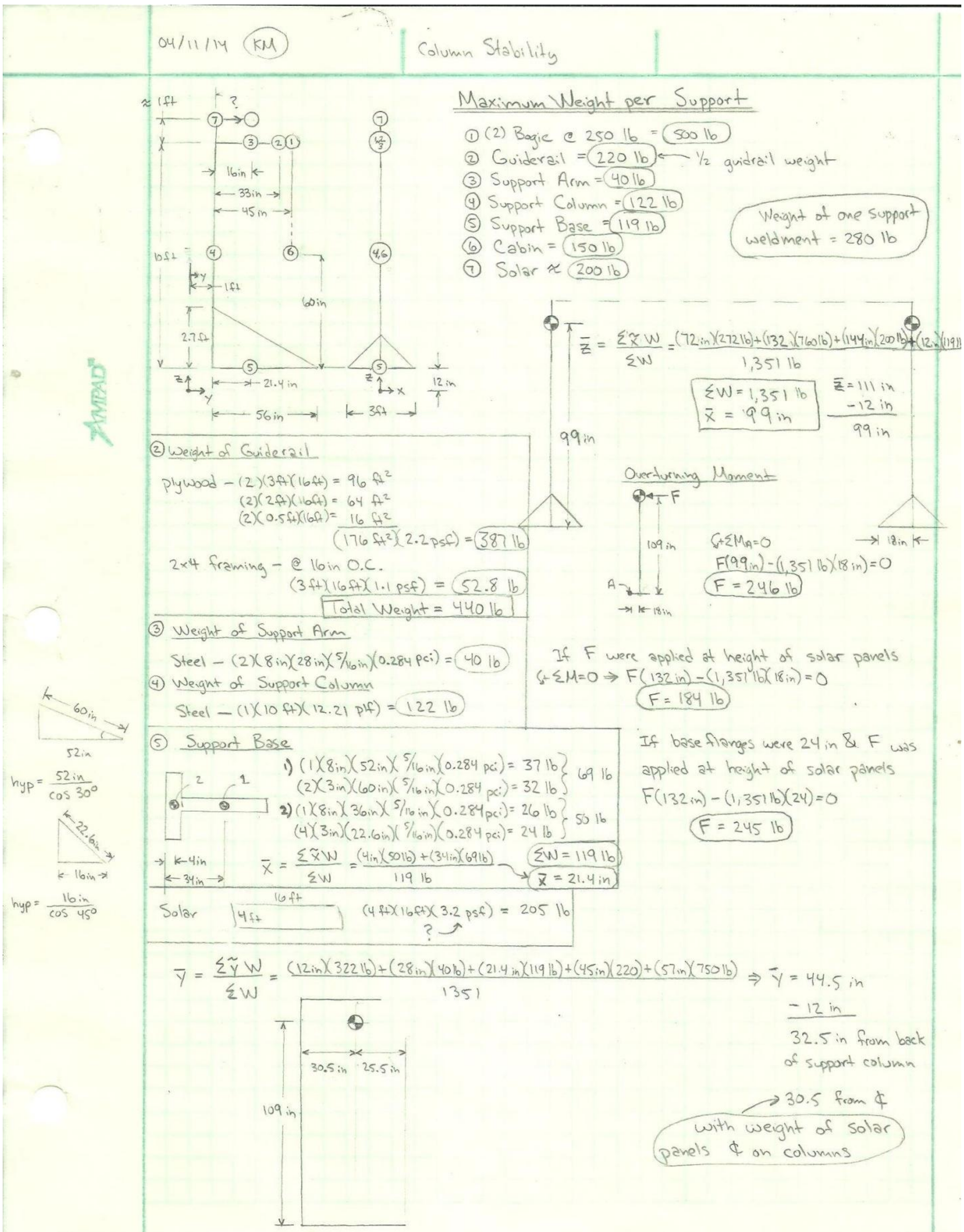


Deflection $= \dfrac{PL^3}{48\,EI} = \dfrac{(176\,lb)\left[(14\,ft)\left(\frac{12\,in}{1\,ft}\right)\right]^3}{48(1{,}600{,}000\,\frac{lb}{in^2})(\frac{1}{12})(3.5\,in)(5.5\,in)^3} \Rightarrow \boxed{\Delta = 0.22\ in}$

Appendix (Author's Technical Assistance)



Appendix (Author's Technical Assistance)



04/11/14 (KM) Column Stability

Maximum Weight per Support

① (2) Bogie @ 250 lb = (500 lb)
② Guiderail = (220 lb) ← ½ guidrail weight
③ Support Arm = (40 lb)
④ Support Column = (122 lb)
⑤ Support Base = (119 lb)
⑥ Cabin = (150 lb)
⑦ Solar ≈ (200 lb)

Weight of one support weldment = 280 lb

$\bar{z} = \frac{\Sigma \tilde{z} W}{\Sigma W} = \frac{(72 in)(272 lb)+(132)(760 lb)+(144 in)(200 lb)+(12 in)(119 lb)}{1,351 lb}$

ΣW = 1,351 lb
$\bar{x}$ = 99 in

$\bar{z}$ = 111 in
−12 in
99 in

② Weight of Guiderail

plywood − (2)(3ft)(16ft) = 96 ft²
(2)(2ft)(16ft) = 64 ft²
(2)(0.5ft)(16ft) = 16 ft²
(176 ft²)(2.2 psf) = (387 lb)

2×4 framing − @ 16in O.C.
(3ft)(16ft)(1.1 psf) = (52.8 lb)
Total Weight = 440 lb

Overturning Moment

ΣM_A = 0
F(99 in) − (1,351 lb)(18 in) = 0
(F = 246 lb)

③ Weight of Support Arm

Steel − (2)(8 in)(28 in)(5/16 in)(0.284 pci) = (40 lb)

④ Weight of Support Column

Steel − (1)(10 ft)(12.21 plf) = (122 lb)

If F were applied at height of solar panels
ΣM = 0 ⇒ F(132 in) − (1,351 lb)(18 in) = 0
(F = 184 lb)

⑤ Support Base

1) (1)(8in)(52in)(5/16 in)(0.284 pci) = 37 lb
(2)(3in)(60in)(5/16 in)(0.284 pci) = 32 lb } 69 lb
2) (1)(8in)(36in)(5/16 in)(0.284 pci) = 26 lb
(4)(3in)(22.6in)(5/16 in)(0.284 pci) = 24 lb } 50 lb

$\bar{x} = \frac{\Sigma \tilde{x} W}{\Sigma W} = \frac{(4in)(50 lb) + (34in)(69 lb)}{119 lb}$

ΣW = 119 lb
$\bar{x}$ = 21.4 in

If base flanges were 24 in & F was applied at height of solar panels
F(132 in) − (1,351 lb)(24) = 0
(F = 245 lb)

hyp = 52 in / cos 30°

hyp = 16 in / cos 45°

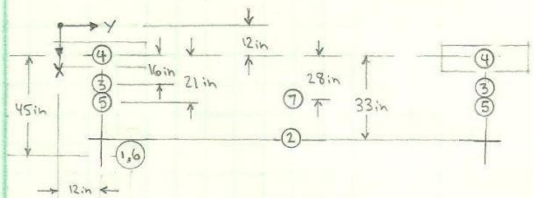
Solar (4 ft)(16 ft)(3.2 psf) = 205 lb

$\bar{y} = \frac{\Sigma \tilde{y} W}{\Sigma W} = \frac{(12in)(322 lb)+(28in)(40 lb)+(21.4 in)(119 lb)+(45in)(220)+(57in)(750 lb)}{1351}$ ⇒ $\bar{y}$ = 44.5 in
− 12 in
32.5 in from back of support column

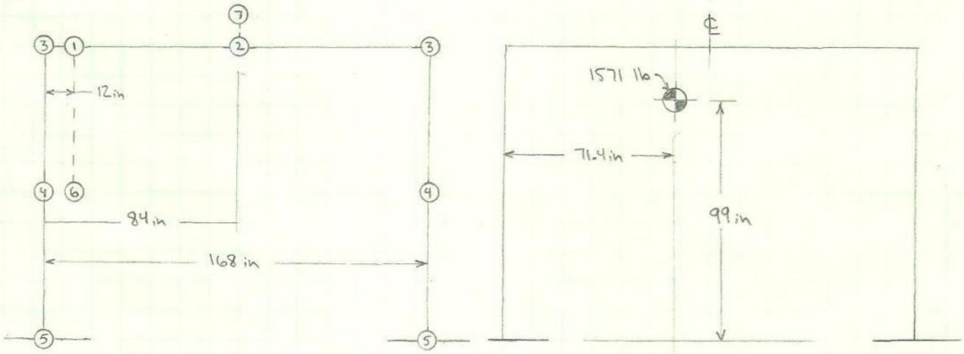
→ 30.5 from ℄ with weight of solar panels ℄ on columns

Appendix (Author's Technical Assistance)

04/11/14 (KM) | Column Stability



1. Bogie (500 lb)
2. Guiderail (440 lb) total weight
3. Support Arm (40 lb)
4. Support Column (122 lb)
5. Support Base (119 lb)
6. Cabin (150 lb)
7. Solar ≈ (200 lb)



$$\bar{y} = \frac{\Sigma \tilde{y} W}{\Sigma W} = \frac{(12in)(281lb)+(24in)(650\,lb)+(96in)(640lb)+(180in)(281\,lb)}{1571\,lb} \Rightarrow \bar{y} = 83.4\,in$$

$$- 12\,in$$

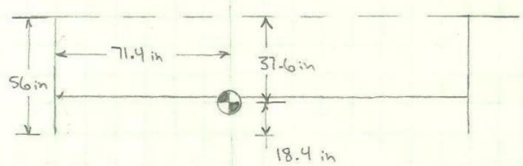
$$\boxed{71.4\,in}$$

$$\bar{x} = \frac{\Sigma \tilde{x} W}{\Sigma W} = \frac{(12\,in)(244\,lb)+(28\,in)(80\,lb)+(33\,in)(238\,lb)+(40\,in)(200\,lb)+(45\,in)(440\,lb)+(57\,in)(650\,lb)}{1571\,lb}$$

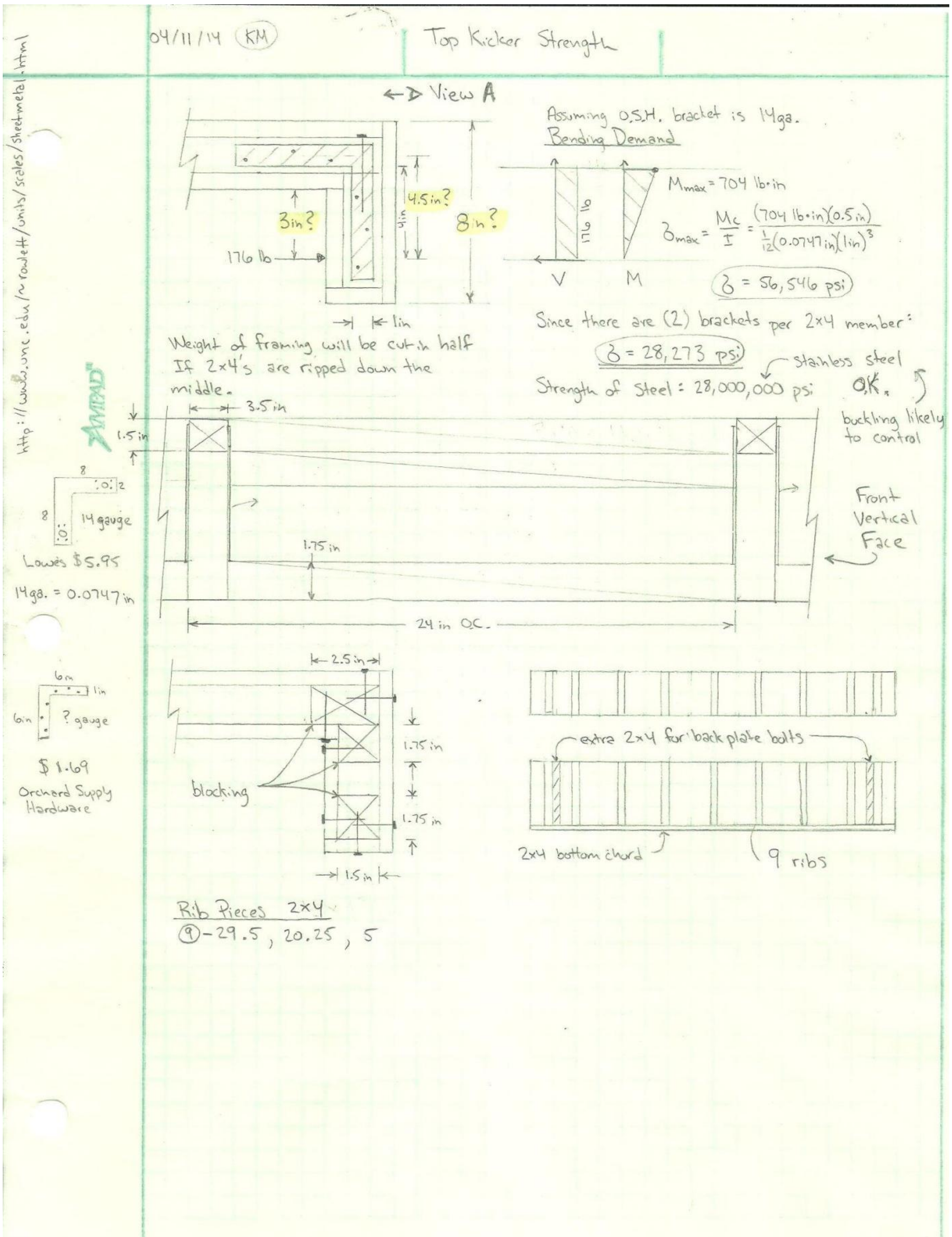
$$\bar{x} = 49.6\,in$$

$$-12\,in$$

$$\boxed{37.6\,in}$$



Appendix (Author's Technical Assistance)



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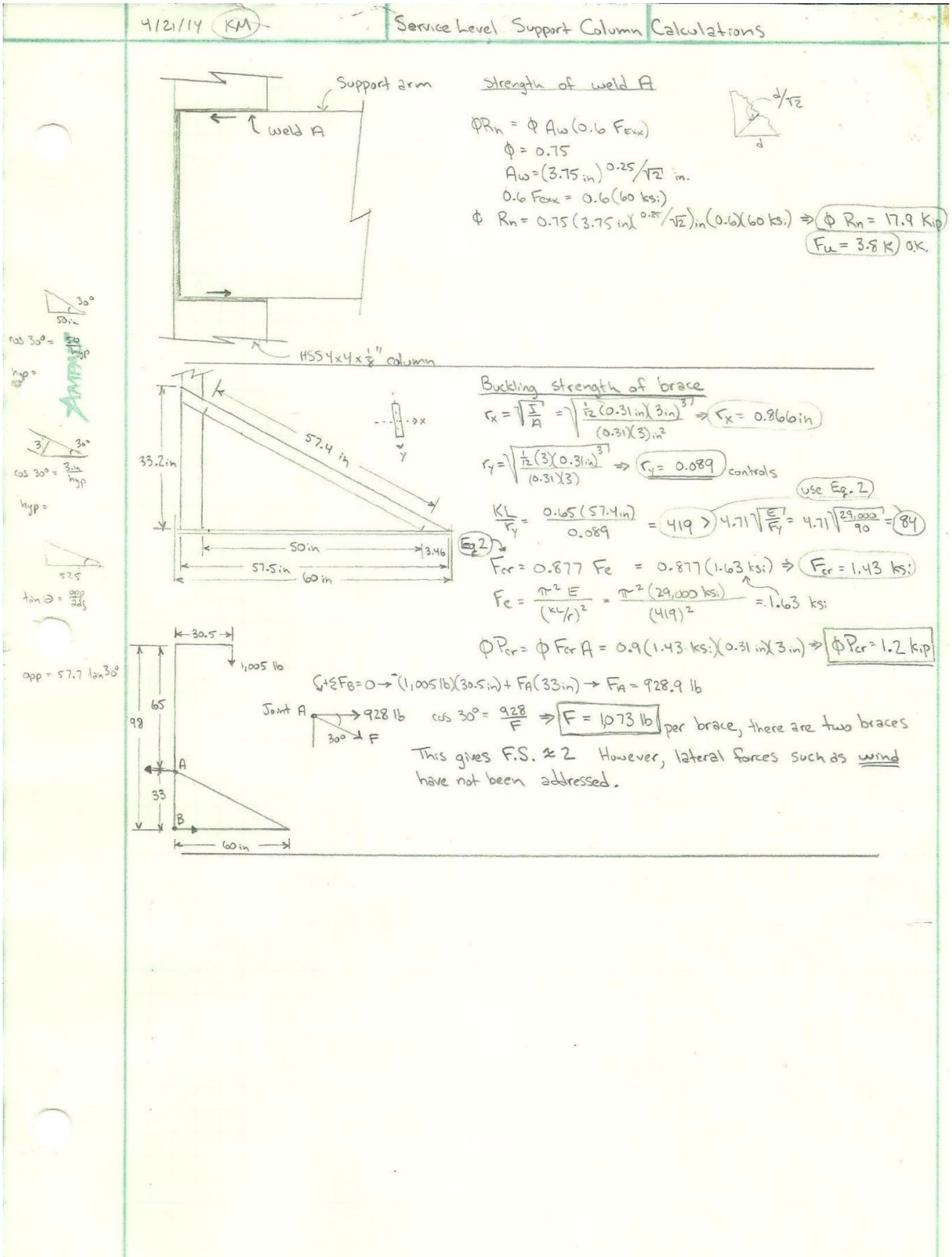


4/21/14 (KM)

Service Level Support Column Calculations

Strength of weld A

$\phi R_n = \phi A_w (0.6 F_{exx})$

$\phi = 0.75$

$A_w = (3.75_{in})\, 0.25/\sqrt{2}$ in.

$0.6 F_{exx} = 0.6(60 \text{ ksi})$

$\phi R_n = 0.75(3.75\text{ in})(0.25/\sqrt{2})_{in}(0.6)(60\text{ ksi}) \Rightarrow \phi R_n = 17.9$ Kip

$F_u = 3.8$ K OK.

Buckling strength of brace

$r_x = \sqrt{\frac{I}{A}} = \sqrt{\frac{\frac{1}{12}(0.31\text{ in})(3\text{ in})^3}{(0.31)(3)_{in^2}}} \Rightarrow r_x = 0.866\text{ in}$

$r_y = \sqrt{\frac{\frac{1}{12}(3)(0.31\text{ in})^3}{(0.31)(3)}} \Rightarrow r_y = 0.089$ controls

(use Eq. 2)

$\frac{KL}{r_y} = \frac{0.65(57.4\text{ in})}{0.089} = 419 > 4.71\sqrt{\frac{E}{F_y}} = 4.71\sqrt{\frac{29{,}000}{90}} = 84$

(Eq 2)

$F_{cr} = 0.877 F_e = 0.877(1.63\text{ ksi}) \Rightarrow F_{cr} = 1.43$ ksi

$F_e = \frac{\pi^2 E}{(KL/r)^2} = \frac{\pi^2(29{,}000\text{ ksi})}{(419)^2} = 1.63$ ksi

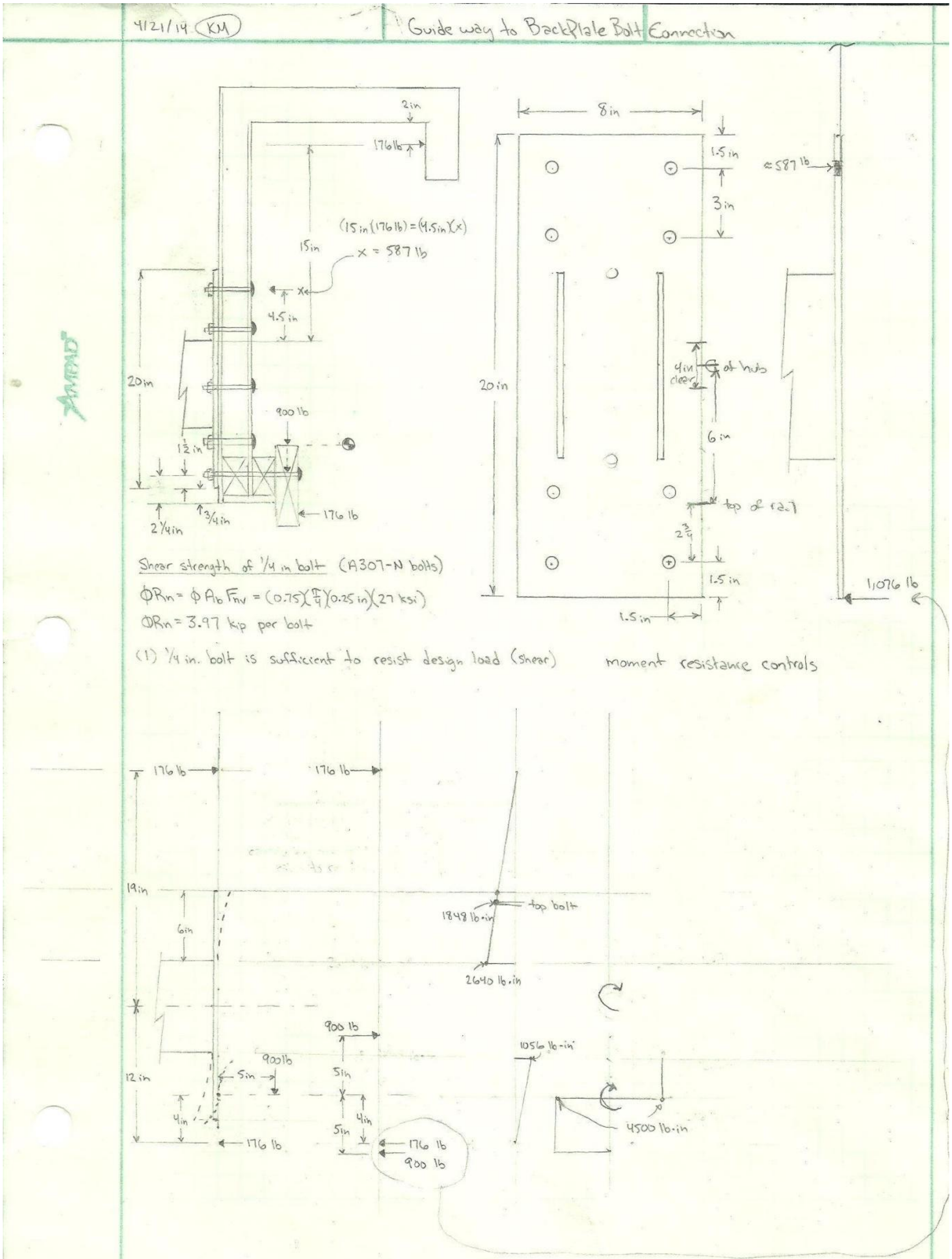
$\phi P_{cr} = \phi F_{cr} A = 0.9(1.43\text{ ksi})(0.31\text{ in})(3\text{ in}) \Rightarrow \phi P_{cr} = 1.2$ kip

$\circlearrowleft + \Sigma F_B = 0 \rightarrow (1{,}005\text{ lb})(30.5\text{ in}) + F_A(33\text{ in}) \rightarrow F_A = 928.9$ lb

Joint A: $\cos 30° = \frac{928}{F} \Rightarrow F = 1073$ lb per brace, there are two braces

This gives F.S. ≈ 2. However, lateral forces such as wind have not been addressed.

Appendix (Author's Technical Assistance)



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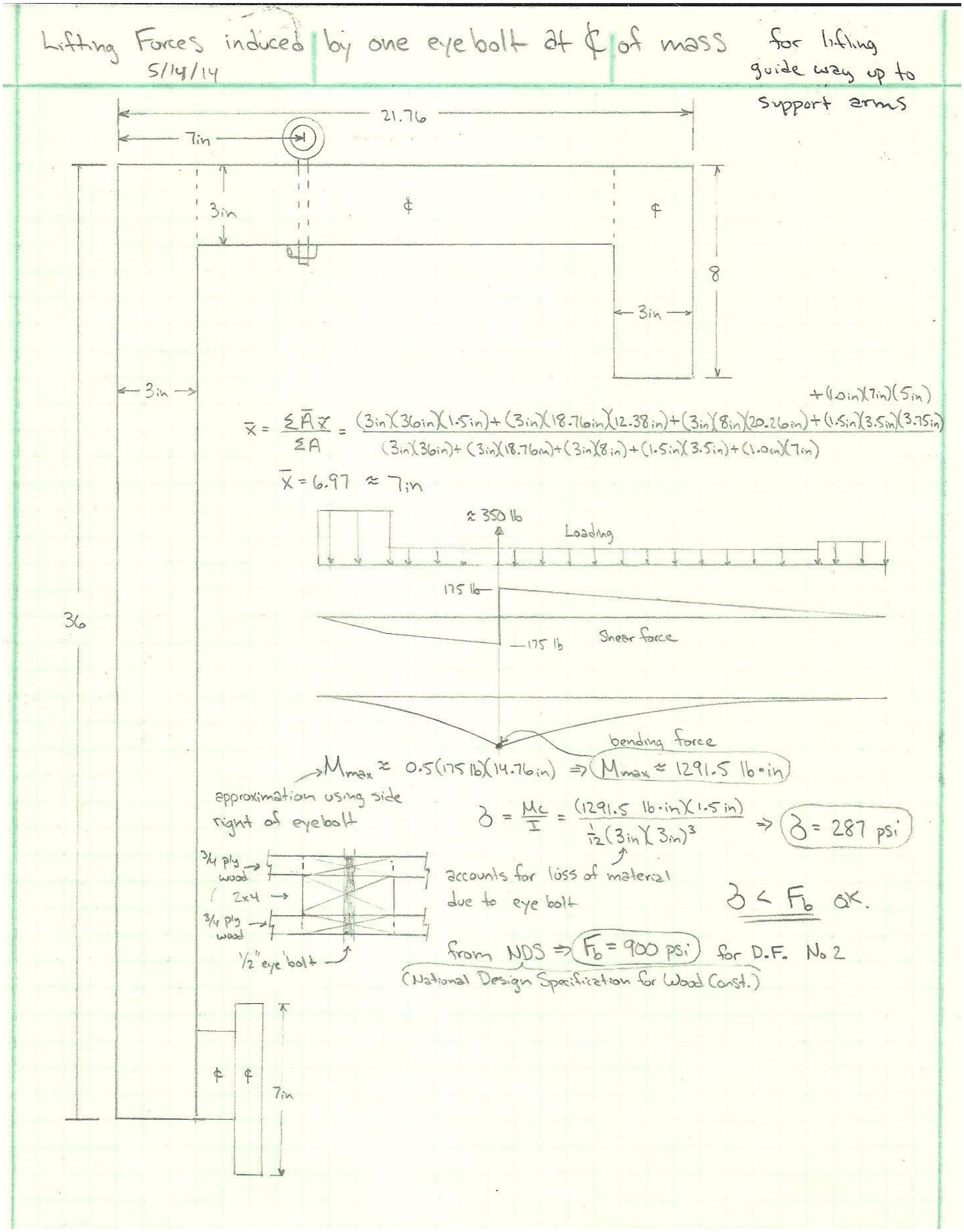


Appendix (Guide Way Team's Initial Analysis of Support Columns, presented to Author 03/24/2014)

$$\vec{M}_{max} = 40{,}241 in \cdot lb$$

$$\vec{P}\sin 30 \cdot 8in + \vec{P}\cos 30 \cdot 21in = 40{,}241 in \cdot lb$$

$$\vec{P} = 1{,}820 lb$$

$$Two\ braces\ per\ Support\ \therefore$$

$$\vec{P}_{crit} = 910lb \rightarrow With\ 1.8\ safety\ factor \rightarrow \vec{P}_{crit} = 1{,}638lb$$

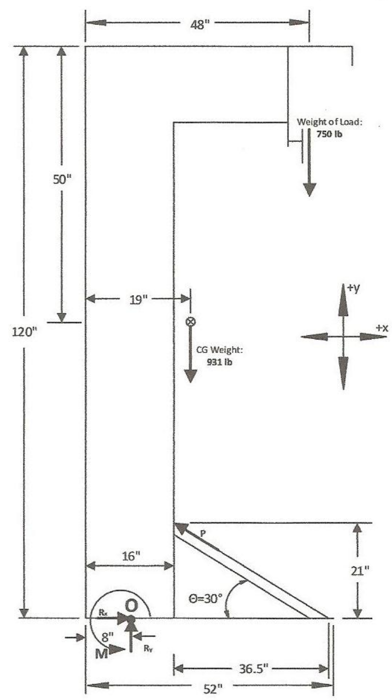
$$To\ Avoid\ Buckling: the\ following\ analysis:$$

$$Conservative\ effective\ length = 42.11in$$

$$ASCI\ effective\ length = 27.37in$$

$$Theoretical\ effective\ length = 21.06in$$

Free Body Diagram



	Mechanical Parameters			
	Thickness [in]	*I [in⁴]*	*A [in²]*	*k [in]*
7 Gauge	0.1793	0.00144	0.5379	0.05176
3/16"	0.1875	0.00165	0.5625	0.05413
1/4"	0.2500	0.00391	0.7500	0.07217
5/16"	0.3125	0.00763	0.9375	0.09021

Slenderness Ratio				
L_{eff} [in]	*7 Gauge*	*3/16"*	*1/4"*	*5/16"*
42.11	813.571	777.991	583.493	466.795
27.37	528.792	505.666	379.250	303.400
21.06	406.882	389.088	291.816	233.453

$P_{critical}$ *[lb]*				
L_{eff} [in]	*7 Gauge*	*3/16"*	*1/4"*	*5/16"*
42.11	240.620	275.166	652.245	1273.915
27.37	569.577	651.351	1543.944	3015.515
21.06	962.022	1100.140	2607.740	5093.242

Appendix (Guide Way Team's Initial Analysis of Support Columns, presented to Author 03/24/2014)

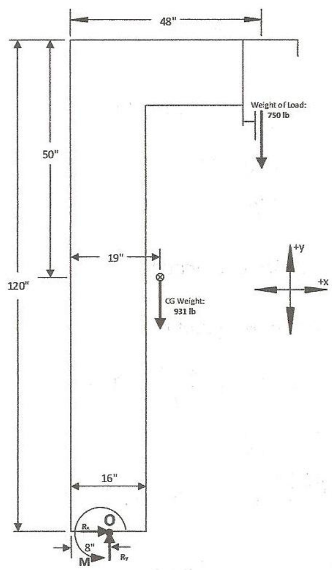


Figure 1: Non Braced Support tower Free Body Diagram

$$\sum \vec{F_y} = \vec{R_y} = 1681\ lb$$

$$\sum \vec{F_x} = \vec{R_x} = 0$$

$$\sum \vec{M_O} = \vec{M} = 40{,}241\ in \cdot lb$$

$$\sigma_{Max_{Steel}} = Y_s = 100ksi$$

$$b_{foot} = 16in$$

$$thickness_{min_{footer}} = \sqrt{\frac{6\vec{M}}{b \cdot \sigma}}$$

$$thickness_{min_{foot}} = 0.388in \cong 0.4in$$

$$Will\ use\ standard\ thickness\ of\ 0.5in$$

$$\sigma_{sf} = 1.8 \times \sigma_{max} = 55{,}000\ ksi$$

$$Determine\ maximum\ acceptable\ moment$$

$$\vec{M}_{maximum} = \frac{{t_{min}}^2 \cdot b \cdot \sigma}{6}$$

$$\vec{M}_{maximum} = 29{,}827in \cdot lb = 30{,}000in \cdot lb$$

$$I_{min_{footer}} = \frac{1}{12} b \cdot t^3 = \frac{1}{12} \times 16\text{in} \times 0.5in^3 = 0.167in^4$$

$$E_{Steel} = 30Mpsi$$

$$M = F(L - x) \rightarrow F = \frac{M}{L} = \frac{30{,}000in \cdot lb}{52in} = 577lb$$

$$Deflection\ of\ a\ cantilevered\ beam$$

$$to\ determine\ if\ maximum\ moment\ is\ acceptable$$

$$\delta = \frac{FL^3}{3EI} = \frac{577lb \cdot 52in^3}{3 \cdot 30Mpsi \cdot 0.167in^4} = 5.4in$$

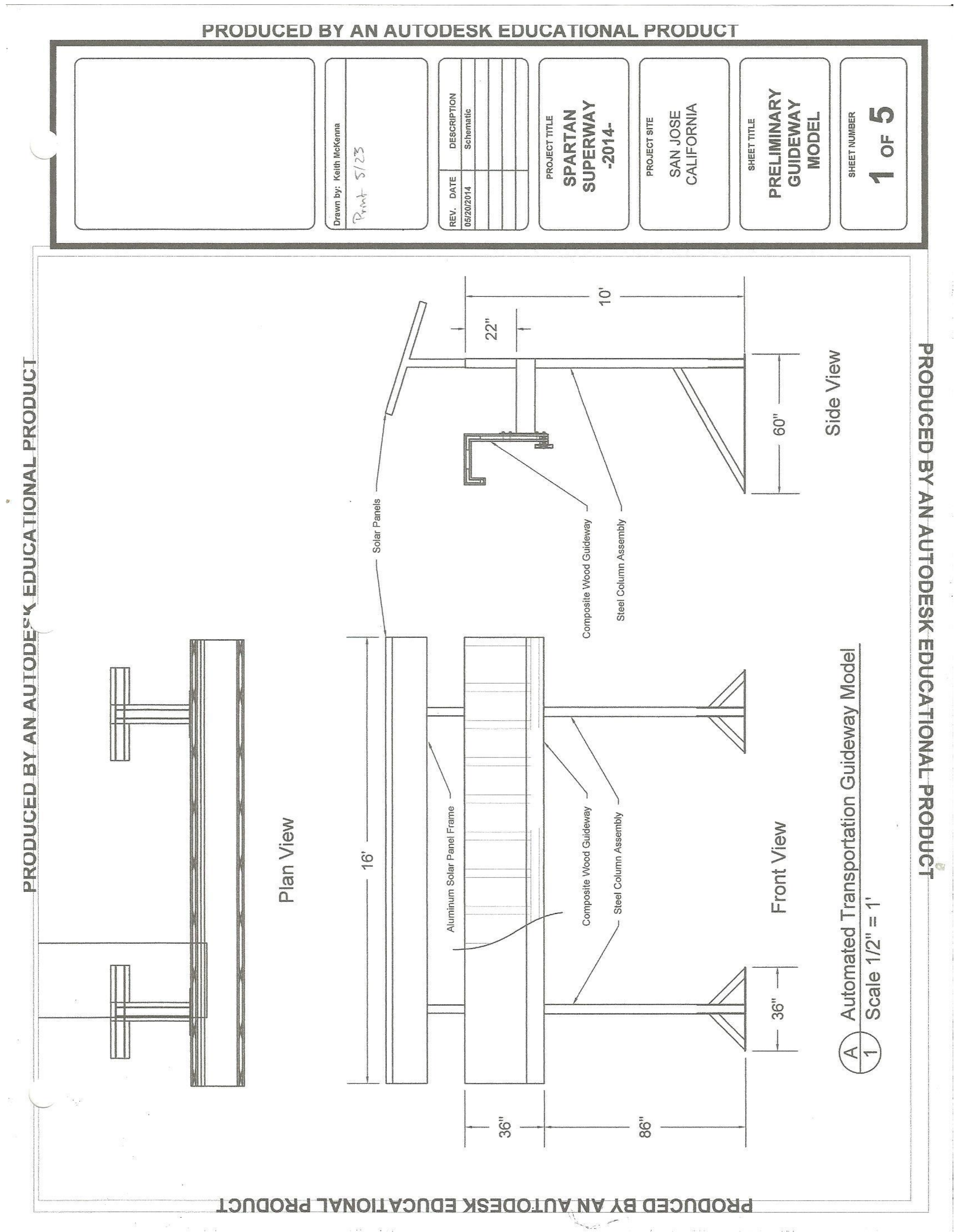
$$unacceptable\ deflection\ therefore$$

$$moment\ needs\ to\ be\ reduced$$

$$Goal{:}\ Reduce\ Moment\ to\ Zero, therefore\ deflection$$

$$will\ only\ occur\ under\ additional\ loading\ conditions$$

Appendix (Author's Shop Drawings)



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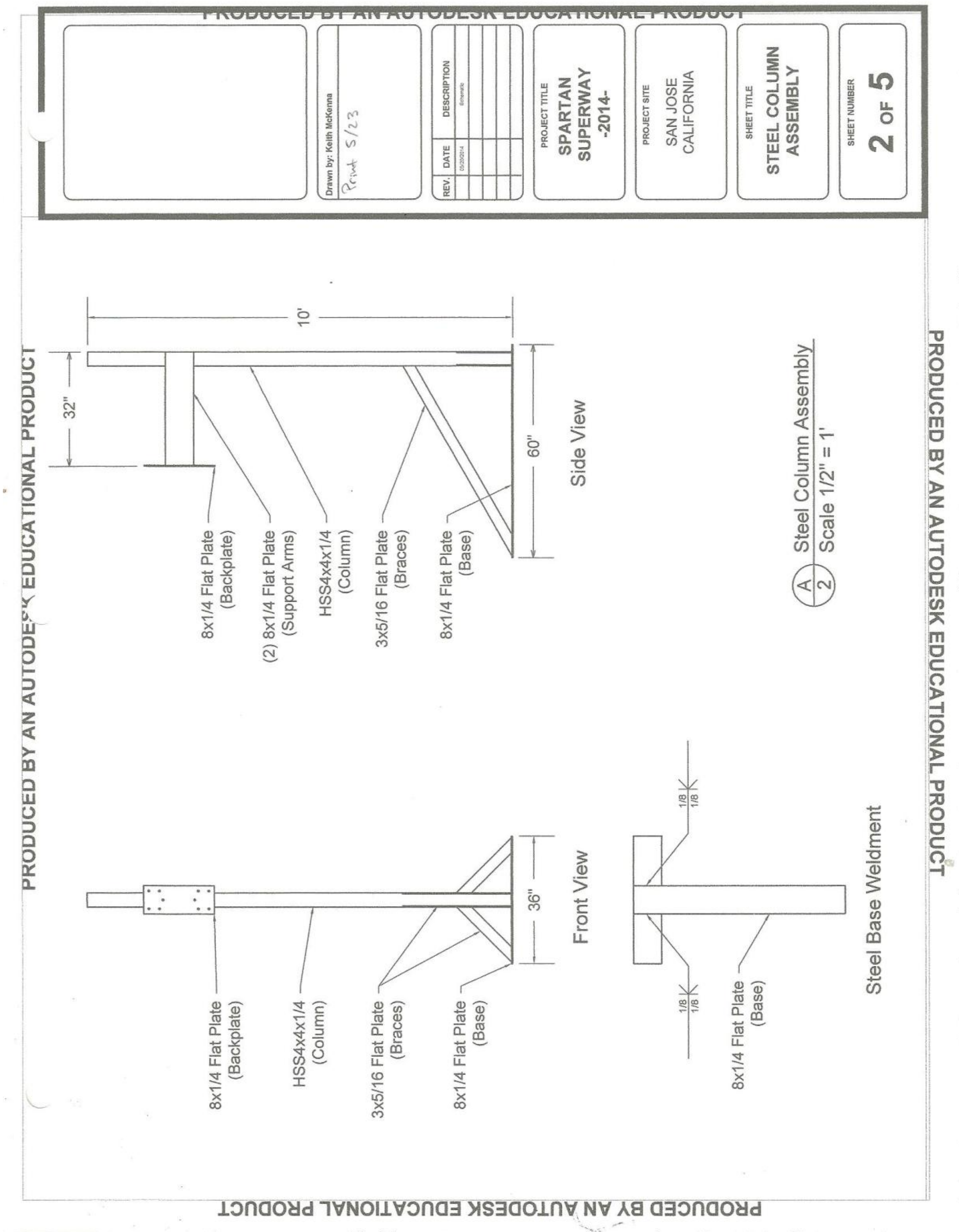

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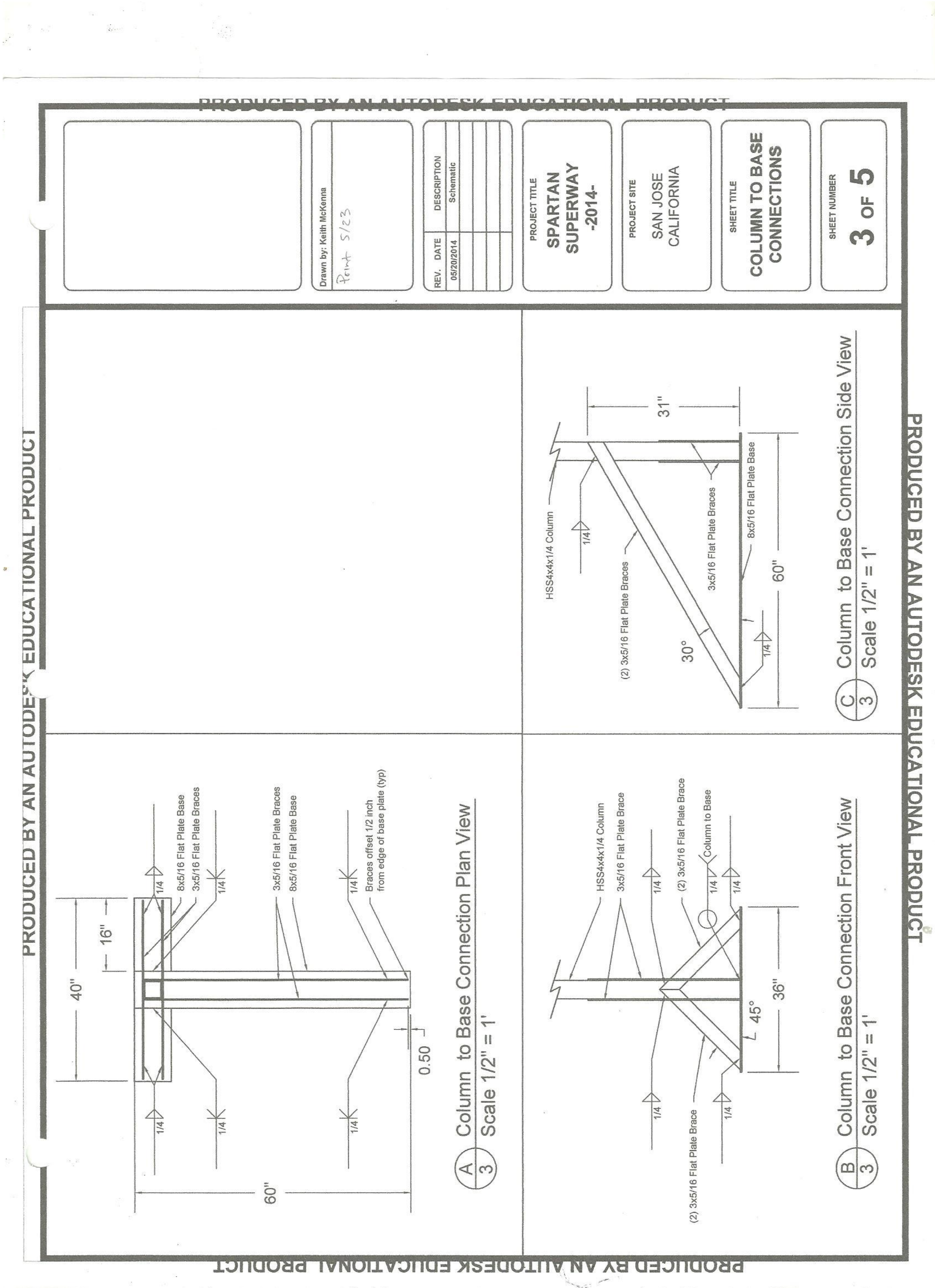

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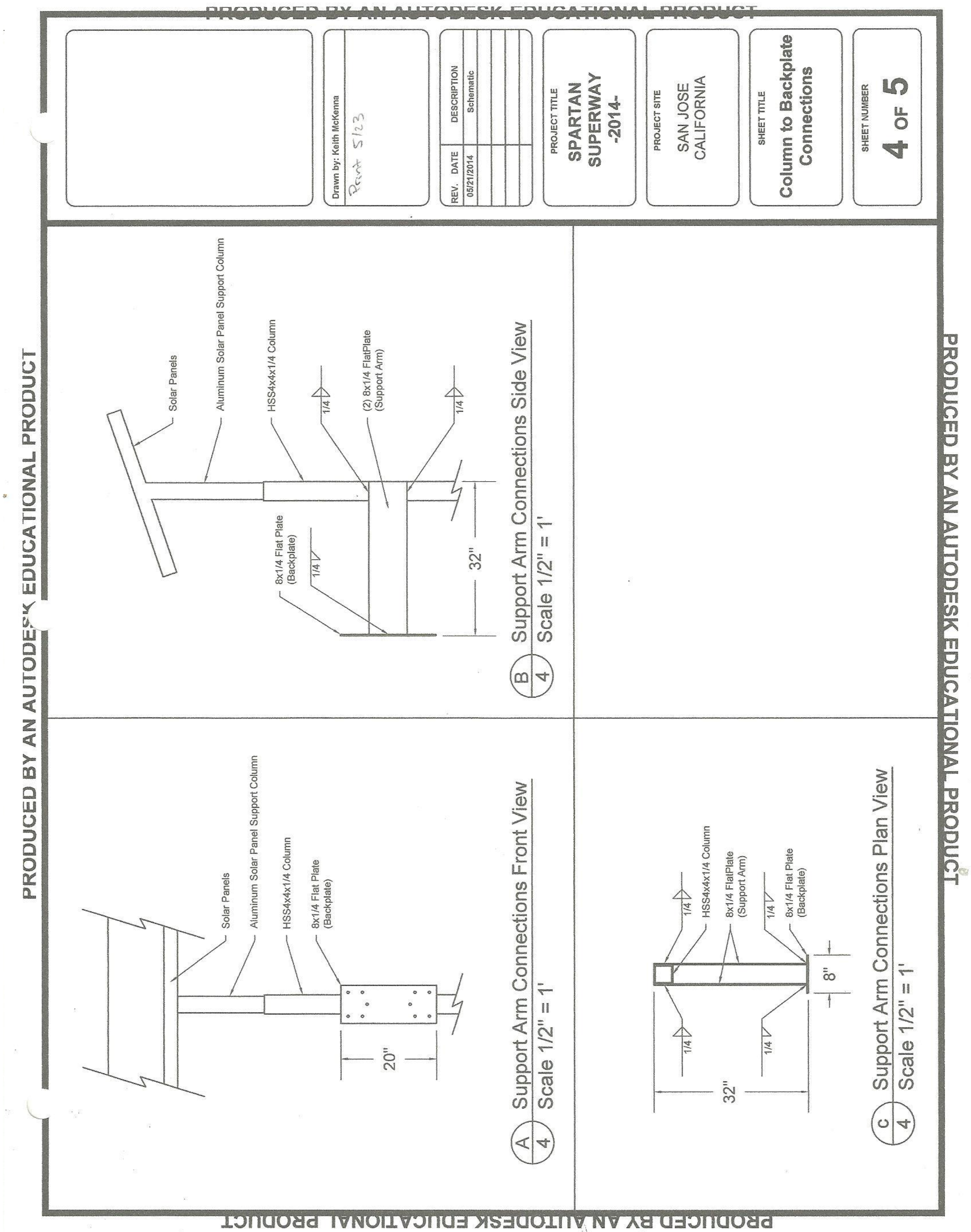

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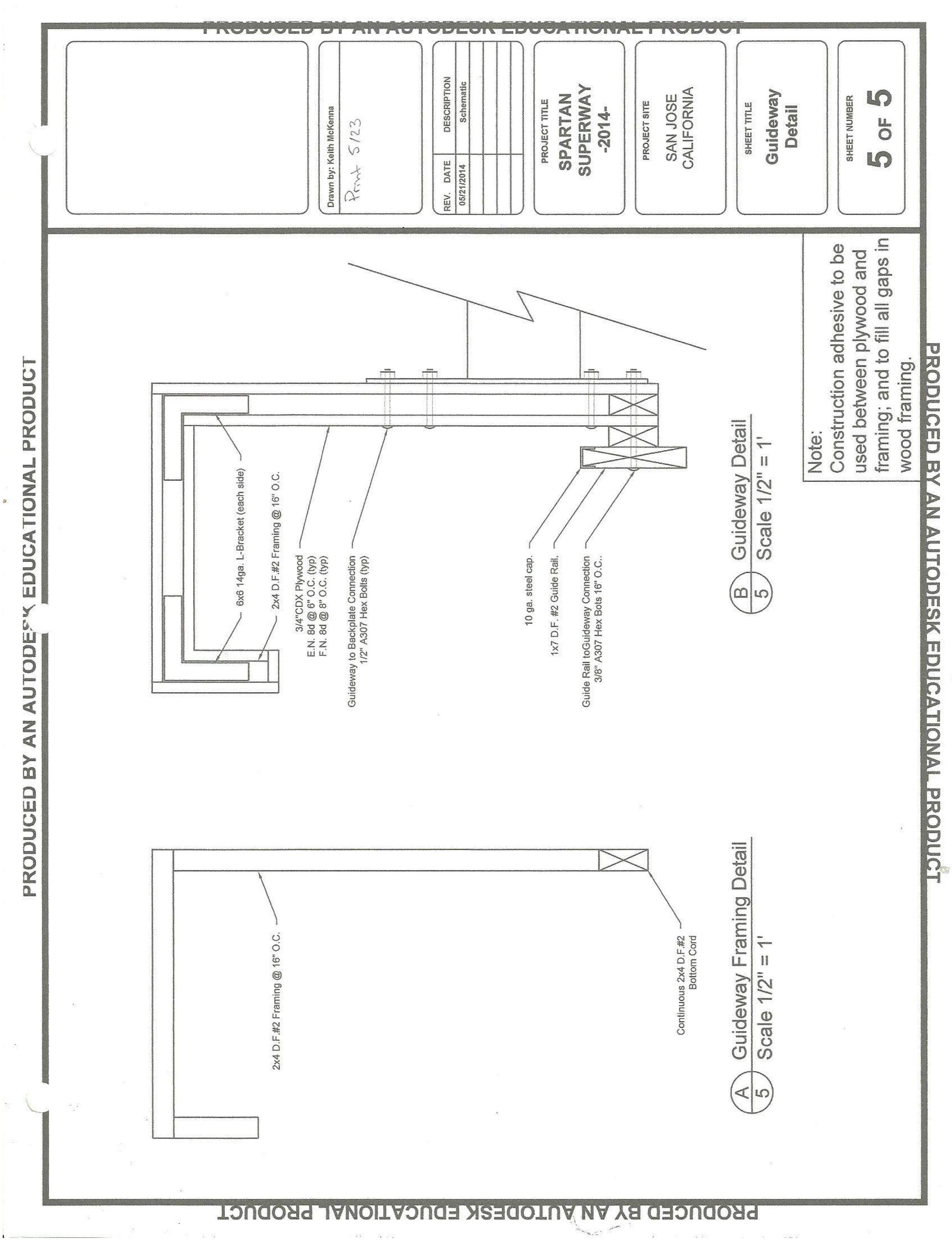
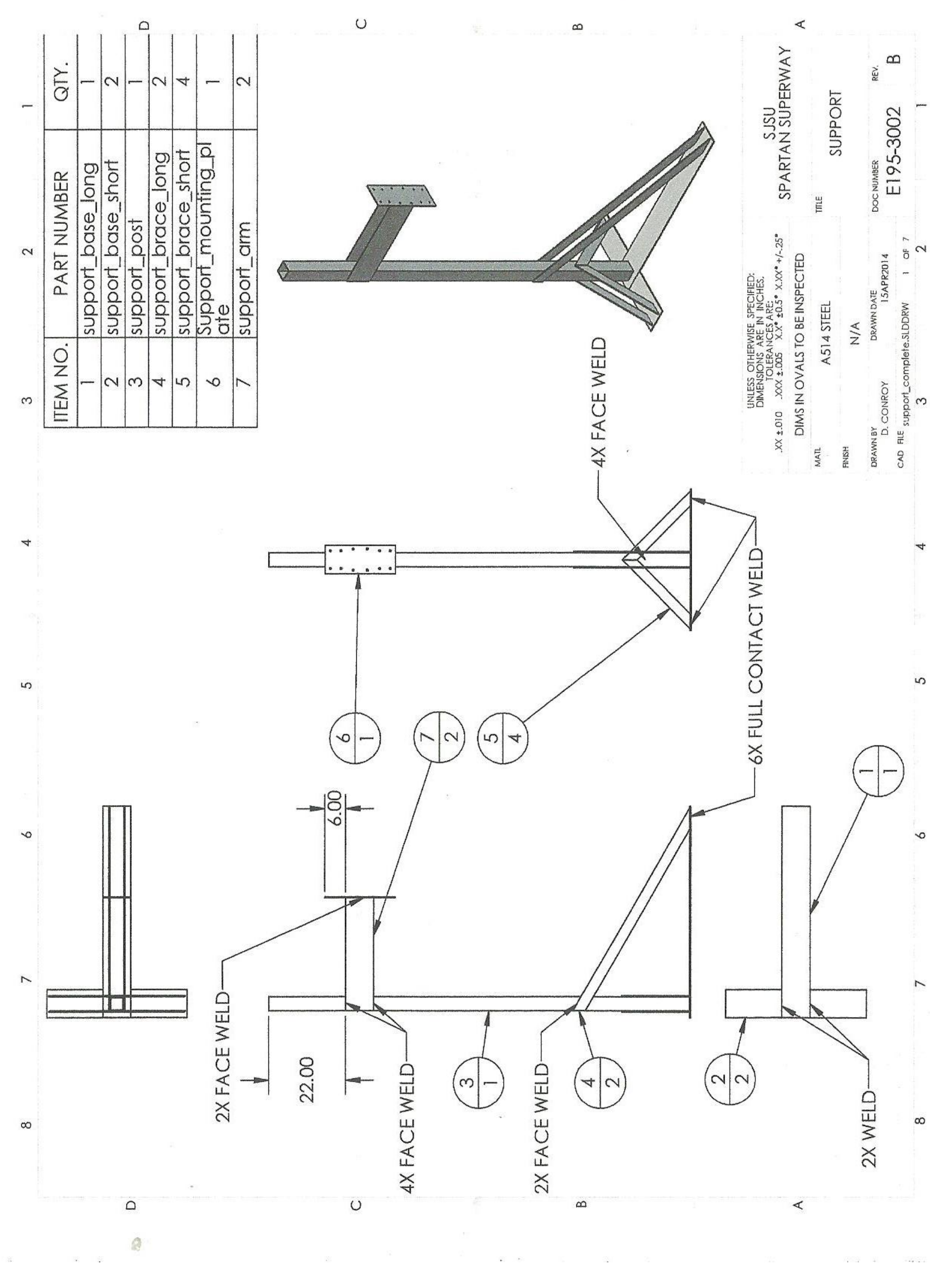


Appendix (Guide Way Team Drawings)



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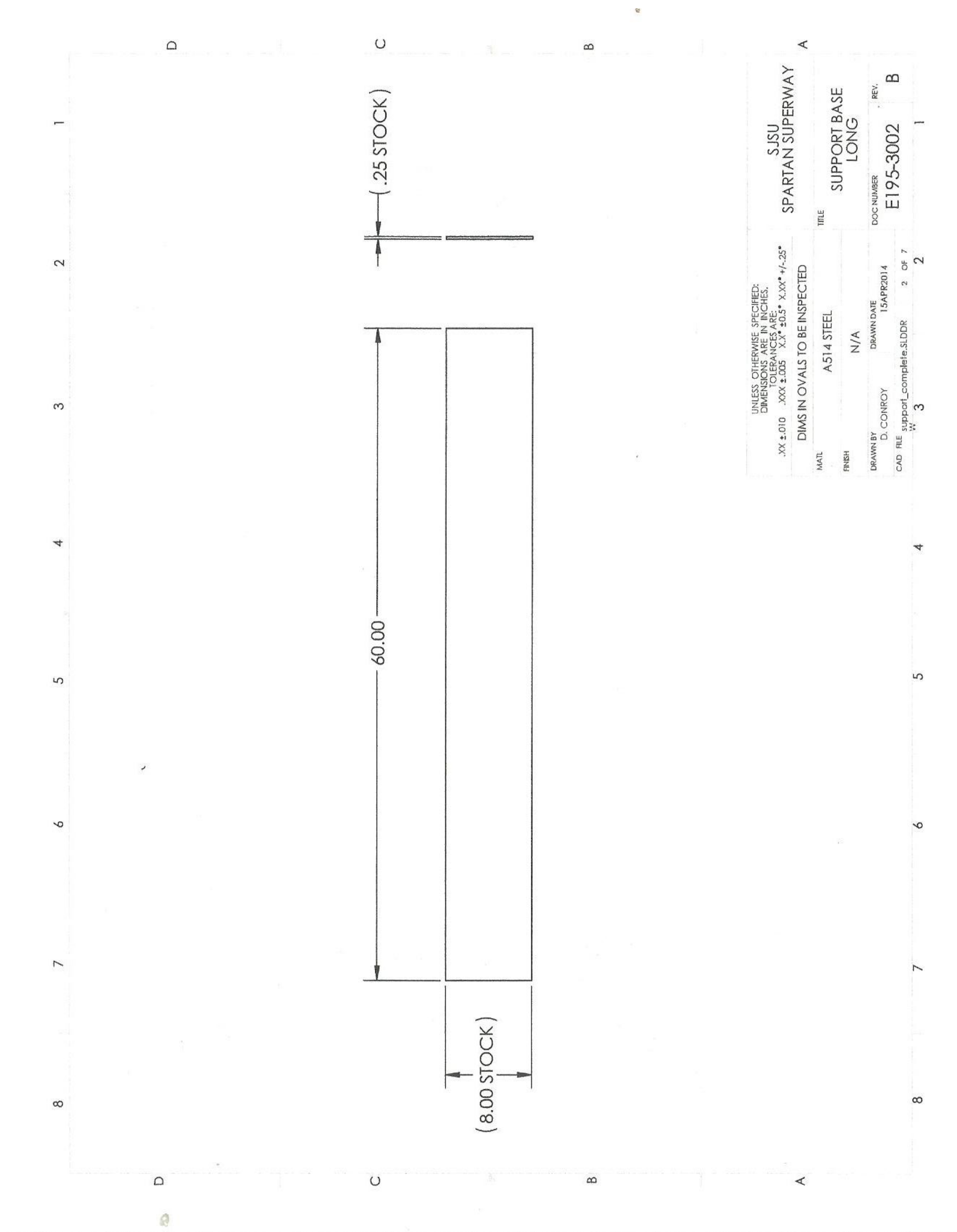

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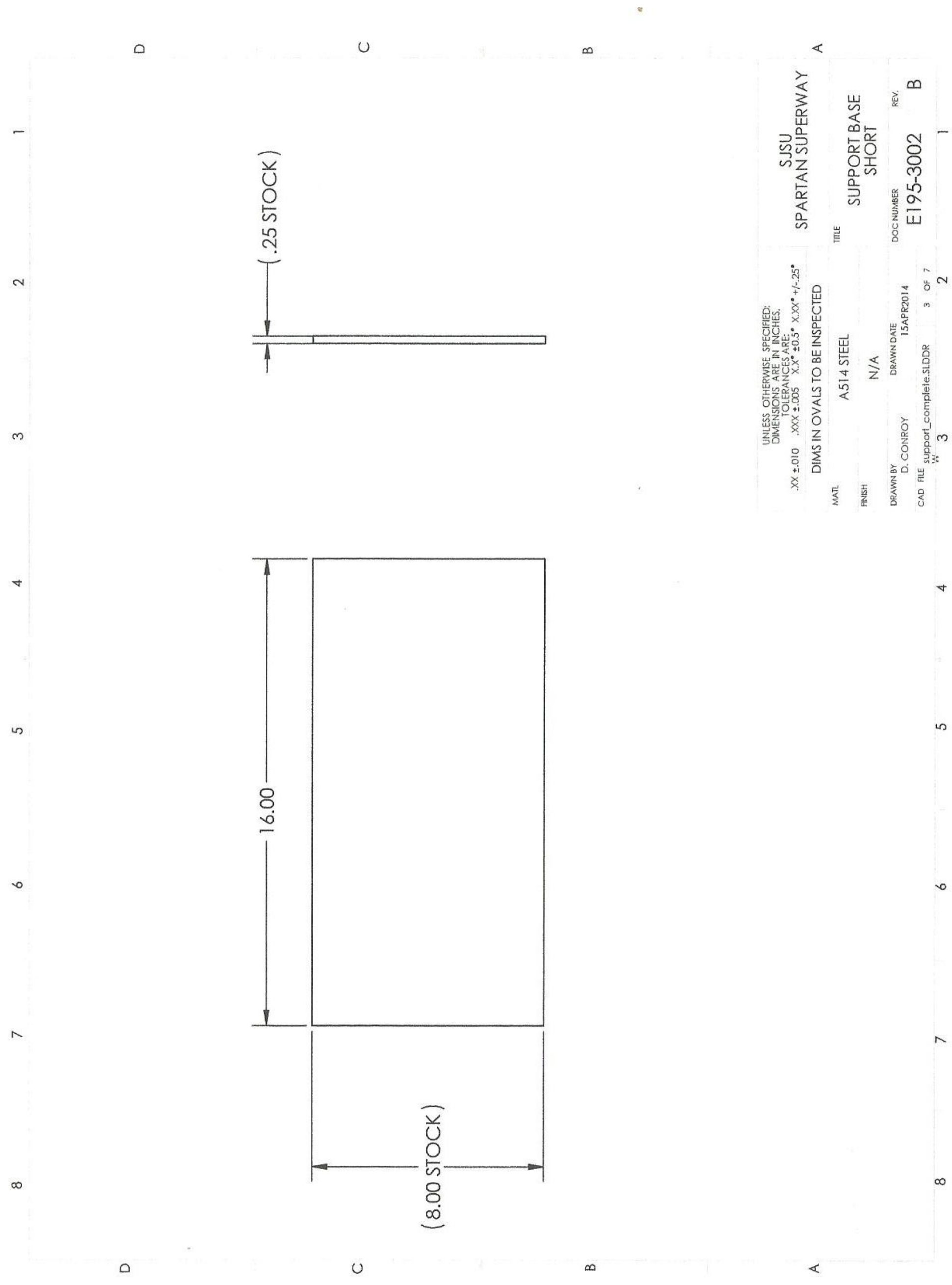

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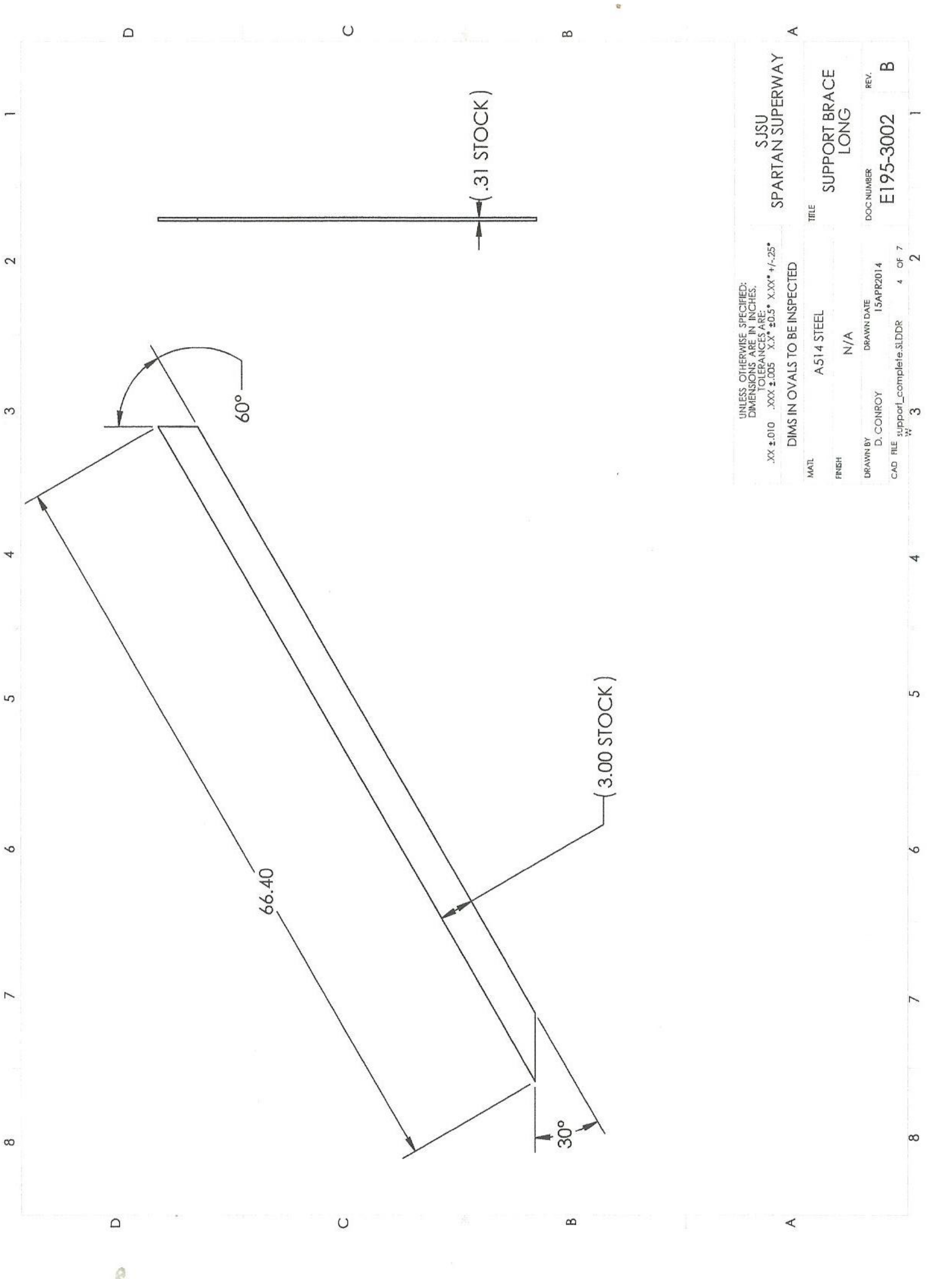

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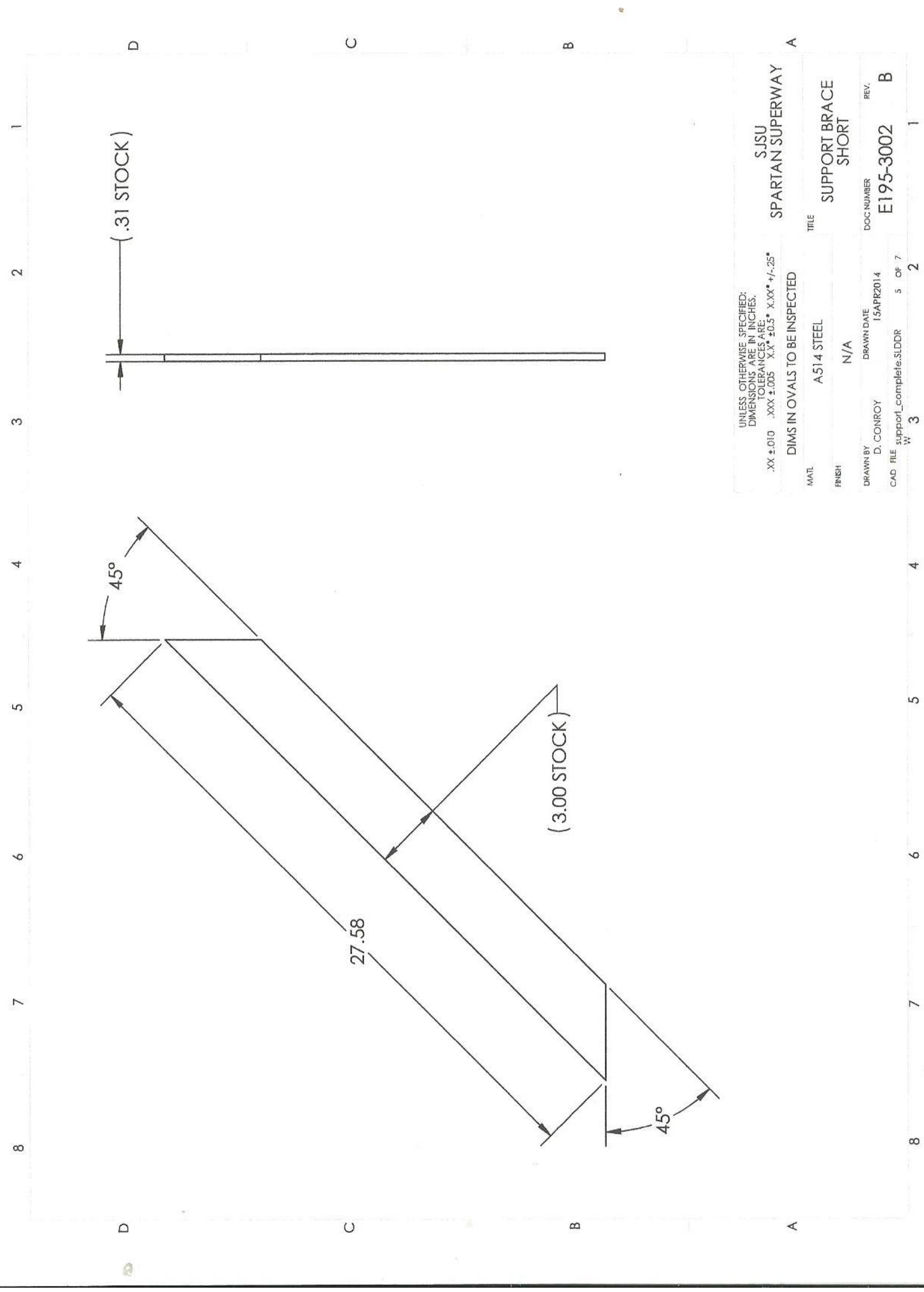

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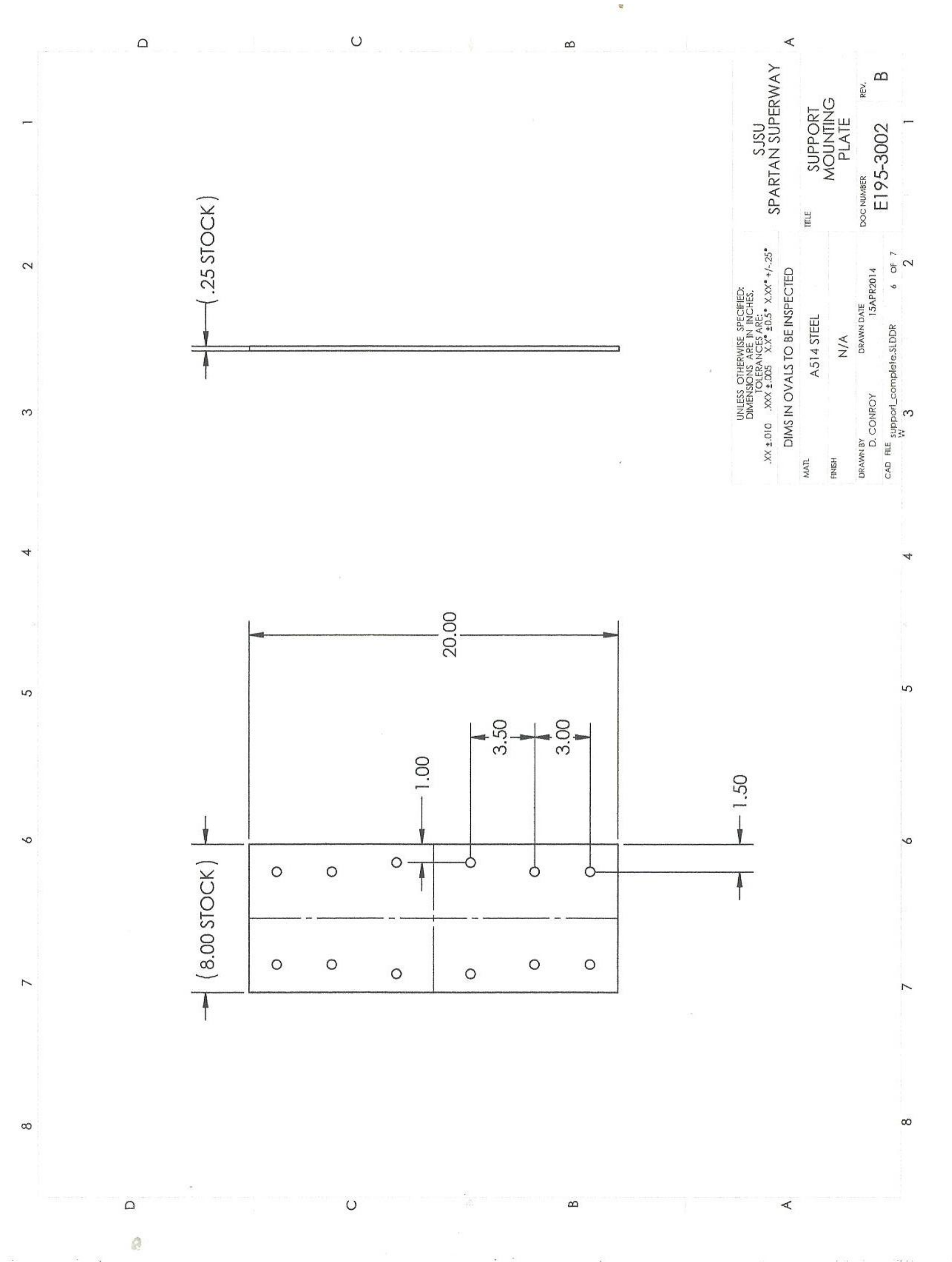

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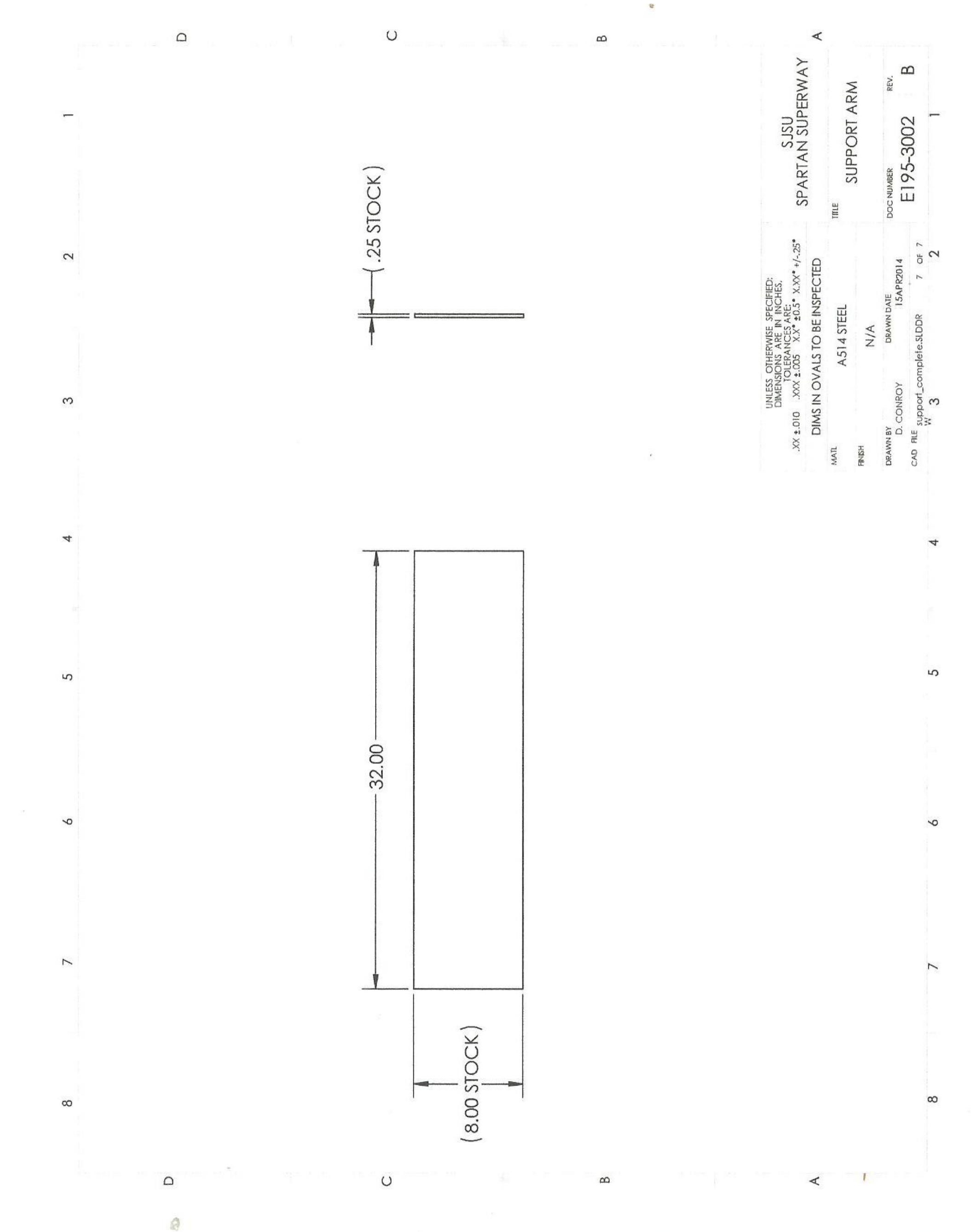

Appendix (Estimated Steel Fabrication Schedule)

		Units		Time per Unit (hr)	Total Time (hr)
Column					
Cut HSS4x4x1/4 to size		1		0.5	0.5
Debur		1		0.25	0.25
set-up		1		0.25	0.25
				Total for Item	1
Base Plate					
plate fabrication	Cut 8" plate to size	3		0.5	1.5
plate fabrication	grind cut ends	3		0.5	1.5
plate fabrication	grind for groove weld	2		0.5	1
fabbrication set-up		3		0.15	0.45
welding set-up		2		0.5	1
welding		1.4	feet	0.1	0.14
				Total for Item	5.59
Column to Base Bracing					
plate fabrication	Cut 3" plate to size	6		0.2	1.2
plate fabrication	grind cut ends	12		0.2	2.4
fabbrication set-up		6		0.1	0.6
					4.2
Support Arms					
plate fabrication	Cut 8" plate to size	2		0.5	1
plate fabrication	grind cut ends	4		0.5	2
fabrication set-up		2		0.25	0.5
				Total for Item	3.5
Back Plate					
plate fabrication	Cut 8" plate to size	1		0.5	0.5
plate fabrication	grind cut ends	2		0.5	1
drilling bolt holes		10		0.25	2.5
fabrication set-up		1		0.25	0.25
					4.25
Guide Rail					0
rail fabrication					0
set-up					0
welding					0
				Total for Item	?
Connections					
Base to Column					
welding set-up		1		0.75	0.75
welding	4 sides 4 inches	1	ft	0.3	0.3
				Total for Item	1.05
Base to Column Braces					
welding set-up		6		0.25	1.5
welding		4.5	feet total	0.3	1.35
				Total for Item	2.85
Column to Support Arm					
welding set-up		2		0.2	0.4
welding		1.4	feet total	0.3	0.42
				Total for Item	0.82
Support Arm to Back Plate					
welding set-up		1		0.2	0.2
welding		1.4	feet total	0.3	0.42
				Total for Item	0.62
				Total for Column Weldment	**24.5 hrs**

Appendix (Project Time Line)

Summary of Guide Way Development and Construction Timeline

Task	Personnel		Location	Date (2014)
	McKenna	M.E. Guideway Team		
Initial Schematic Design of Guide Way System		X	SJSU Campus	3/14
Final Schematic Design of Guide Way System	X	X	SJSU Campus	3/25
Design Development	X	X	SJSU Campus	4/1
Bill of Materials (Timber & Steel)	X	X	SJSU Campus	4/2
Transport Timber Building Materials	X		Santa Cruz	4/9
Construct Timber Guideway	X	X	7th St. Building Site	4/14
Aquire Steel Building Materials		X	SJSU Campus	4/20
Construct Steel Column Assemblies	X	X	SJSU Campus	5/2
Connect Timber Guideway to Steel Column Assemblies	X	X	7th St. Building Site	5/3
Construct Exhibit Entry	X		7th St. Building Site	5/10
Transport and Assemble ExhibitModel	X	X	7th St. Building Site to San Mateo Convention Center	5/15
Makers Faire		X	San Mateo	5/17
Break-Down and Transport Exhibit Model	X	X	San Mateo Convention Center to 7th St. Building Site	5/18 -

Steel Columns Fabrication Work Log					
Date	Worker Hours				Cumulative Work Hours
	Pat Joice	Cormac Whitlow	Daniel Conroy	Keith McKenna	
04/21/2014		1		1	2
04/26/2014				8	
04/28/2014	8	8	8	8	32
04/30/2014				1.5	1.5
05/02/2014	5	5	5		15
Total	13	14	13	18.5	**58.5**

Appendix (Sample Calculations)

Demand stress analysis of composite timber guide way beam about neutral axis horizontal to beam cross section.

Distance to neutral axis from top of cross section **($\bar{x}$)**:

$$\bar{x} = \frac{\sum \breve{x}A}{\sum A} = \frac{(18)(3)(36) + (1.5)(3)(16) + (4.5)(3)(9) + (36)(3)(6)}{(3)(36) + (3)(16) + (3)(9) + (3)(6)} = \mathbf{13.86\ in.}$$

Moment of Inertia **(I)**:

$$I = \sum \bar{I} + A(d_y)^2$$

$$= \left(\frac{1}{12}\right)(3)(36)^3 + (3)(36)(18 - 13.86)^2 + \left(\frac{1}{12}\right)(16)(3)^3 + (16)(3)(13.86 - 1.5)^2$$

$$+ \left(\frac{1}{12}\right)(3)(9)^3 + (3)(9)(13.86 - 4.5)^2 + \left(\frac{1}{12}\right)(3)(6)^3 + (3)(6)(36 - 13.86)^2$$

$$= \mathbf{32{,}3089\ in.^4}$$

Area of the guide way beam bottom portion below the neutral axis **(A')**:

$$A' = (36 - 13.86)(3) + (3)(6) = \mathbf{40.14 in.^2}$$

Lower distance from neutral axis to centroid of area($\bar{y}'$):

$$\bar{y}' = \frac{\sum \breve{y}\bar{A}}{\sum \bar{A}} = \frac{\left(\frac{36 - 13.86}{2}\right)(36 - 13.86)(3) + (36 - 13.86)(3)(6)}{(36 - 13.86)(3) + (3)(6)} = \mathbf{13.43\ in.}$$

Maximum shear stress calculated at neutral axis of cross section **(τ)**:

$$\tau = \frac{VQ}{It} = \frac{(536lb)(1134in.^3)}{(32{,}309in.^4)(1.5in.)} = \mathbf{12.5\ psi}$$

Maximum tensile bending stress at bottom of beam (σ_t):

$$\sigma_t = \frac{Mc_u}{I} = \frac{(1.68kip \cdot ft)\left(\frac{12in.}{1ft}\right)(13.86in.)}{32{,}309in.^4} = \mathbf{8.65\ psi}$$

Maximum compressive bending stress at top of beam ($\boldsymbol{\sigma_c}$):

$$\sigma_c = \frac{Mc_b}{I} = \frac{(1.68kip \cdot ft)\left(\frac{12in.}{1ft}\right)(36 - 13.86)in.}{32{,}309\ in.^4} = \mathbf{13.81\ psi}$$

Bolt Connections

Shear strength of one ½" A307-N Bolt:

$$\frac{R_n}{\Omega} = \frac{F_{nv}A_b}{\Omega} = \frac{(27ksi)(\pi/4)\ (0.5in)^2}{2} = \mathbf{2.65\ kip}$$

Tensile strength of one ½" A307-N Bolt:

$$\frac{R_n}{\Omega} = \frac{F_{nt}A_b}{\Omega} = \frac{(45ksi)\left(\frac{\pi}{4}\right)(0.5in)^2}{2} = \mathbf{4.42\ kip}$$

Bearing strength of one ½" A307-N Bolt through ¼" A500 Grade B steel plate:

$$\frac{R_n}{\Omega} = \frac{2.4dtF_u}{\Omega} = \frac{(2.4)(0.5in)(0.25in)(58ksi)}{2} = \mathbf{8.7\ kip}$$

Plywood service level crushing demand induced by one ½" washer:

$$\sigma = \frac{F}{A} = \frac{616\ lb}{\left(\frac{\pi}{4}\right)[(1.375 - 0.5)in]^2} = \mathbf{1024\ psi}$$

Steel Column Assemblies

Axial Demand (Each Column)

Description	Weight (lb)
Cabin	150
(2) Bogies	500
(1/2) Guide Way	317
(2) Support Arms	40
(1/2) Solar Array	100
Column	122
Total Load=	1.23 kip

Item	**Slenderness ($\frac{KL}{r}$)**
Column	83
Diagonal Brace (Long)	
Diagonal Brace (Short)	
Support Arm	14
Back Plate	9

Steel Column Buckling Capacity

Slenderness ($\frac{KL}{r}$):

$$\frac{KL}{r} = \frac{(2)(63\ in.)}{1.52\ in.} = 83$$

Euler Buckling Stress (F_e):

$$F_e = \frac{\pi^2 E}{(\frac{KL}{r})^2} = \frac{\pi^2 (29{,}000\ ksi)}{(\frac{(2)(63\ in.)}{1.52\ in})^2} = \mathbf{41.7\ ksi}$$

Critical Buckling Stress (F_{cr}):

$$F_{cr} = \left[0.658^{\frac{F_y}{F_e}}\right] F_y = \left[0.658^{\frac{42}{41.7}}\right](42\ ksi) = \mathbf{27.5\ ksi}$$

Nominal Axial Strength (P_n):

$$P_n = F_{cr} A_g = (27.5\ ksi)(3.37\ in.^2) = \mathbf{92.7\ kip}$$

Allowable Axial Strength Considering Buckling ($\frac{P_n}{\Omega}$):

$$\frac{P_n}{\Omega} = \frac{92.7\ kip}{1.67} = \mathbf{55.5\ kip}$$

Bending Allowable Elastic Strength ($\frac{F_y}{\Omega}$):

$$\frac{F_y}{\Omega} = \frac{50\ ksi}{1.67} = \mathbf{29.9\ ksi}$$

Bending Demand ($\frac{Mc}{I}$):

$$\frac{Mc}{I} = \frac{(7.34\ kip \cdot ft)\left(\frac{12\ in.}{1\ ft}\right)(2\ in.)}{7.8\ in.^4} = \mathbf{22.6\ ksi}$$

Yield Strength (P_a):

$$P_a = \frac{F_y A_g}{\Omega} = \frac{(50\ ksi)(3.37\ in.^2)}{1.67} = \mathbf{100.9\ kip}$$

Combined Shear and Torsion Demand on Back Plate to Support Arm Weld

Vertical Shear Component (R_v):

$$R_v = \frac{P}{L} = \frac{0.967\ kip}{(2)(8\ in.)} = \mathbf{0.06}\ \frac{\boldsymbol{kip}}{\boldsymbol{in.}}$$

Horizontal Tension Component ($R_t = \frac{Mc}{I}$):

$$R_t = \frac{Mc}{I} = \frac{(0.967\ kip)(10.36\ in.)(4\ in.)}{(2)\left(\frac{1}{12}\right)(1)(8\ in.)^3} = \mathbf{0.47}\frac{\boldsymbol{kip}}{\boldsymbol{in.}}$$

Resultant Force (R_n):

$$R_n = \sqrt{{R_v}^2 + {R_t}^2 =} \sqrt{0.06^2 + 0.47^2} = \mathbf{0.47}\ \frac{\boldsymbol{kip}}{\boldsymbol{in.}}$$

Method for determining weld strengths was on a weld strength per inch basis. Specific weld lengths were multiplied by the determined allowable weld strength of a one inch long ¼ inch fillet weld (R_a) as given below:

$$R_a = \frac{R_n}{\Omega} = \frac{F_{nw}A_{we}}{\Omega} = \frac{(0.60F_{EXX})(0.707wL)}{\Omega} = \frac{(0.60)(70\ ksi)(0.707)(0.25\ in.)(1\ in.)}{2} =$$

$$\boldsymbol{R_a = 3.7\ kip\ per\ one\ inch\ of\ weld}$$