Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project:	NuMI
Title:	Carriages for NuMI Target Hall
Author:	Sami A. Kamal – Argonne National Lab
Reviewer:	Andy Stefanik A. Stefanik
Key Words:	carriage, supports, module support, beamline components
Abstract Summary:	Structural calculations for the carriages were performed at Argonne National Lab. The Argonne calculations show that the main structural members are ok. The calculations also cover details that were not used in the final design. The checker's calculations cover the final design of all three carriages.
Applicable Codes:	AISC Manual of Steel Construction – 9th Edition.

NuMI Target Pile
CARRIAGE STRESS REPORT

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November 8, 2000

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1. Introduction:

The purpose of this report is to demonstrate that the carriage design as presented in the Conceptual design review on 9-19-2000 meets the Specified design requirements. These requirements are:

1. Maximum deflection of carriage structure when subjected to Horn weight (assumed in this report to be 48,000 lbs) is less than 0.100 inches,

2. Structural Components of the Carriage (Pro/E model is Shown in Figure 1.1) meet the allowable stress limits of AISC Manual of Steel Construction, Reference 1.

The PTC Pro/Mechanica finite element program is utilized to accurately determine the maximum deflection of the Carriage Structure. The Pro/Mechanica model represents only one half of the structure and Simplifies some of the Carriage features, See Figure 1.2. All the Simplifications are on the Conservative Side, i.e. they lead to higher deflections and higher stresses.

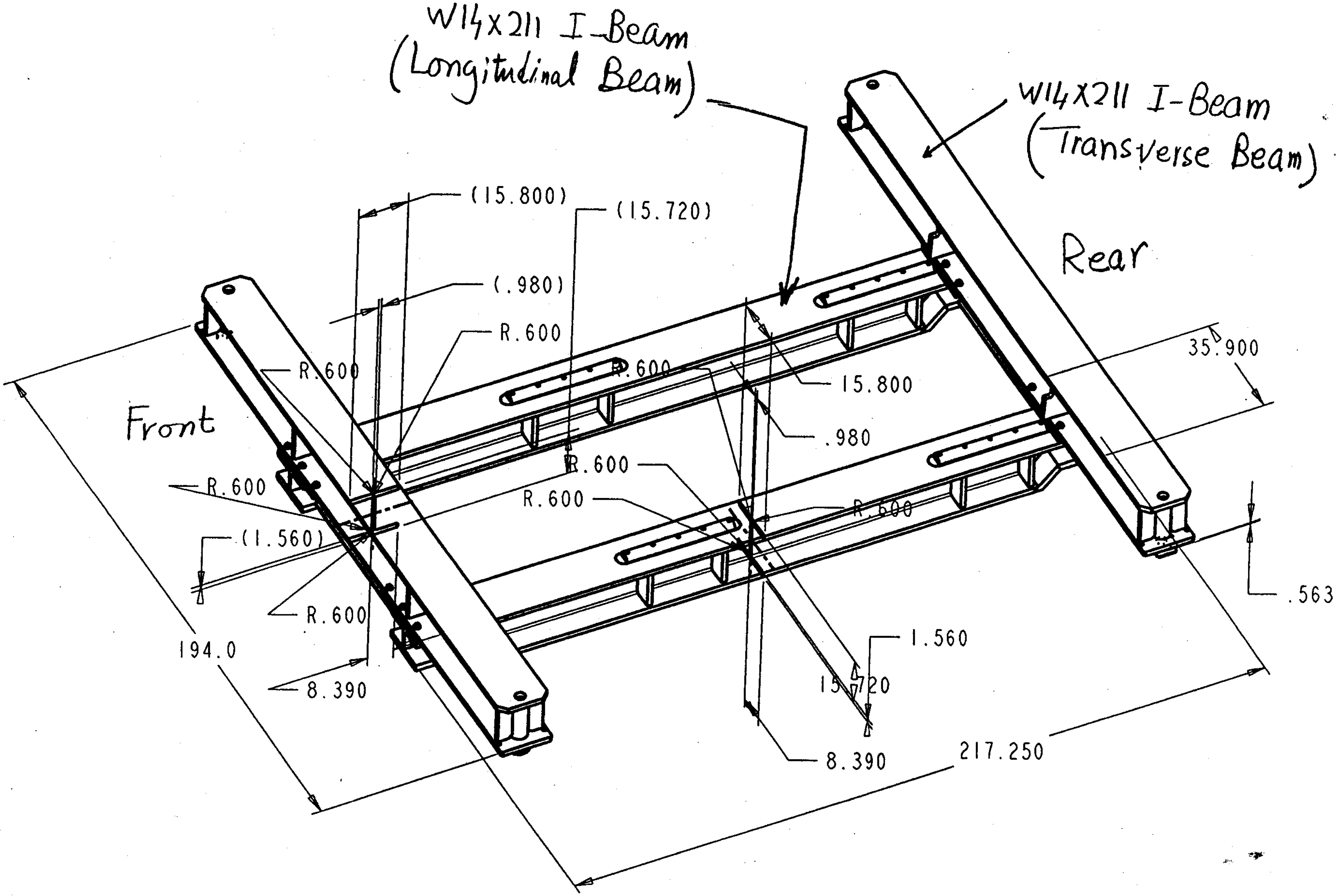


Figure 1.1. Pro/E Model of Carriage Conceptual Design

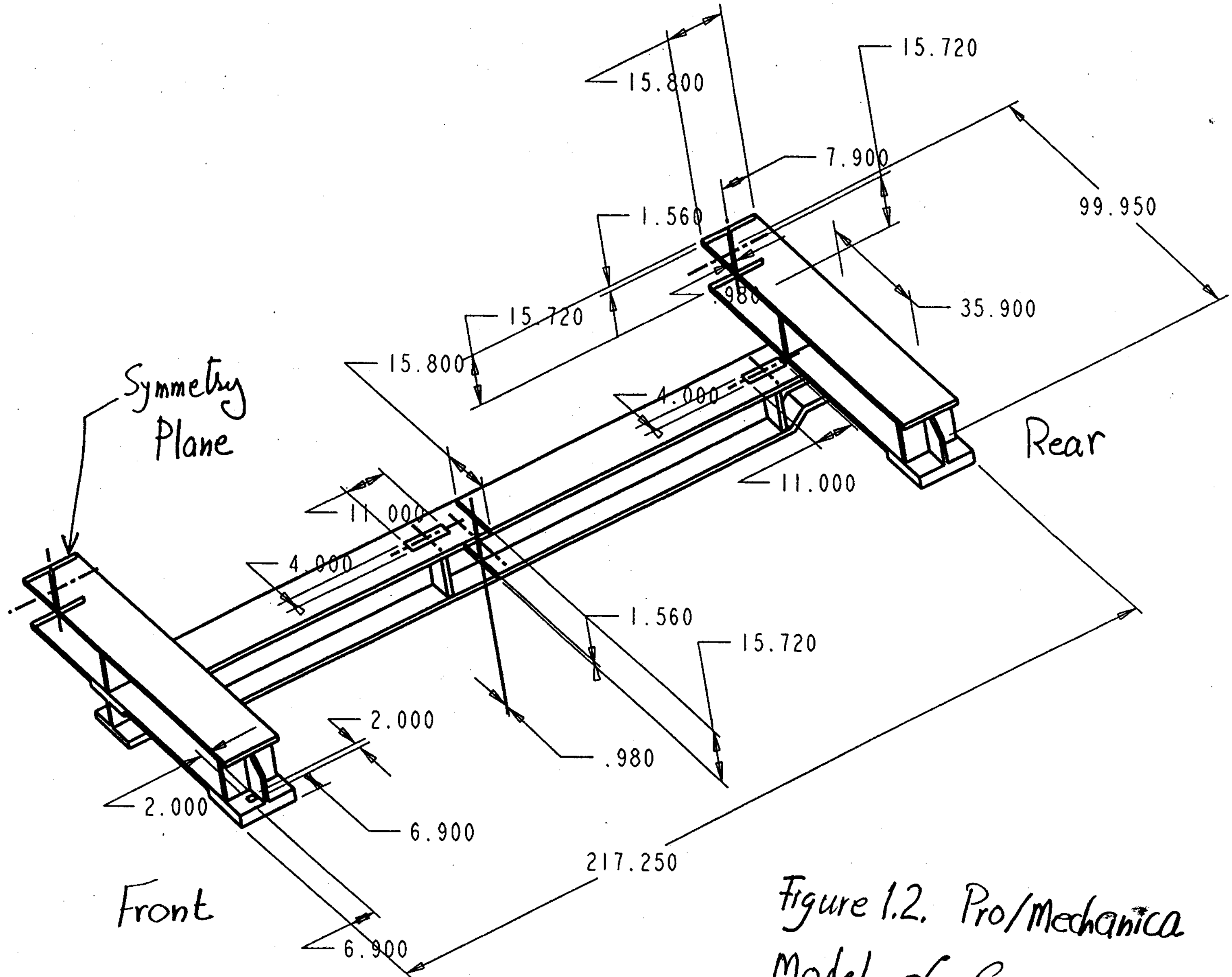


Figure 1.2. Pro/Mechanica Model of Carriage Conceptual Design

2. Pro/Mechanica Finite Element 3-D Analyses

PTC Pro/Mechanica finite element program (Rev. 2000i) was used extensively during the preliminary stage of the Carriage design to evaluate various design concepts based on the maximum deformation criterion. In these analyses, the longitudinal and transverse beams were modeled using 3-D solid elements. The single-pass adaptive method of solution convergence was utilized because of the large number of model elements.

Two sets of Pro/Mechanica analyses are presented in this report: (1) Analyses of the entire Carriage and (2) analyses of a single longitudinal beam. The loadings in each set consist of the Horn weight and of the structure own weight. The main purpose of the first set is to determine the maximum deflection of the carriage structure. And the main purpose of the second set is to provide the maximum possible loading on the bolted connections between the longitudinal and transverse beams (See Section 4).

The Pro/Mechanica model and results of the Carriage structure subjected to the Horn Weight of

48,000 lbs are summarized in Figure 2.1. The maximum deflection, $|(u_x^2 + u_y^2 + u_z^2)^{1/2}|_{max}$, is 0.0795 inch compared to an allowable deflection of 0.100 inch (design requirement). The beam maximum bending stress (longitudinal beam) is about 3,380 psi, which has to be combined with the stress due to the weight of the structure itself and then compared to the allowable limit. The Pro/Mechanica output file of this analysis (Anlys41B) is provided in Appendix A.

Similarly, the Pro/Mechanica model and results of the carriage structure subjected to its own weight are summarized in Figure 2.2. Possible future changes in the design are considered by increasing the gravitational acceleration (G_y) to 425 in/sec^2 (10% increase) which leads to a total weight of about 18,000 lbs. The maximum deflection and maximum bending stress in this analysis (Anlys41A) are 0.0153 inch and 603 psi. The maximum deflection due to carriage own weight does not have to be added to the maximum deflection due to Horn weight in order to satisfy the design deformation requirements. However, the bending stresses of the two analyses have to be combined prior to the comparison with the allowable stress, F_b. Assuming that the maximum stress in the two analyses occur at the same location, then

$$f_b = f_{b/A} + f_{b/B}$$
$$= 603 + 3380$$
$$= 3,983 \text{ psi} < F_b = 21,600 \text{ psi}$$

(See Section 3.3.1 for more details about the allowable stress basis). The Pro/Mechanica output file of 'Anlys 41A' is given in Appendix B.

The second set of analyses are for a single longitudinal beam with its top flange at its two ends constrained such that $\theta_x = 0$ as shown in Figures 2.3 and 2.4. The analysis results with these end conditions provide conservative estimates for the bending moment M_x that the bolted-connection will have to withstand (See Section 4) in addition to the reaction force R_y. The single beam analysis with the Horn weight is labeled 'Longit_Beam_B' and analysis with the beam weight is labeled 'Longit_Beam_A'. The Pro/Mechanica output file of Longit_Beam_B analysis is given in Appendix C and Longit_Beam_A analysis is given in Appendix D.

HORN WEIGHT

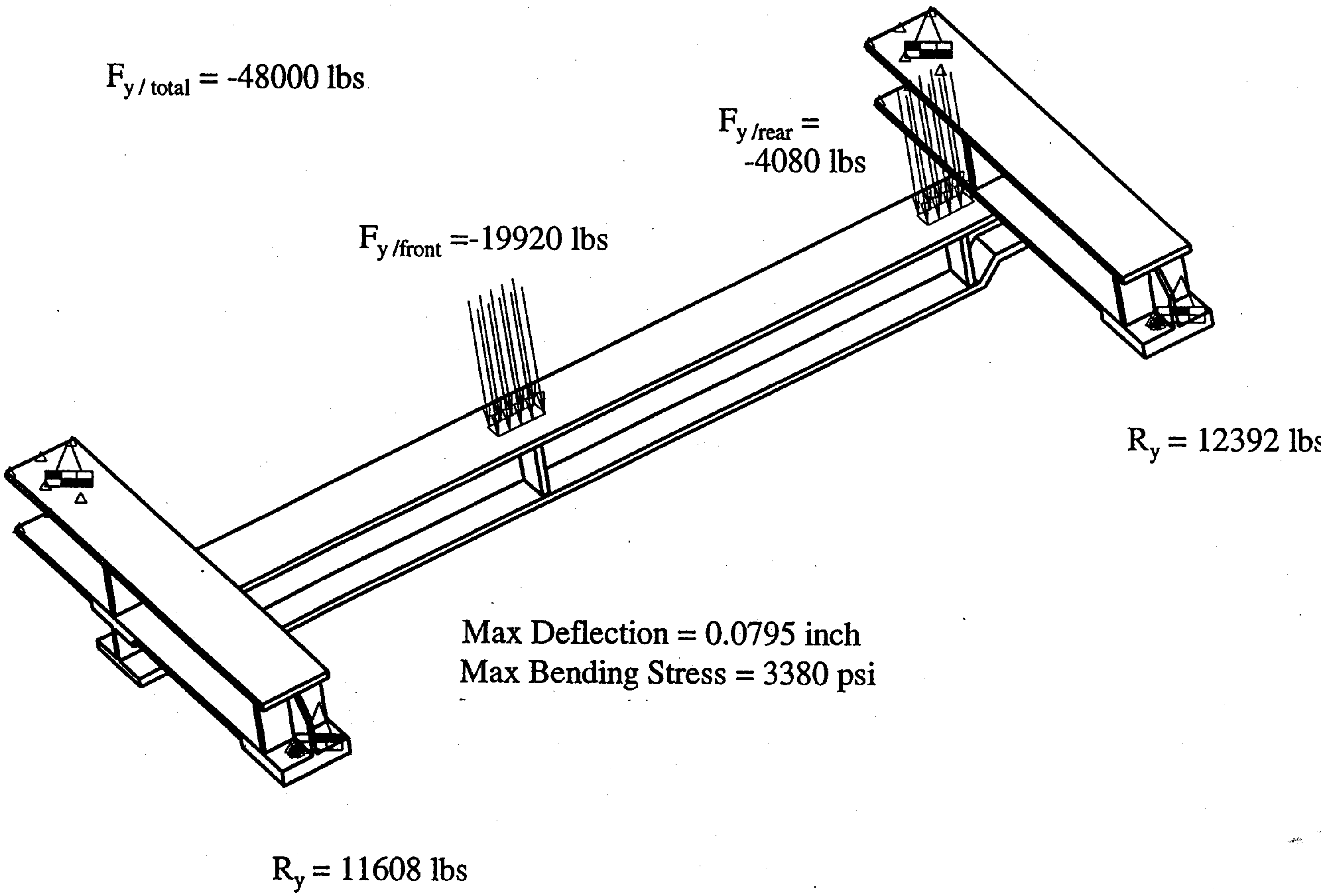
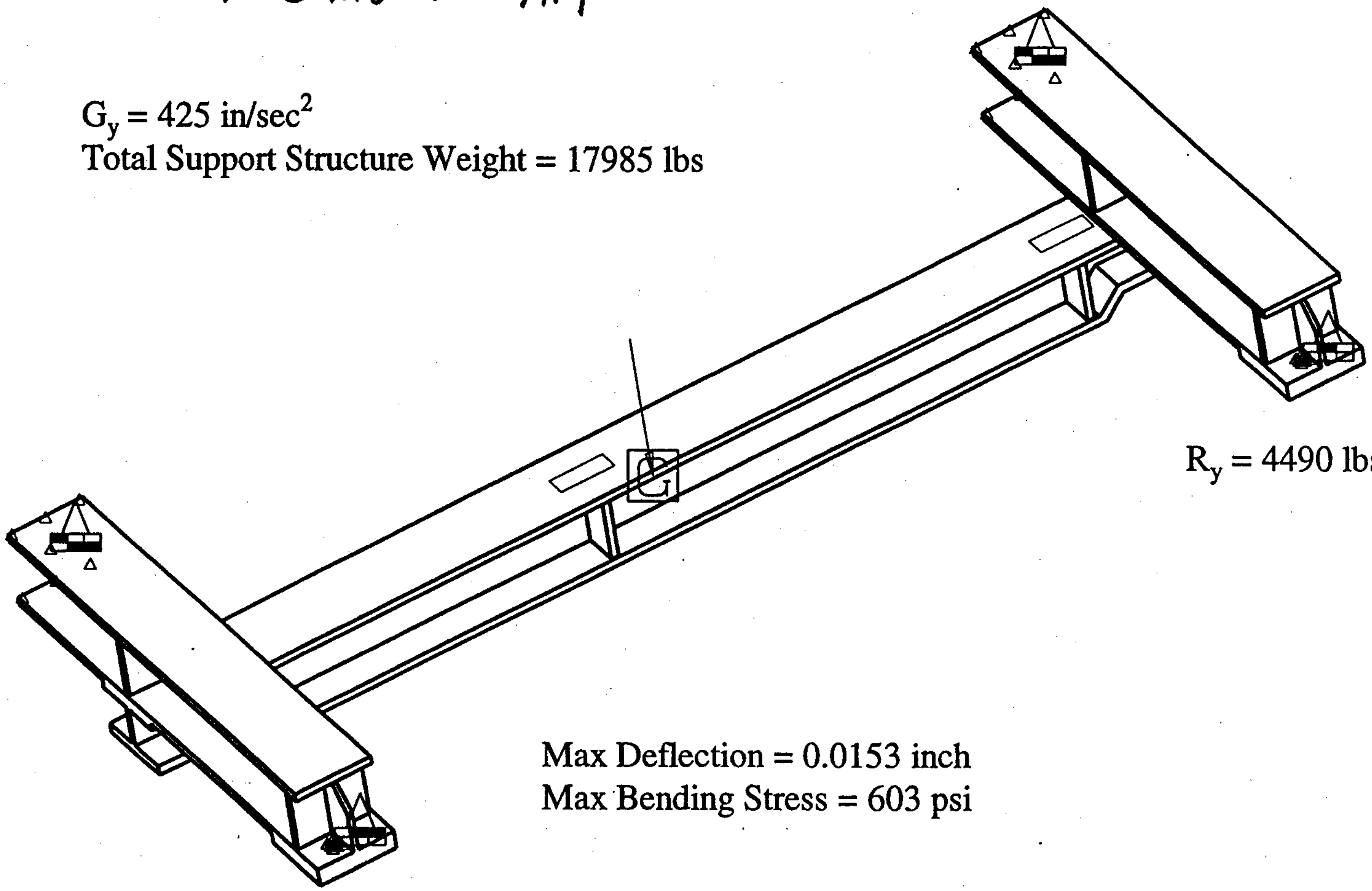


Figure 2.1. Pro/Mechanica Model and Results of Analysis 'Anlys41B'

CARRIAGE OWN WEIGHT

$G_y = 425$ in/sec^2
Total Support Structure Weight = 17985 lbs



$R_y = 4490$ lbs

Max Deflection = 0.0153 inch
Max Bending Stress = 603 psi

$R_y = 4503$ lbs

Figure 2.2. Pro/Mechanica Model and Results of Analysis Anlys41A

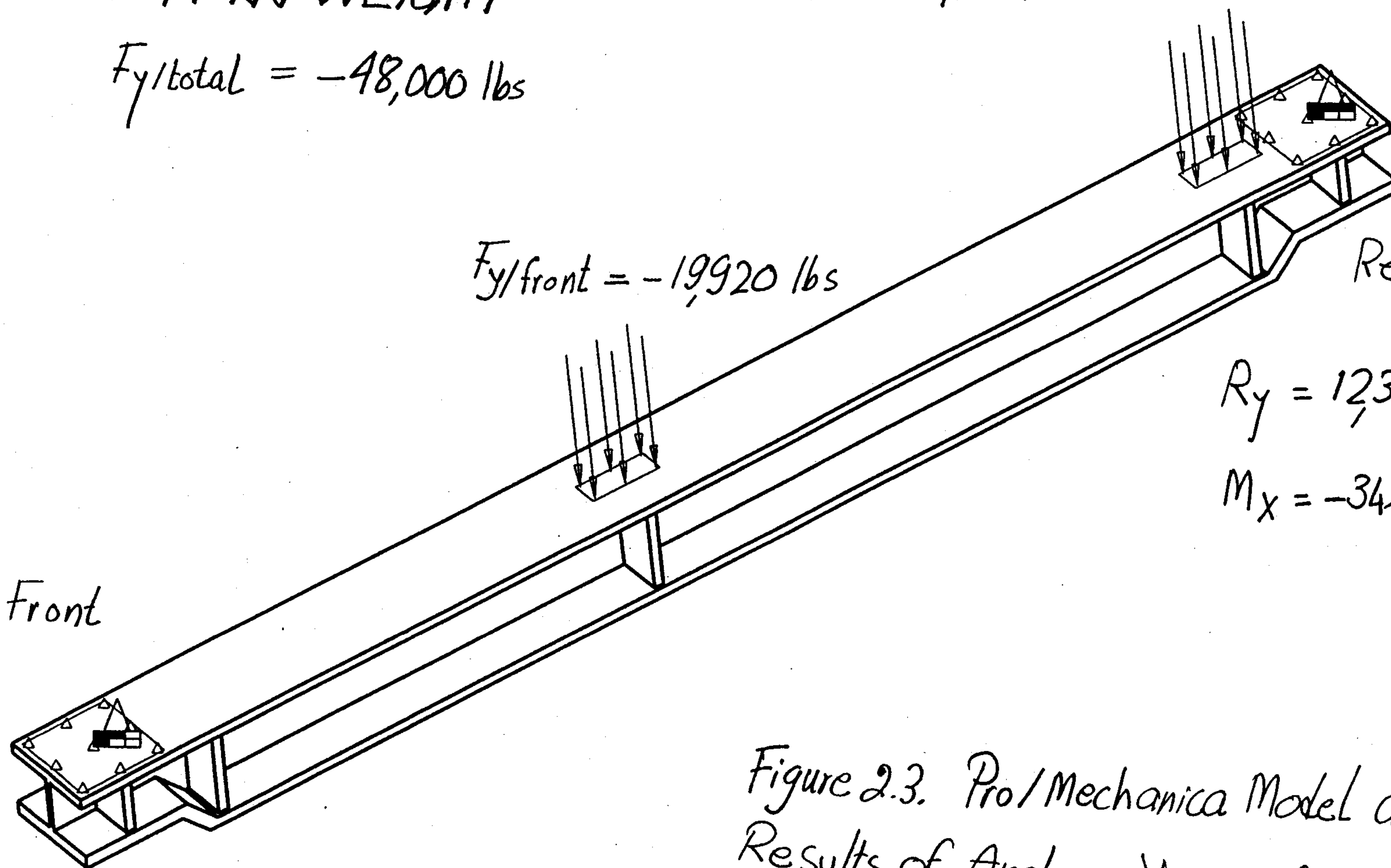


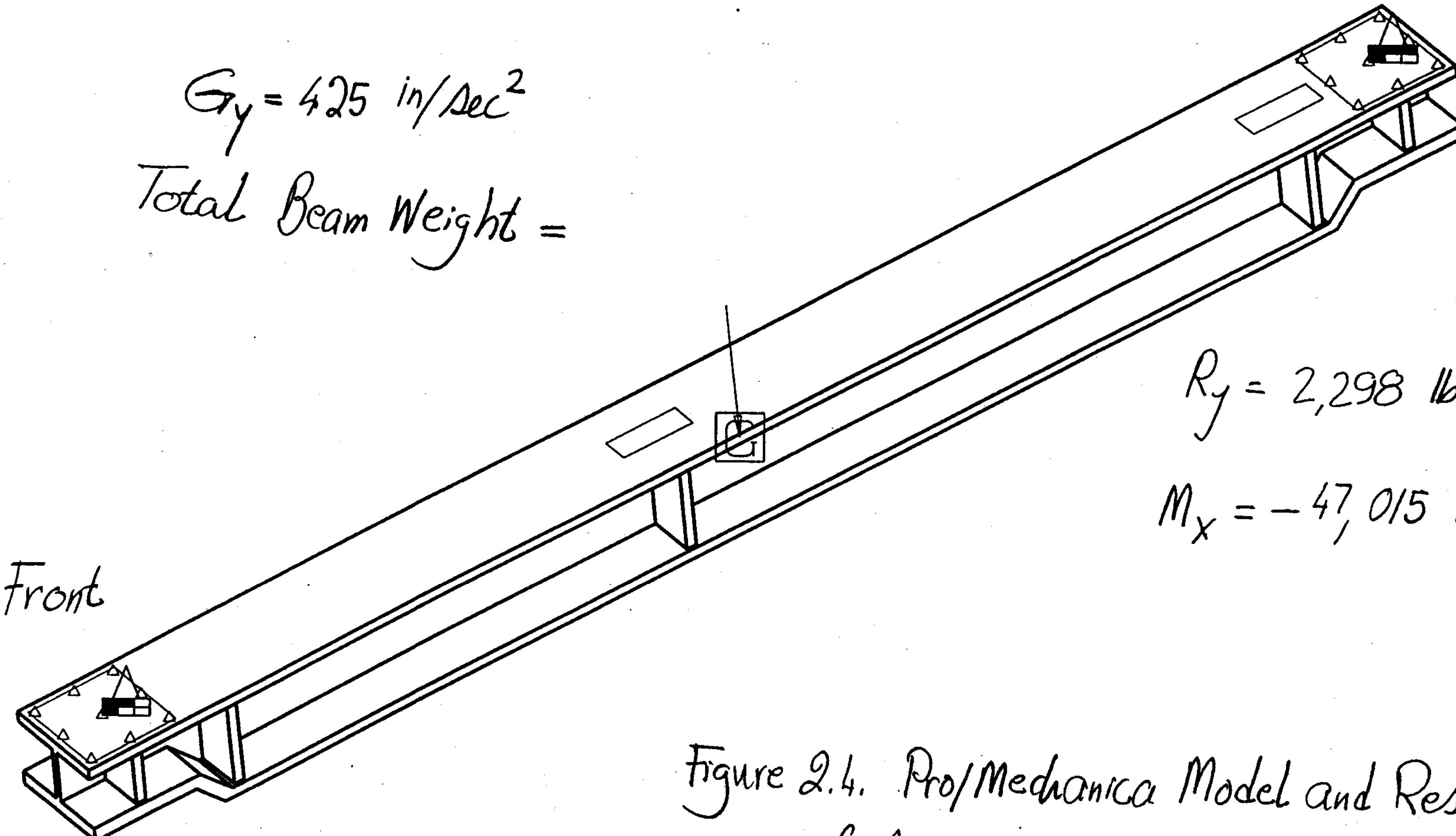
Figure 2.3. Pro/Mechanica Model and Results of Analysis 'Longit_Beam_B'.

BEAM OWN WEIGHT

$G_y = 425 \text{ in/sec}^2$

Total Beam Weight =

Rear



$R_y = 2{,}298$ lbs

$M_x = -47{,}015$ lb.in

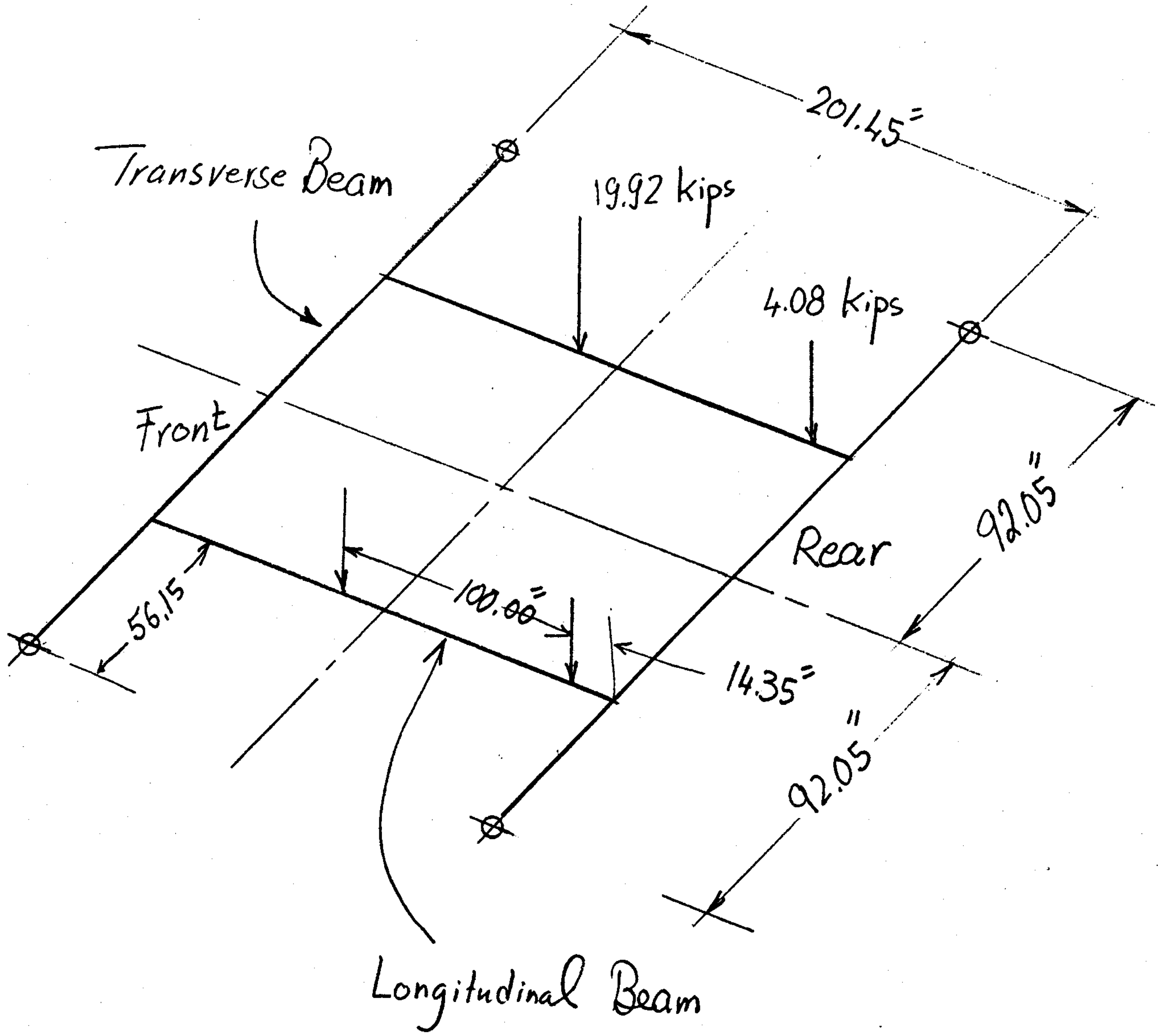
Front

$R_y = 2{,}290$ lbs

$M_x = 45{,}172$ lb.in

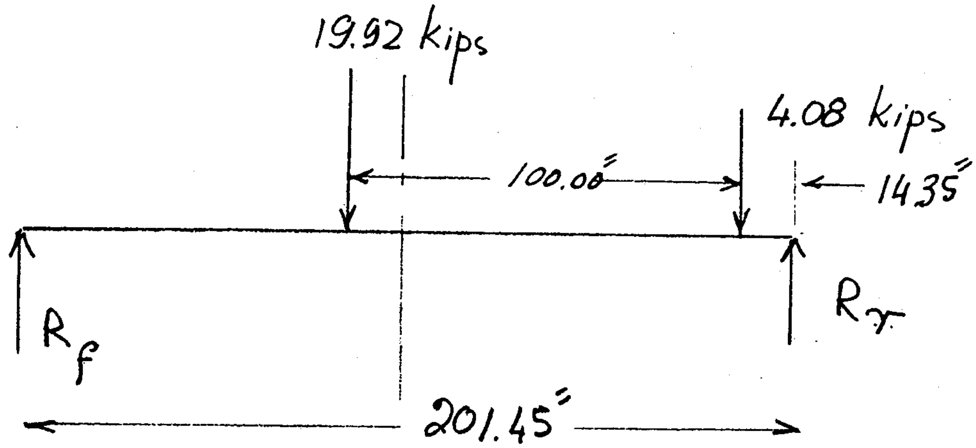
Figure 2.4. Pro/Mechanica Model and Results of Analysis 'Longit_Beam_A'

3. Shear and Bending Moment Diagrams



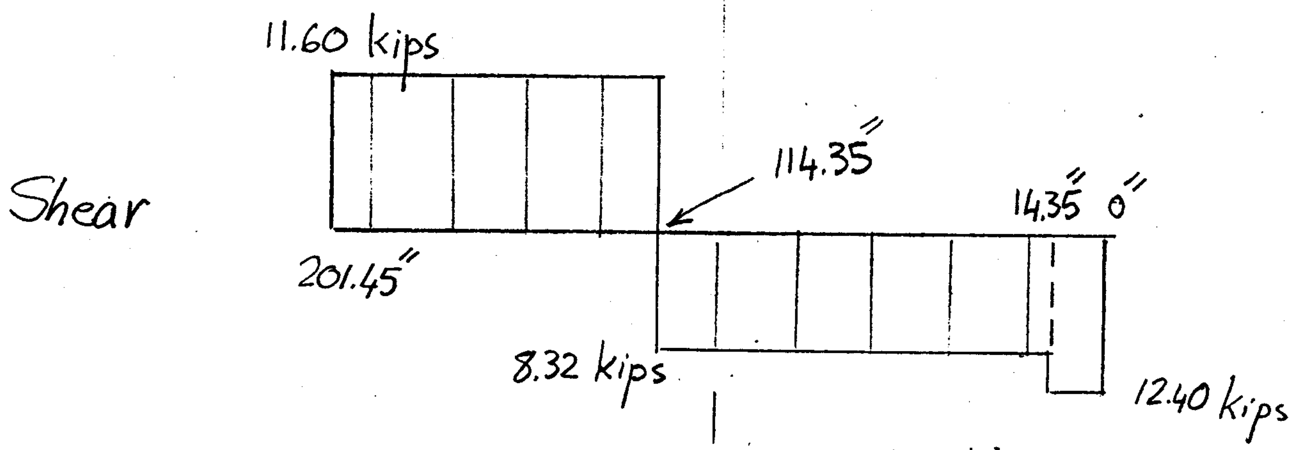
3.1. Longitudinal Beams:

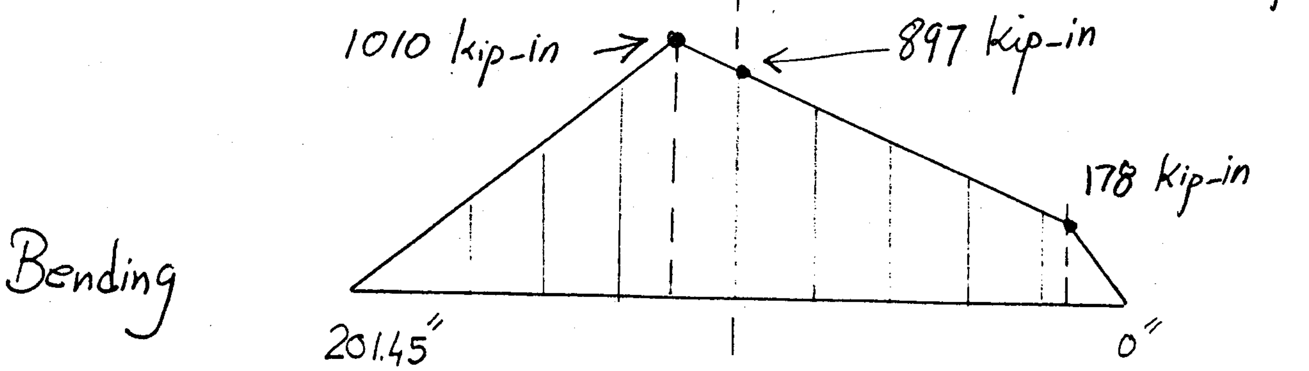
3.1.1 Subjected to Horn Weight (48 Kips)



$$R_r = [4.08 \times (201.45 - 14.35) + 19.92 \times (201.45 - 114.35)]/201.45$$
$$= 12.40 \text{ kips}$$

$$R_f = 19.92 + 4.08 - 12.40 = 11.60 \text{ kips}$$

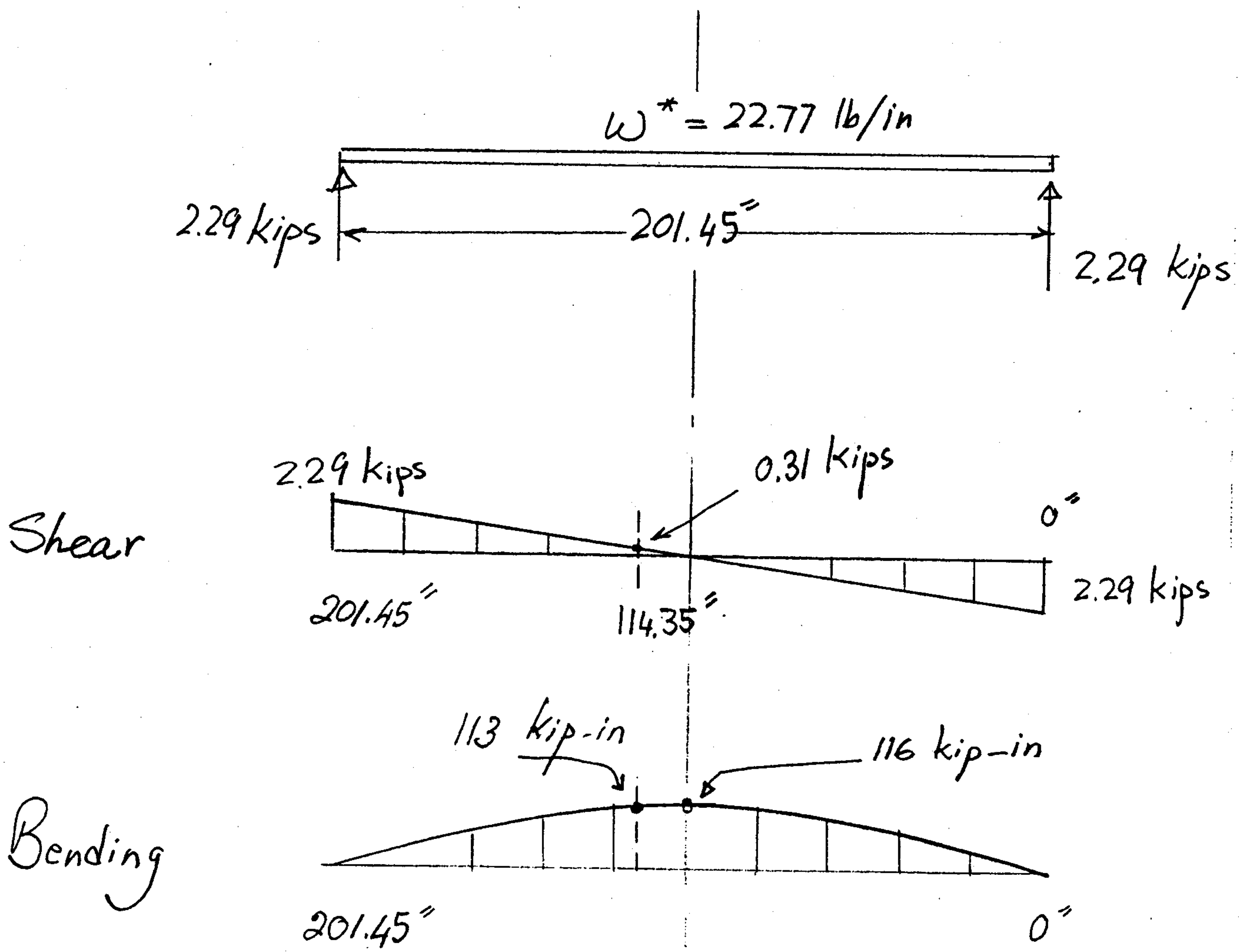




3.1.2 Structure Own Weight

Instead of assuming a uniform Cross Section (W14x211), with $w = 1.1 \times 211 / 12 = 19.34$ lb/in, the calculations will be based on the total weight of the longitudinal beam as obtained by Pro/Mechanica analysis (see Appendix D).

$$w^* = \frac{4588}{201.45} = 22.77 \text{ lb/in}$$



3.1.3 Beam Stresses

Beam bending stress at maximum bending moment location,

$$f_b = \frac{M_{max}}{S}$$

$$M_{max} = 1010 + 113 = 1124 \text{ kip-in}$$

$S = 338 \text{ in}^3$ for W14X211 ; Ref. 1, p. 1-25

$$f_b = \frac{1124}{338} = 3.325 \text{ ksi}$$

Allowable bending stress, F_b*, will be based on Eqn (F1-5) of Ref. 1 as follows,

$$F_b = 0.60 F_y$$

$$= 0.60 \times 36$$ for ASTM A-36 Carbon Steel

$$= 21.6 \text{ ksi}$$

Evidently, $f_b < F_b$.

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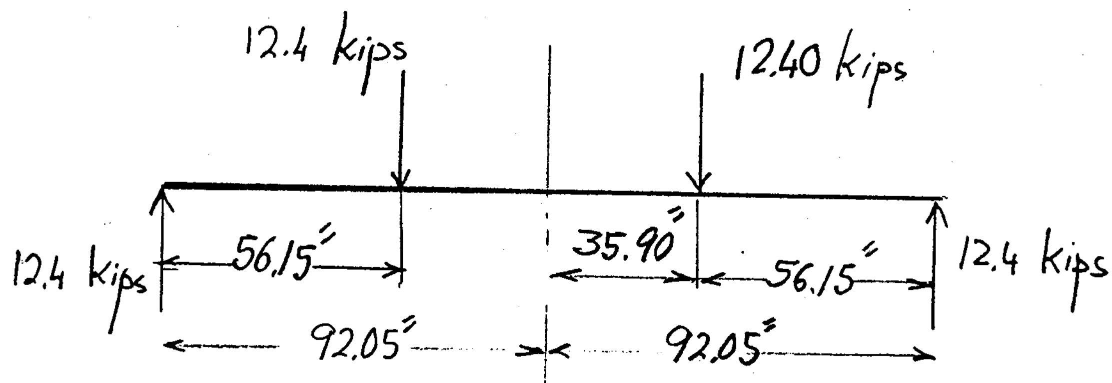
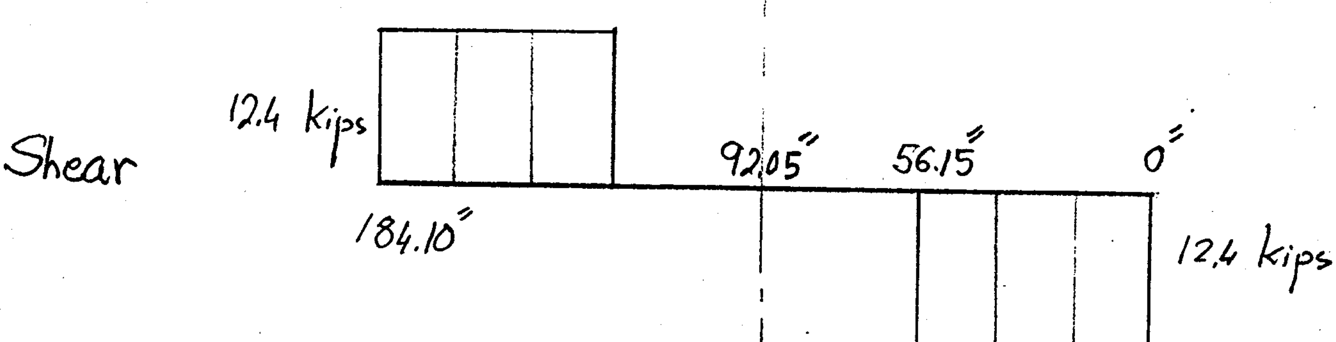
* It can be shown, however, that a higher allowable stress applies ($F_b = 0.66 F_y$) for the compact W14X211 beam with $L_b < L_c$ per Section F1 in Ref. 1.

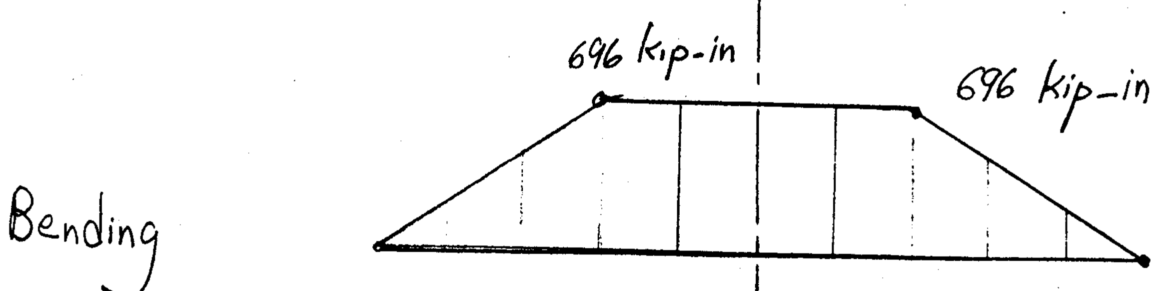
3.2. Transverse Beams:

3.2.1 Subjected to Horn Weight (48 kips)

The rear transverse beam is subjected to 24.80 kips, whereas the front beam is subjected to 23.20 kips. Analysis therefore will focus on the rear beam.

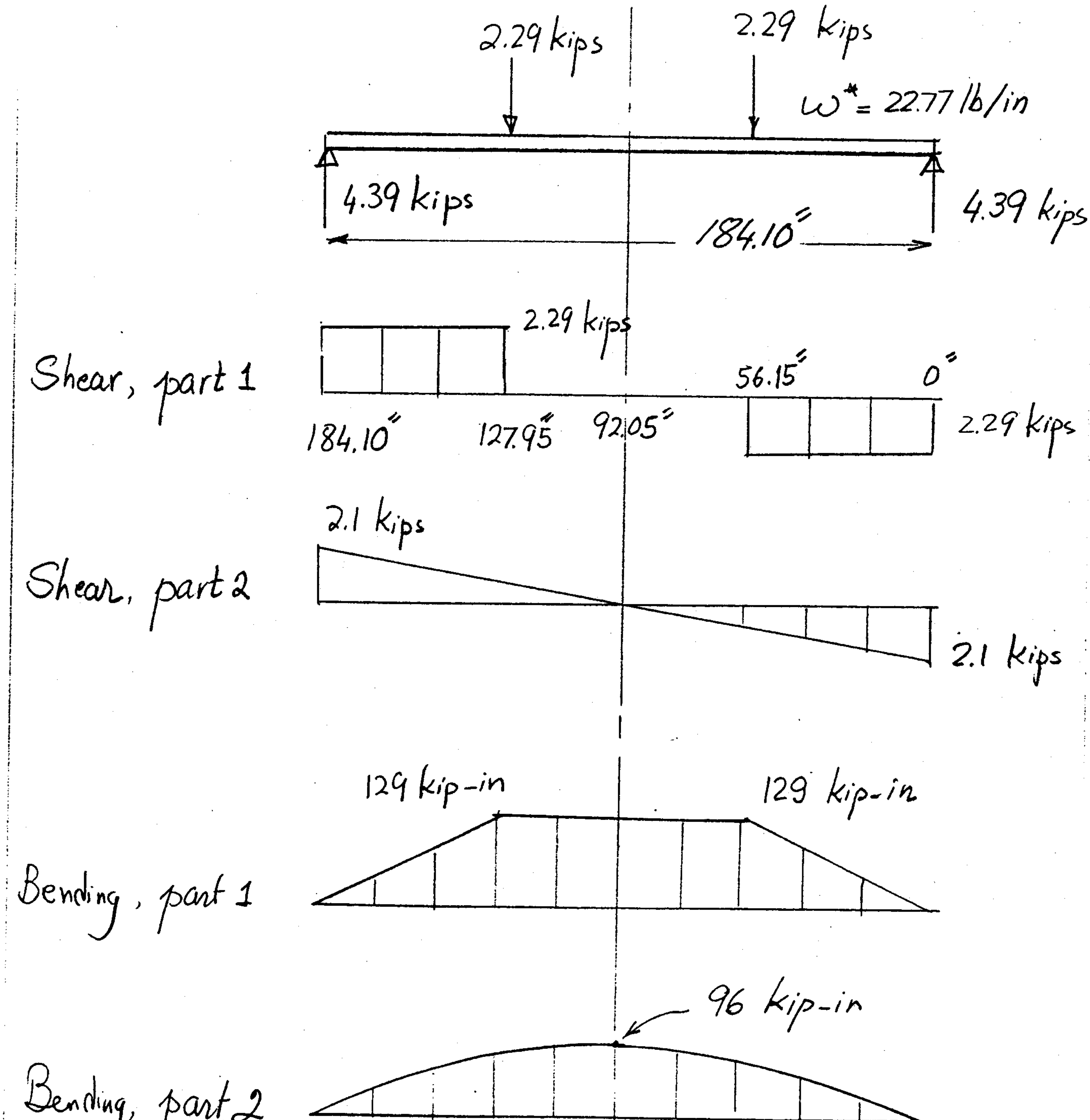






3.22 Structure Own Weight

The uniformly distributed load ω^* of the longitudinal beams will be used for the transverse beams as well



3.2.3 Beam Stresses

Beam bending stress at maximum bending moment location,

$$f_b = \frac{M_{max}}{S}$$

$M_{max} = 696 + 129 + 96 = 921$ kip-in

$S = 338 \ in^3$ for W14X211 ; Ref 1, p.1-25

$$f_b = \frac{921}{338} = 2.725 \text{ ksi}$$

Allowable bending stress, F_b, is the same as for the longitudinal beams,

$$F_b = 0.6 F_y$$
$$= 21.6 \text{ ksi}$$

Therefore, $f_b < F_b$.

4. Bolted Connections between Longitudinal and Transverse Beams:

Since the lateral beams rest on pads (attached to the concrete ledge) that allow rotations in the x and z global directions, then these bolted connections are not expected to transfer any significant bending moments. The bolts of these connections, however, will be designed to withstand bending moments obtained by constraining the top flange of the longitudinal beams as shown in Figures 2.3 & 2.4. This is in addition to transferring the reaction forces in the y-direction. These reaction forces at each end will be distributed uniformly among the six bolts in each connection.

Total Reaction Force at Rear Support, $R_{y/Rear}$

$= R_{y/A} + R_{y/B}$ (Results of Anlys 41A & 41B)

$= 4490 + 12392 = \underline{16,882 \text{ lbs}}$

Total Reaction Force at Front Support, $R_{y/Front}$

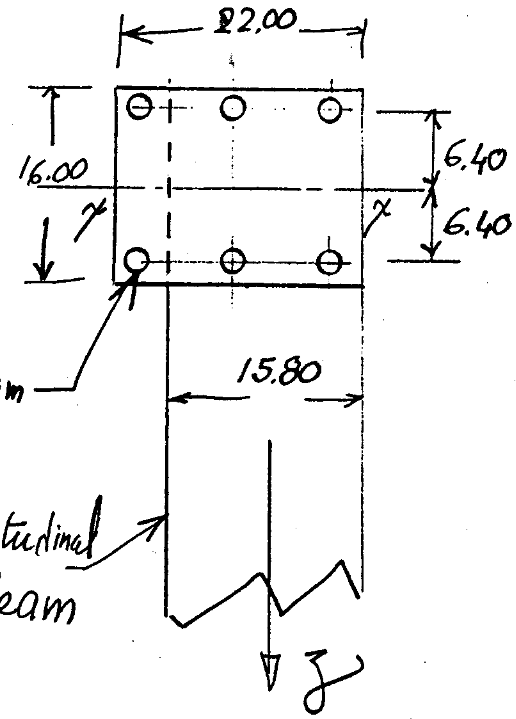
$= 4503 + 11608 = 16,111$ lbs

Axial Force / bolt due to $R_{y/Rear}$, $F_{t/1}$

$= 16882/6 = 2,814$ lbs

Corresponding tension stress, $f_{t/1} = \dfrac{2814}{0.6013} = 4,680$ psi

Equivalent moment of inertia of section with respect to axis x-x (see Ref. 2, p.1-27);



$$I_{xx} = 6 \times 0.6013 \times \overline{6.40}^2$$
$$= 147.8 \ in^4$$

$$S = I_{xx}/C = \frac{147.8}{6.4}$$
$$= 23.1 \ in^3$$

Total Reaction Moment at Rear Support, $M_{x/Rear}$

$$= M_{x/A} + M_{x/B}$$ (Results of Longit_Beam_A & B)

$$= -47,015 \ -342,956 \ = -389,971 \ lb.in$$

Total Reaction Moment at Front Support, $M_{x/Front}$

$$= 45,172 + 352,079 = \underline{397,251} \ lb.in$$

Corresponding tension stress (maximum positive), $f_{t/2}$

$$= 397,251/23.1 = 17,197 \ psi$$

Total tension stress $= f_{t/1} + f_{t/2}$

$$= 4680 + 17,197$$
$$= 21,877 \ psi$$
$$\simeq 21.9 \ ksi$$

This tension stress of 21.9 ksi is to be compared with an allowable stress of 44.0 ksi for A325 bolts or with 54.0 ksi for A490 bolts (see Ref. 1, p. 4-3).

Because of the design limit on the Carriage structure deformation, it would be useful to estimate (Conservatively) the deformation of the bolt subjected to the maximum stress of 21.9 ksi.

$$\delta_{bolt} = \frac{ft_{max}}{E} \times L$$

where $E \simeq 30 \times 10^3$ ksi, $L \simeq 6.00''$

Therefore $\delta_{bolt} \simeq \frac{21.9}{30 \times 10^3} \times 6 = 0.0044''$

With $\delta_{carriage} = 0.0795''$, δ_{bolt}, under the most conservative assumptions, would have an insignificant effect on the carriage maximum deformation.

5. Stresses in Critical Welds

At two welded connections in the Carriage Structure, welds are considered critical and accordingly require stress evaluation at the present stage of the design.

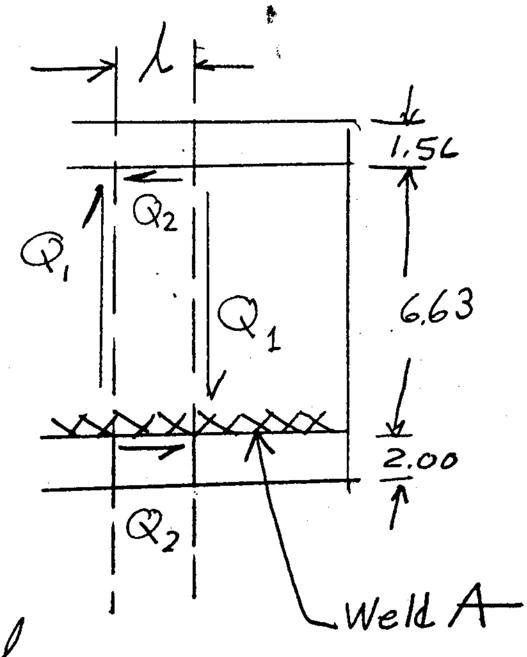
5.1 Welds at the ends of Longitudinal Beams.

As shown in Figure 5.1, there are three types of welds that relate to the 2-inch bottom flange. Weld A is a fillet weld that connects the flange to the shortened web, the weld is on both sides of the web. Weld B is a double groove weld that connects the horizontal part of the 2-inch flange to the 45° inclined part of the flange. Weld C is also a double groove weld that connects the inclind part of the flange to the original flange of the W14 X211 beam.

The three types of welds are assumed to be made by E70XX electrodes (filler metal) with a nominal tensile strength of 70 ksi. The allowable stress on the welds will be per Table J2.5 of Ref. 1

5.1.1 Weld A

Assume that the fillet weld will have the same capacity in shear as that of the W14 X 211 web.



Shear capacity of weld

$= F_{v/weld} \times A_{weld}$

$= 0.30\ F_{u/weld} \times 0.707 \times w\,l$

$= 0.3 \times 70 \times 0.707 \times w\,l = 14.85\ w\,l$

Shear capacity of web $= F_{v/web} \times A_{web}$

$= 0.4 \times F_{y/cs} \times t \times l$ (Beam is made of ASTM A-36 Carbon Steel)

$= 0.4 \times 36 \times 0.98\,l$

$= 14.11\,l$

Therefore $14.85\ w\cancel{l} = 14.11\cancel{l}$

$$W = \frac{14.11}{14.85} = 0.950 \text{ inch}$$

Since the weld is on both sides, the required leg size is

$$W' = \frac{W}{2} = 0.475 \text{ inch}$$

Based on the shear diagrams given in Sections 3.1.1 & 3.1.2, the corresponding shear stress in the weld becomes approximately;

$$f_v \simeq (12.40 + 2.29)/(6.63 \times 0.98)$$
$$= 2.26 \text{ ksi} \ll F_{v/weld} = 21.0 \text{ ksi}$$

And since weld leg sizes are usually given as multiple of 1/16, Weld A will be specified as 7/16-inch (92% of w'), instead of increasing its size to 1/2-inch

5.1.2 Welds B and C

The double-groove welds A and B are subjected to either tension or compression as a result of the loads on the carriage. And according to Table J2.5 of Ref. 1, the weld allowable stress in this case is the same as the base metal. Therefore, in order for these welds to have the same load capacity as the flanges. they would normally be full penetration welds.

Figure 5.2 shows the local stresses near these two welds according to Pro/Mechanica results of analysis Anlys41B (Horn weight of 48,000 lbs).

Near Weld B, the largest tensile stress is 1,100 psi on the bottom side of the flange and the largest compressive stress is 450 psi on the top side. And near Weld C, the largest tensile is 1,000 psi on the top side of the flange, whereas the compressive stresses on the bottom side are below 100 psi. The stresses near the welds according to analysis Anlys41A (structure own weight) are only small fractions (less than 20%) of the stresses due to the Horn weight. The combined stresses of both loadings can be compared to an allowable stress of $0.6\,F_y = 21{,}600$ psi.

Evidently, the stresses in the weld regions are very small compared to the allowable value. These stresses are also small compared to the largest stresses in the structure overall (top flange sees a maximum stress of -3380 psi near the longitudinal beam mid plane). Taking into account the small values of the stresses in the weld regions and the difficulty in making large welds, it was decided to have the following weld sizes.

Weld B: $S_1 = S_2 = 0.750$ inch, which gives a total weld size of 1.50 inch (75% of the 2-inch flange thickness).

Weld C: $S_1 = S_2 = 0.625$ inch, which gives a total weld size of 1.25 inch (80% of the 1.56-inch flange thickness).

5.2 Welds at the Ends of Transvers Beams:

According to the present design, a large part of all possible reaction forces and moments could be transmitted through the welds between the cylindrical Housing of the jacking screw and the transverse beam. As shown in Figure 5.3 the cylindrical housing is welded to the top and bottom flanges and to the web of the transverse beam and to two gussets that are in turn welded to the transverse beam. Although the design shows that the jacking screw engages with both the cylindrical housing and the bottom flange, see Figure 5.4, we will conservatively assume that all the reaction forces are transmitted thru the welds. In the following calculations these welds are assumed to be Continous and have a leg size of 0.313 inch. The Capacity of these welds to resist the maximum possible resultant reaction force (R_{tot}) will be assessed. The resultant reaction force has a vertical component (R_y) that is in equilibrium with the Horn weight and weight of the structure itself and a horizontal Component (R_x) that is in equilibrium with the friction forces that arise during the thermal expansion and Contraction of the Carriage structure.

Total weld Capacity, $P_{V/weld} = F_{V/weld}\,[2A_1 + 2A_2] \times 0.707$

where $F_{V/weld} = 0.3\, F_{u/weld} = 21.0$ ksi

$2A_1 + 2A_2$ = Length of weld, directly to beam

$A_1 = \pi \times 5.00 \times 0.313 = 4.917\ in^2$

$A_2 = 12.6 \times 0.313 = 3.944\ in^2$

Therefore, total weld capacity, $P_{V/weld}$

$= 21 \times [2 \times 4.917 + 2 \times 3.944] \times 0.707$

$= 263$ kips.

$$R_{tot} = (R_x^2 + R_y^2)^{1/2}$$

where $R_x = \mu R_y$,

$\mu = 1.00$ maximum possible value

$R_y = 12.4 + 2.29 + 2.10$ (See Section 3.2)

$= 16.79$ Kips

Therefore, $R_{tot} = \sqrt{2} \times 16.79$

$= 23.7$ kips $\ll 263$ kips

Although the stress analysis of the jacking screw itself, is beyond the scope of the present preliminary evaluation, it would be interesting to check the shear capacity of the screw against the reaction force R_x.

$$F_{v/screw} = \frac{\pi d^2}{4} f_{v/screw} \quad \text{(Single Shear plane)}$$

$$= \frac{\pi d^2}{4} \times 0.17\ f_{u/screw}$$

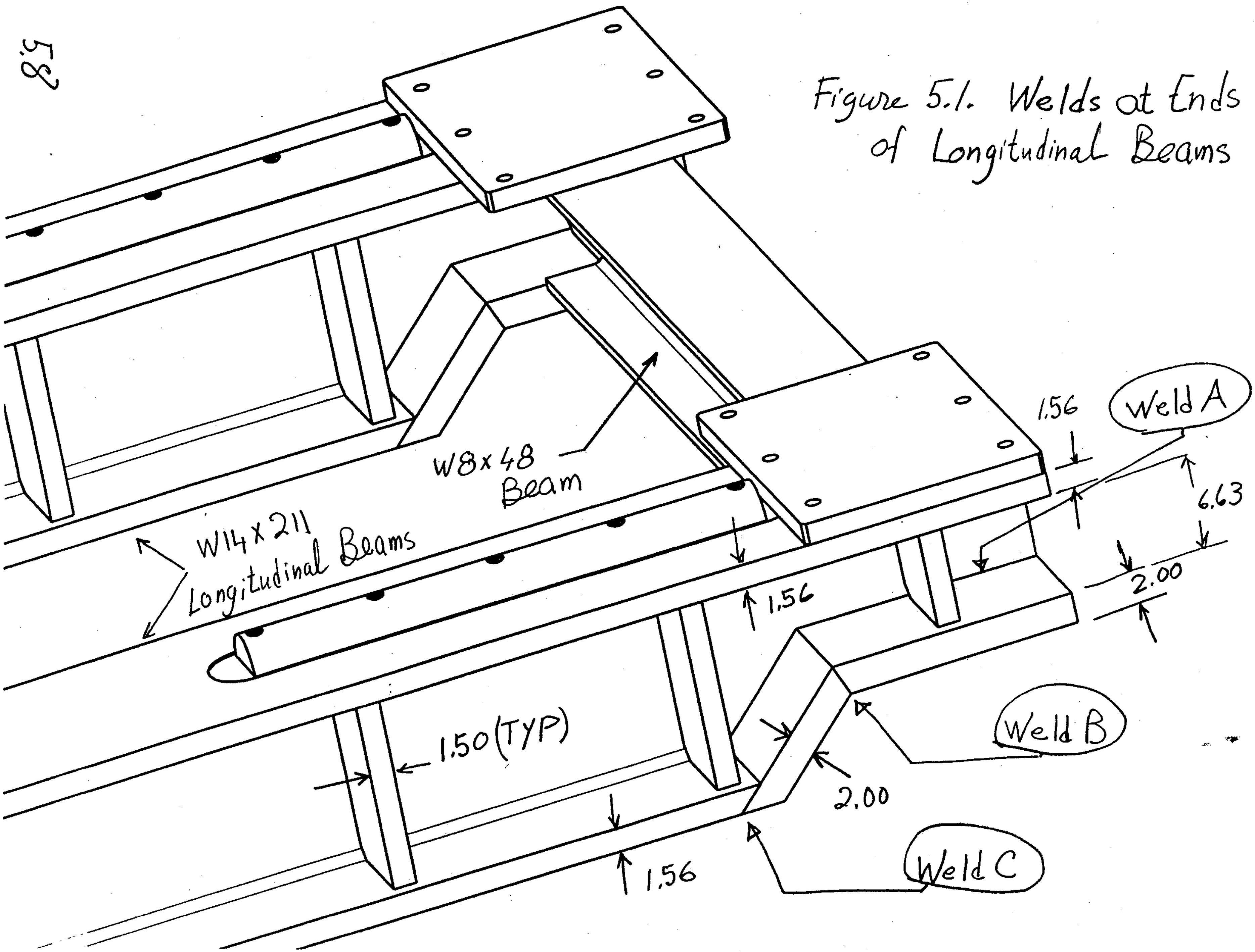
with $d = 2$ inch, (See Table 1-D in Ref. 1)

$f_{u/screw} = 150$ ksi (assuming screw made of ASTM A354 Gr BD)

$$F_{v/screw} = 3.14 \times 0.17 \times 150$$

$$= 80 \text{ kips} > R_x = 16.8 \text{ kips}$$

Figure 5.1. Welds at Ends of Longitudinal Beams



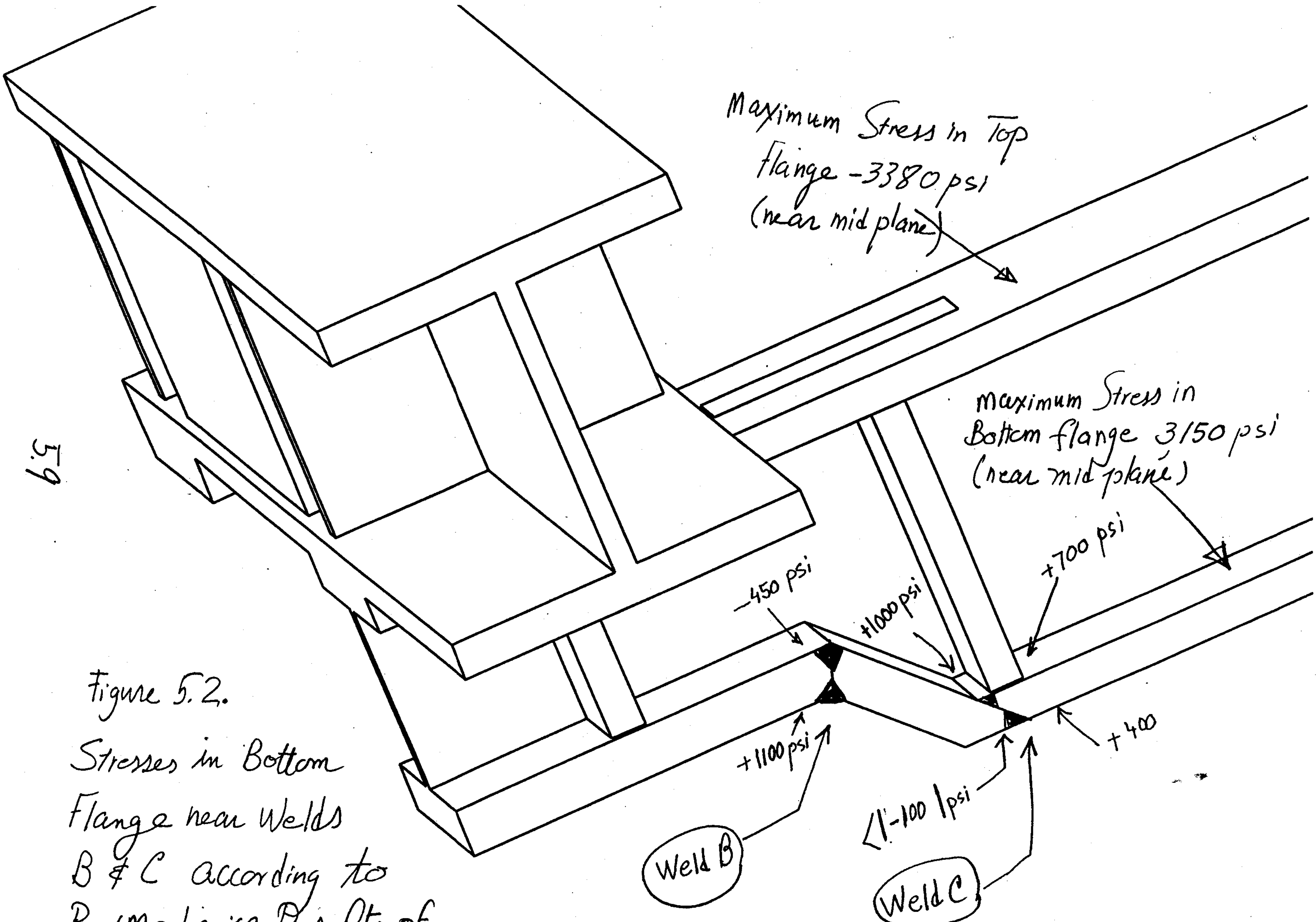
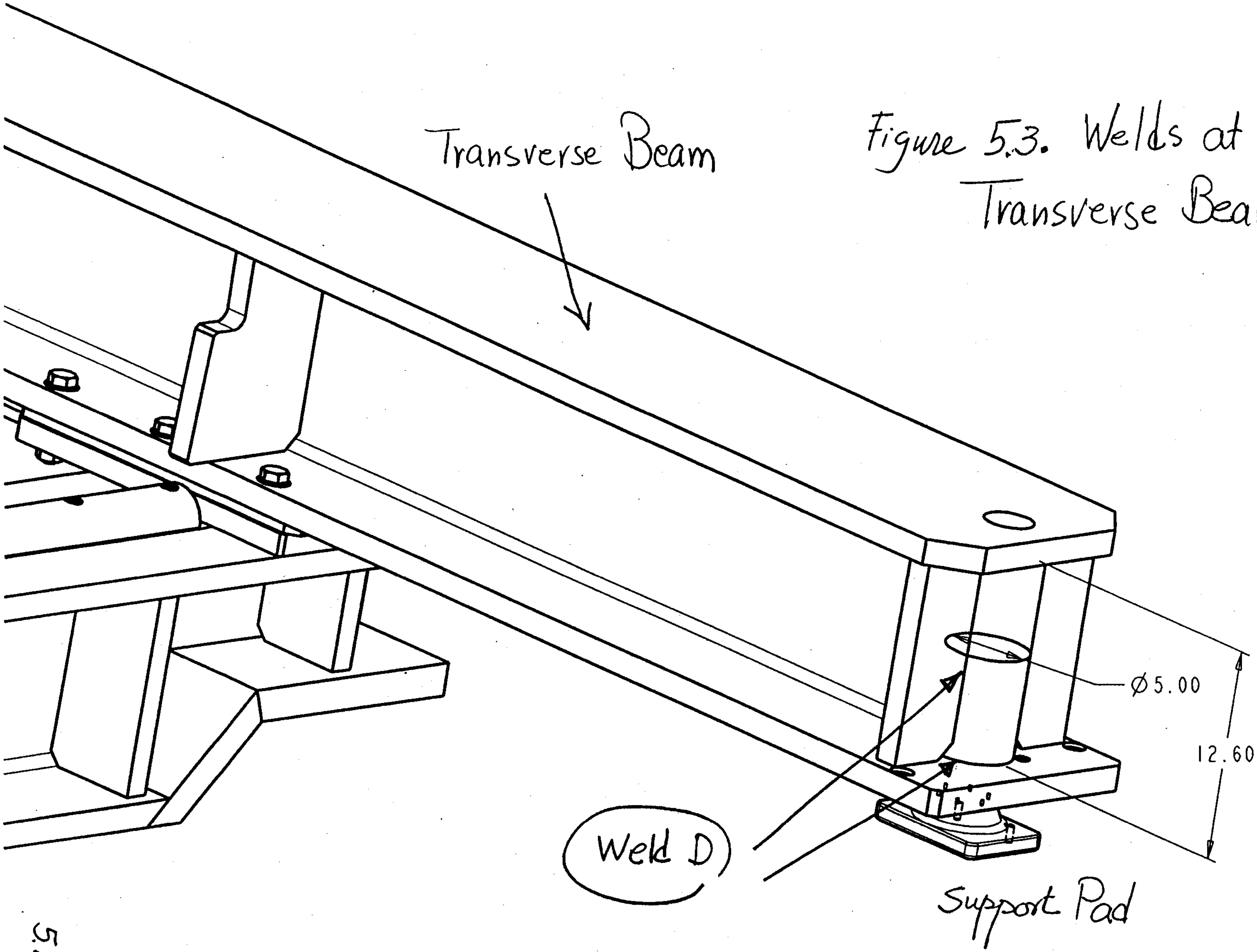


Figure 5.2.
Stresses in Bottom Flange near Welds B & C according to Pro/Mechanica Results of Analysis Anlys41R.

Figure 5.3. Welds at Ends of Transverse Beams



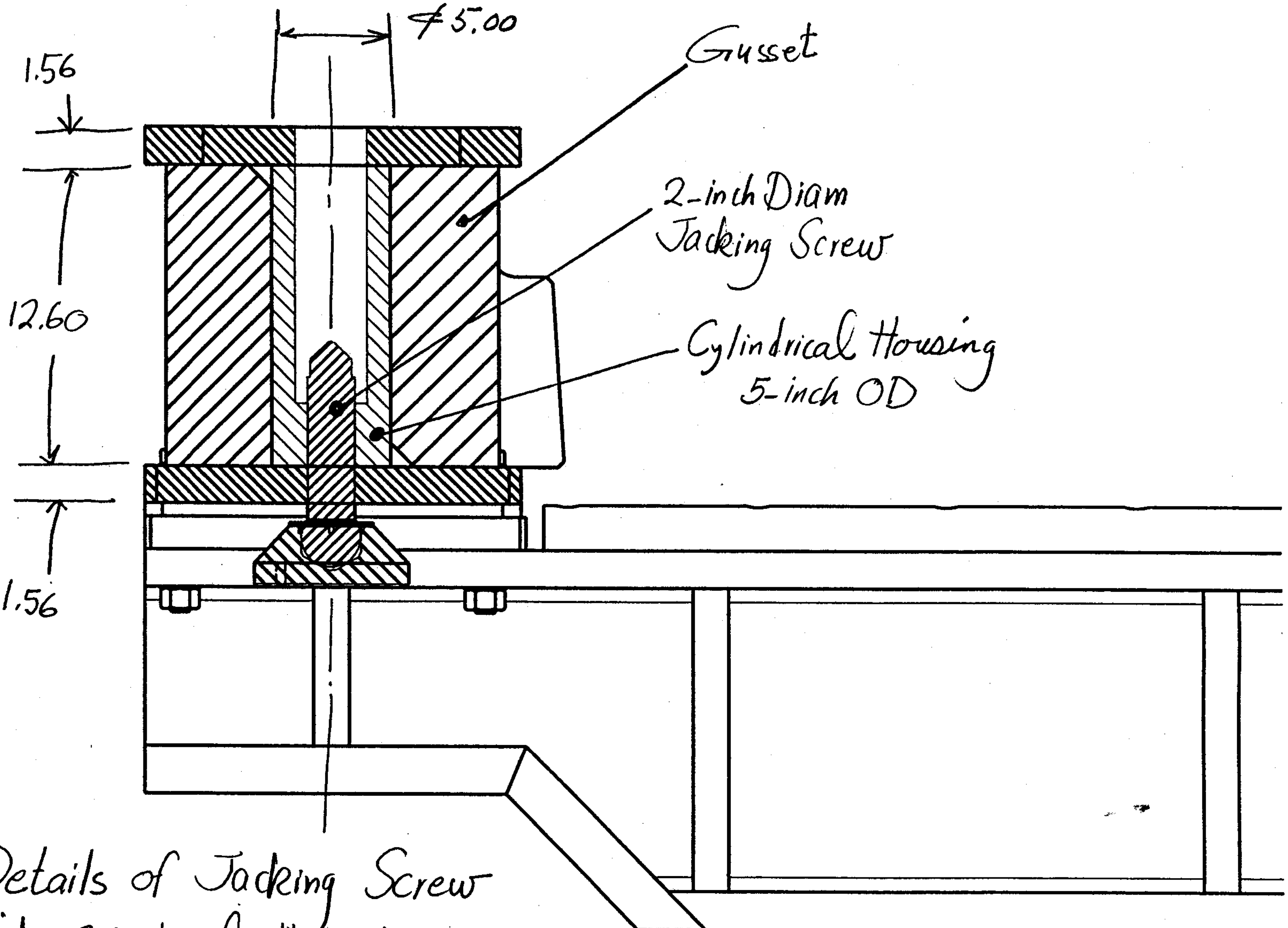


Figure 5.4. Details of Jacking Screw and its Cylindrical Housing

6. References

1. "Manual of Steel Construction - Allowable Stress Design," AISC, 9th Edition (January 1991).

2. "Engineering for Steel Construction," AISC (1984)

APPENDIX A

Pro/Mechanica Analysis Ouput File

Carriage Structure Subjected to Horn Weight

Pro/MECHANICA STRUCTURE Version 21.0(74)
Summary for Design Study "Anyls41B"
Fri Sep 08, 2000   16:23:22

```
Run Settings
   Memory allocation for block solver: 48.0
   Generate elements automatically.
Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
calculated for materials with failure data.
No errors were found in the model.

Pro/MECHANICA Structure Model Summary

   Principal System of Units: Inch Pound Second (IPS)

   Length:          in
   Force:           lbf
   Time:            sec
   Temperature:     F

   Model Type: Three Dimensional

   Points:        1192
   Edges:         5900
   Faces:         8300

   Springs:          0
   Masses:           0
   Beams:            0
   Shells:           0
   Solids:        3591

   Elements:      3591
```

```
Standard Design Study

Static Analysis "Anyls41B":

   Convergence Method: Single-Pass Adaptive
   Plotting Grid:        4

   Convergence Loop Log:                                (16:24:17)

   >> Pass  1 <<
         Calculating Element Equations                  (16:24:19)
            Total Number of Equations:    63601
            Maximum Edge Order:               3
```

```
        Solving Equations                                 (16:24:44)
        Checking Convergence                              (16:27:40)
        Resource Check                                    (16:28:08)
           Elapsed Time      (sec):      288.75
           CPU Time          (sec):      169.95
           Memory Usage       (kb):      171669
           Wrk Dir Dsk Usage (kb):      193536

>> Pass  2 <<
        Calculating Element Equations                     (16:28:12)
           Total Number of Equations:  71617
           Maximum Edge Order:              7
        Solving Equations                                 (16:29:10)
        Calculating Disp and Stress Results               (16:32:03)
        Checking Convergence                              (16:34:11)
        Resource Check                                    (16:34:52)
           Elapsed Time      (sec):      692.97
           CPU Time          (sec):      345.36
           Memory Usage       (kb):      213788
           Wrk Dir Dsk Usage (kb):      234496

        RMS Stress Error Estimates:

        Load Set              Stress Error  % of Max Prin Str
        ----------------      ------------  -----------------
        Horn_Weight            1.64e+02        0.6% of  2.90e+04

Total Mass of Model:  2.115930e+01

Total Cost of Model:  0.000000e+00

Mass Moments of Inertia about WCS Origin:

  Ixx:  1.53874e+05
  Ixy: -2.39503e+03  Iyy:  1.63106e+05
  Ixz:  9.85989e-13  Iyz:  2.06724e-12  Izz:  1.55804e+04

Principal MMOI and Principal Axes Relative to WCS Origin:

           Max Prin            Mid Prin            Min Prin
        1.63690e+05         1.53290e+05         1.55804e+04

WCS X: -2.37038e-01         9.71500e-01         0.00000e+00
WCS Y:  9.71500e-01         2.37038e-01         0.00000e+00
WCS Z:  0.00000e+00         0.00000e+00         1.00000e+00

Center of Mass Location Relative to WCS Origin:
               ( 8.49683e+00,  7.48260e+00,  1.23184e-01)

Mass Moments of Inertia about the Center of Mass:

  Ixx:  1.52689e+05
```

Ixy:	-1.04976e+03	Iyy:	1.61578e+05		
Ixz:	2.21468e+01	Iyz:	1.95033e+01	Izz:	1.28681e+04

Principal MMOI and Principal Axes Relative to COM:

	Max Prin	Mid Prin	Min Prin
	1.61700e+05	1.52567e+05	1.28681e+04
WCS X:	-1.15714e-01	9.93283e-01	-1.59387e-04
WCS Y:	9.93283e-01	1.15714e-01	-1.32275e-04
WCS Z:	1.12943e-04	1.73623e-04	1.00000e+00

Constraint Set: constraint2

Load Set: Horn_Weight

Resultant Load on Model:
in global X direction: -2.259100e-08
in global Y direction: -2.400000e+04
in global Z direction: 8.517926e-08

Measures:

max_beam_bending:	0.000000e+00
max_beam_tensile:	0.000000e+00
max_beam_torsion:	0.000000e+00
max_beam_total:	0.000000e+00
max_disp_mag:	7.947461e-02
max_disp_x:	6.952019e-03
max_disp_y:	-7.878064e-02
max_disp_z:	2.508057e-02
max_prin_mag:	-2.903142e+04
max_rot_mag:	0.000000e+00
max_rot_x:	0.000000e+00
max_rot_y:	0.000000e+00
max_rot_z:	0.000000e+00
max_stress_prin:	1.441452e+04
max_stress_vm:	2.165913e+04
max_stress_xx:	-1.529881e+04
max_stress_xy:	6.588849e+03
max_stress_xz:	2.061446e+03
max_stress_yy:	-2.554252e+04
max_stress_yz:	-7.601375e+03
max_stress_zz:	-1.433819e+04
min_stress_prin:	-2.903142e+04
strain_energy:	8.285429e+02
Ry_Back:	1.239168e+04
Ry_Front:	1.160832e+04

Analysis "Anyls41B" Completed (16:34:55)

Memory and Disk Usage:

Machine Type: Windows NT/x86
RAM Allocation for Solver (megabytes): 48.0

Total Elapsed Time (seconds): 695.95
Total CPU Time (seconds): 346.89
Maximum Memory Usage (kilobytes): 213788
Working Directory Disk Usage (kilobytes): 234496

Results Directory Size (kilobytes):
36142 .\Anyls41B

Maximum Data Base Working File Sizes (kilobytes):
146432 .\Anyls41B.tmp\kblk1.bas
70656 .\Anyls41B.tmp\kel1.bas
2048 .\Anyls41B.tmp\kpak1.bas
15360 .\Anyls41B.tmp\oel1.bas

Run Completed
Fri Sep 08, 2000 16:34:56

APPENDIX B

Pro/Mechanica Analysis Ouput File

Carriage Structure Subjected to its Own Weight

```
Pro/MECHANICA STRUCTURE Version 21.0(74)
Summary for Design Study "anlys41A"
Fri Sep 08, 2000   13:12:40
------------------------------------------------------------

Run Settings
   Memory allocation for block solver: 48.0
   Generate elements automatically.
Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
calculated for materials with failure data.
No errors were found in the model.

Pro/MECHANICA Structure Model Summary

   Principal System of Units: Inch Pound Second (IPS)

   Length:           in
   Force:            lbf
   Time:             sec
   Temperature:      F

   Model Type: Three Dimensional

   Points:        1192
   Edges:         5900
   Faces:         8300

   Springs:          0
   Masses:           0
   Beams:            0
   Shells:           0
   Solids:        3591

   Elements:      3591

------------------------------------------------------------

Standard Design Study

Static Analysis "anlys41A":

   Convergence Method: Single-Pass Adaptive
   Plotting Grid:      4

   Convergence Loop Log:                           (13:14:44)

   >> Pass  1 <<
         Calculating Element Equations             (13:14:45)
            Total Number of Equations:   63601
            Maximum Edge Order:              3
```

```
        Solving Equations                                   (13:15:10)
        Checking Convergence                                (13:18:05)
        Resource Check                                      (13:18:30)
           Elapsed Time       (sec):     352.30
           CPU Time           (sec):     247.16
           Memory Usage        (kb):     173525
           Wrk Dir Dsk Usage  (kb):      193536

  >> Pass  2 <<
        Calculating Element Equations                       (13:18:33)
           Total Number of Equations:     72832
           Maximum Edge Order:                7
        Solving Equations                                   (13:19:44)
        Calculating Disp and Stress Results                 (13:22:46)
        Checking Convergence                                (13:25:32)
        Resource Check                                      (13:26:06)
           Elapsed Time       (sec):     808.08
           CPU Time           (sec):     455.16
           Memory Usage        (kb):     217884
           Wrk Dir Dsk Usage  (kb):      238592

        RMS Stress Error Estimates:

        Load Set          Stress Error  % of Max Prin Str
        ----------------  ------------  -----------------
        Gravity            4.57e+01       0.5% of  8.66e+03

  Total Mass of Model:  2.115930e+01

  Total Cost of Model:  0.000000e+00

  Mass Moments of Inertia about WCS Origin:

    Ixx:  1.53874e+05
    Ixy: -2.39503e+03  Iyy:  1.63106e+05
    Ixz:  9.85989e-13  Iyz:  2.06724e-12  Izz:  1.55804e+04

  Principal MMOI and Principal Axes Relative to WCS Origin:

            Max Prin            Mid Prin             Min Prin
          1.63690e+05         1.53290e+05          1.55804e+04

  WCS X: -2.37038e-01         9.71500e-01          0.00000e+00
  WCS Y:  9.71500e-01         2.37038e-01          0.00000e+00
  WCS Z:  0.00000e+00         0.00000e+00          1.00000e+00

  Center of Mass Location Relative to WCS Origin:
                 ( 8.49683e+00,  7.48260e+00,  1.23184e-01)

  Mass Moments of Inertia about the Center of Mass:

    Ixx:  1.52689e+05
```

```
  Ixy: -1.04976e+03  Iyy:  1.61578e+05
  Ixz:  2.21468e+01  Iyz:  1.95033e+01   Izz:   1.28681e+04

Principal MMOI and Principal Axes Relative to COM:

           Max Prin             Mid Prin           Min Prin
          1.61700e+05          1.52567e+05        1.28681e+04

WCS X: -1.15714e-01          9.93283e-01        -1.59387e-04
WCS Y:  9.93283e-01          1.15714e-01        -1.32275e-04
WCS Z:  1.12943e-04          1.73623e-04         1.00000e+00

Constraint Set: constraint2

Load Set: Gravity

   Resultant Load on Model:
      in global X direction: -1.294346e-08
      in global Y direction: -8.992704e+03
      in global Z direction:  1.650358e-08

   Measures:

   max_beam_bending:    0.000000e+00
   max_beam_tensile:    0.000000e+00
   max_beam_torsion:    0.000000e+00
   max_beam_total:      0.000000e+00
   max_disp_mag:        1.533830e-02
   max_disp_x:          2.149859e-03
   max_disp_y:         -1.516392e-02
   max_disp_z:          3.449381e-03
   max_prin_mag:       -8.662153e+03
   max_rot_mag:         0.000000e+00
   max_rot_x:           0.000000e+00
   max_rot_y:           0.000000e+00
   max_rot_z:           0.000000e+00
   max_stress_prin:     3.941549e+03
   max_stress_vm:       6.093570e+03
   max_stress_xx:      -4.428541e+03
   max_stress_xy:       1.849800e+03
   max_stress_xz:       6.080232e+02
   max_stress_yy:      -7.735667e+03
   max_stress_yz:      -2.136818e+03
   max_stress_zz:      -3.955425e+03
   min_stress_prin:    -8.662153e+03
   strain_energy:       3.891447e+01
   Ry_Back:             4.490108e+03
   Ry_Front:            4.502596e+03

Analysis "anlys41A" Completed  (13:26:08)
```

Memory and Disk Usage:

```
   Machine Type: Windows NT/x86
   RAM Allocation for Solver (megabytes): 48.0

   Total Elapsed Time (seconds): 811.08
   Total CPU Time     (seconds): 456.70
   Maximum Memory Usage (kilobytes): 217884
   Working Directory Disk Usage (kilobytes): 238592

   Results Directory Size (kilobytes):
   36192 .\anlys41A

   Maximum Data Base Working File Sizes (kilobytes):
   148480 .\anlys41A.tmp\kblk1.bas
   72704 .\anlys41A.tmp\kel1.bas
   2048 .\anlys41A.tmp\kpak1.bas
   15360 .\anlys41A.tmp\oel1.bas
```

Run Completed
Fri Sep 08, 2000   13:26:09

APPENDIX C

Pro/Mechanica Analysis Ouput File

Single Longitudinal Beam Subjected to Horn Weight

```
Pro/MECHANICA STRUCTURE Version 21.0(74)
Summary for Design Study "Longit_Beam_B"
Mon Oct 09, 2000    09:41:28
------------------------------------------------------------

Run Settings
   Memory allocation for block solver: 48.0
   Generate elements automatically.
Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
calculated for materials with failure data.
No errors were found in the model.

Pro/MECHANICA Structure Model Summary

   Principal System of Units: Inch Pound Second (IPS)

   Length:          in
   Force:           lbf
   Time:            sec
   Temperature:     F

   Model Type: Three Dimensional

   Points:         667
   Edges:         3299
   Faces:         4647

   Springs:          0
   Masses:           0
   Beams:            0
   Shells:           0
   Solids:        2014

   Elements:      2014

------------------------------------------------------------

Standard Design Study

Static Analysis "Longit_Beam_B":

   Convergence Method: Single-Pass Adaptive
   Plotting Grid:      4

   Convergence Loop Log:                          (09:43:08)

   >> Pass  1 <<
         Calculating Element Equations            (09:43:09)
```

```
      Total Number of Equations:   35410
      Maximum Edge Order:              3
   Solving Equations                              (09:43:21)
   Checking Convergence                           (09:44:27)
   Resource Check                                 (09:44:42)
      Elapsed Time      (sec):     194.97
      CPU Time          (sec):     161.74
      Memory Usage       (kb):     134139
      Wrk Dir Dsk Usage (kb):      104448

>> Pass  2 <<
   Calculating Element Equations                  (09:44:43)
      Total Number of Equations:   38926
      Maximum Edge Order:              7
   Solving Equations                              (09:44:54)
   Calculating Disp and Stress Results            (09:45:47)
   Checking Convergence                           (09:46:40)
   Resource Check                                 (09:46:56)
      Elapsed Time      (sec):     329.03
      CPU Time          (sec):     251.00
      Memory Usage       (kb):     150620
      Wrk Dir Dsk Usage (kb):      117760

   RMS Stress Error Estimates:

   Load Set            Stress Error   % of Max Prin Str
   ----------------    ------------   -----------------
   load1                3.10e+02        1.7% of  1.81e+04

Total Mass of Model:  1.079528e+01

Total Cost of Model:  0.000000e+00

Mass Moments of Inertia about WCS Origin:

  Ixx:  4.57776e+04
  Ixy: -5.55112e-16  Iyy:  4.55593e+04
  Ixz:  6.27054e-13  Iyz: -5.76428e-13  Izz:  5.89203e+02

Principal MMOI and Principal Axes Relative to WCS Origin:

          Max Prin           Mid Prin           Min Prin
         4.57776e+04        4.55593e+04        5.89203e+02

WCS X:  1.00000e+00        0.00000e+00        0.00000e+00
WCS Y:  0.00000e+00        1.00000e+00        0.00000e+00
WCS Z:  0.00000e+00        0.00000e+00        1.00000e+00

Center of Mass Location Relative to WCS Origin:
              (-1.11842e-16,  2.75048e-01,  2.41446e-01)
```

Mass Moments of Inertia about the Center of Mass:

Ixx:	4.57761e+04				
Ixy:	-8.87196e-16	Iyy:	4.55587e+04		
Ixz:	6.26762e-13	Iyz:	7.16909e-01	Izz:	5.88387e+02

Principal MMOI and Principal Axes Relative to COM:

	Max Prin	Mid Prin	Min Prin
	4.57761e+04	4.55587e+04	5.88387e+02
WCS X:	1.00000e+00	0.00000e+00	0.00000e+00
WCS Y:	0.00000e+00	1.00000e+00	-1.59418e-05
WCS Z:	0.00000e+00	1.59418e-05	1.00000e+00

Constraint Set: constraint1

Load Set: load1

Resultant Load on Model:
in global X direction: 2.459759e-08
in global Y direction: -2.400000e+04
in global Z direction: 6.062866e-09

Measures:

max_beam_bending:	0.000000e+00
max_beam_tensile:	0.000000e+00
max_beam_torsion:	0.000000e+00
max_beam_total:	0.000000e+00
max_disp_mag:	2.660468e-02
max_disp_x:	2.292238e-04
max_disp_y:	-2.653698e-02
max_disp_z:	-4.183585e-03
max_prin_mag:	1.812754e+04
max_rot_mag:	0.000000e+00
max_rot_x:	0.000000e+00
max_rot_y:	0.000000e+00
max_rot_z:	0.000000e+00
max_stress_prin:	1.812754e+04
max_stress_vm:	8.515064e+03
max_stress_xx:	8.432209e+03
max_stress_xy:	1.812664e+03
max_stress_xz:	1.273631e+03
max_stress_yy:	1.795798e+04
max_stress_yz:	-2.410697e+03
max_stress_zz:	1.334043e+04
min_stress_prin:	-5.770853e+03
strain_energy:	2.671032e+02

Longit_Beam_B.rpt

Front_Force_y:	1.164320e+04
Front_Moment_xx:	3.520792e+05
Rear_Force_y:	1.235680e+04
Rear_Moment_xx:	-3.429562e+05

Analysis "Longit_Beam_B" Completed (09:46:57)

Memory and Disk Usage:

Machine Type: Windows NT/x86
RAM Allocation for Solver (megabytes): 48.0

Total Elapsed Time (seconds): 330.56
Total CPU Time (seconds): 251.86
Maximum Memory Usage (kilobytes): 150620
Working Directory Disk Usage (kilobytes): 117760

Results Directory Size (kilobytes):
20243 .\Longit_Beam_B

Maximum Data Base Working File Sizes (kilobytes):
71680 .\\Longit_Beam_B.tmp\kblk1.bas
36864 .\\Longit_Beam_B.tmp\kel1.bas
1024 .\\Longit_Beam_B.tmp\kpak1.bas
8192 .\\Longit_Beam_B.tmp\oel1.bas

Run Completed
Mon Oct 09, 2000 09:46:57

APPENDIX D

Pro/Mechanica Analysis Ouput File

Single Longitudinal Beam Subjected to its Own Weight

```
Pro/MECHANICA STRUCTURE Version 21.0(74)
Summary for Design Study "Longit_Beam_A"
Mon Oct 09, 2000   09:17:08
----------------------------------------------------------------

Run Settings
   Memory allocation for block solver: 48.0
   Generate elements automatically.
Not all of the materials assigned to the model contain
failure data. Failure Index measures will only be
calculated for materials with failure data.
No errors were found in the model.

Pro/MECHANICA Structure Model Summary

   Principal System of Units: Inch Pound Second (IPS)

   Length:          in
   Force:           lbf
   Time:            sec
   Temperature:     F

   Model Type: Three Dimensional

   Points:          667
   Edges:          3299
   Faces:          4647

   Springs:           0
   Masses:            0
   Beams:             0
   Shells:            0
   Solids:         2014

   Elements:       2014

----------------------------------------------------------------

Standard Design Study

Static Analysis "Longit_Beam_A":

   Convergence Method: Single-Pass Adaptive
   Plotting Grid:       4

   Convergence Loop Log:                          (09:18:49)

   >> Pass  1 <<
         Calculating Element Equations            (09:18:50)
```


D.1

```
      Total Number of Equations:   35410
      Maximum Edge Order:              3
   Solving Equations                                (09:19:05)
   Checking Convergence                             (09:20:25)
   Resource Check                                   (09:20:41)
      Elapsed Time       (sec):     213.23
      CPU Time           (sec):     168.23
      Memory Usage        (kb):     133819
      Wrk Dir Dsk Usage  (kb):     104448

>> Pass  2 <<
   Calculating Element Equations                    (09:20:42)
      Total Number of Equations:   38605
      Maximum Edge Order:              7
   Solving Equations                                (09:20:55)
   Calculating Disp and Stress Results              (09:21:53)
   Checking Convergence                             (09:22:59)
   Resource Check                                   (09:23:14)
      Elapsed Time       (sec):     366.50
      CPU Time           (sec):     270.75
      Memory Usage        (kb):     153820
      Wrk Dir Dsk Usage  (kb):     116736

   RMS Stress Error Estimates:

   Load Set            Stress Error   % of Max Prin Str
   ----------------    ------------   -----------------
   Gravity              4.03e+01        1.7% of  2.39e+03

Total Mass of Model:  1.079528e+01 ✓

Total Cost of Model:  0.000000e+00

Mass Moments of Inertia about WCS Origin:

  Ixx:  4.57776e+04
  Ixy: -5.55112e-16  Iyy:  4.55593e+04
  Ixz:  6.27054e-13  Iyz: -5.76428e-13  Izz:  5.89203e+02

Principal MMOI and Principal Axes Relative to WCS Origin:

         Max Prin            Mid Prin             Min Prin
        4.57776e+04         4.55593e+04          5.89203e+02

WCS X:  1.00000e+00         0.00000e+00          0.00000e+00
WCS Y:  0.00000e+00         1.00000e+00          0.00000e+00
WCS Z:  0.00000e+00         0.00000e+00          1.00000e+00

Center of Mass Location Relative to WCS Origin:
               (-1.11842e-16,  2.75048e-01,  2.41446e-01)
```

Mass Moments of Inertia about the Center of Mass:

```
  Ixx:  4.57761e+04
  Ixy: -8.87196e-16  Iyy:  4.55587e+04
  Ixz:  6.26762e-13  Iyz:  7.16909e-01  Izz:  5.88387e+02
```

Principal MMOI and Principal Axes Relative to COM:

	Max Prin	Mid Prin	Min Prin
	4.57761e+04	4.55587e+04	5.88387e+02
WCS X:	1.00000e+00	0.00000e+00	0.00000e+00
WCS Y:	0.00000e+00	1.00000e+00	-1.59418e-05
WCS Z:	0.00000e+00	1.59418e-05	1.00000e+00

Constraint Set: constraint1

Load Set: Gravity

Resultant Load on Model:
in global X direction: 2.598574e-09
in global Y direction: -4.587993e+03
in global Z direction: 6.168860e-10

Measures:

max_beam_bending:	0.000000e+00
max_beam_tensile:	0.000000e+00
max_beam_torsion:	0.000000e+00
max_beam_total:	0.000000e+00
max_disp_mag:	3.002933e-03
max_disp_x:	2.832115e-05
max_disp_y:	-2.994675e-03
max_disp_z:	-5.200801e-04
max_prin_mag:	2.389853e+03
max_rot_mag:	0.000000e+00
max_rot_x:	0.000000e+00
max_rot_y:	0.000000e+00
max_rot_z:	0.000000e+00
max_stress_prin:	2.389853e+03
max_stress_vm:	1.127277e+03
max_stress_xx:	1.105996e+03
max_stress_xy:	2.330162e+02
max_stress_xz:	1.698850e+02
max_stress_yy:	2.368284e+03
max_stress_yz:	-3.243292e+02
max_stress_zz:	1.736437e+03
min_stress_prin:	-7.586306e+02
strain_energy:	3.564342e+00

	Longit_Beam_A.rpt
Front_Force_y:	2.290344e+03
Front_Moment_xx:	4.517177e+04
Rear_Force_y:	2.297650e+03
Rear_Moment_xx:	-4.701542e+04

Analysis "Longit_Beam_A" Completed (09:23:15)

Memory and Disk Usage:

```
   Machine Type: Windows NT/x86
   RAM Allocation for Solver (megabytes): 48.0

   Total Elapsed Time (seconds): 367.88
   Total CPU Time     (seconds): 271.64
   Maximum Memory Usage (kilobytes): 153820
   Working Directory Disk Usage (kilobytes): 116736

   Results Directory Size (kilobytes):
   20229 .\Longit_Beam_A

   Maximum Data Base Working File Sizes (kilobytes):
   70656 .\\Longit_Beam_A.tmp\kblk1.bas
   36864 .\\Longit_Beam_A.tmp\kel1.bas
   1024 .\\Longit_Beam_A.tmp\kpak1.bas
   8192 .\\Longit_Beam_A.tmp\oel1.bas
```

Run Completed
Mon Oct 09, 2000   09:23:15

SUBJECT: Carriages for NuMI Target Hall
Checker's Calculations

NAME: AMS
DATE: 2/28/03
REVISION DATE

Index

Note: (No./No.)$|_{subscript}$ ≡ (calculated stress (psi) / allowable stress (psi))$|_{v,b,t,c,a,p}$

v ≡ shear; b ≡ bending; t ≡ tension
c ≡ compression; a ≡ axial; p ≡ bearing

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4.0	Analysis Plan	6
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FERMILAB ENGINEERING NOTE

SECTION | PROJECT | SERIAL-CATEGORY | PAGE I3

SUBJECT

NAME AMS

DATE 2/28/03 REVISION DATE

Index

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1.0 Standards & Codes

• AISC Manual of Steel Construction – 9th Edition

2.0 Allowable Stresses

2.1 W 14 x 211

• Material: A 36 structural steel

• $F_y = 36{,}000$ psi

• $\frac{h}{t_w} \overset{?}{\leq} \frac{970}{\sqrt{F_y}}$ AISC App. F applicablity criterion

$$\frac{d-2t_f}{t_w} \overset{?}{\leq} \frac{970}{\sqrt{F_y}}$$

$$\frac{15.72-2(1.56)}{0.98} \overset{?}{\leq} \frac{970}{\sqrt{36}}$$

$12.9 < 161.7 \Rightarrow$ Use Chapter F

• AISC § F1

Check criteria for compact section (AISC § B5.1):

#1 – Flanges continuously connected to web – ok

#2 – $\frac{b}{t} = \frac{b_f}{2t_f} \overset{?}{\leq} \frac{65}{\sqrt{F_y}}$

$5.1 \leq 10.8$ ok

#3 – $\frac{d}{t_w} \overset{?}{\leq} \frac{640}{\sqrt{F_y}}$

$16 \leq 106$ ok

#4 - Laterally unsupported length

$$L_c = \text{smaller of} \begin{cases} \dfrac{76\, b_f}{\sqrt{F_y}} = \dfrac{76(15.8)}{\sqrt{36}} = 200 \\ \dfrac{20{,}000}{(d/A_f)F_y} = \dfrac{20{,}000}{0.64(36)} = 868 \end{cases}$$

$L_c = 200$ in

$L_b = 203''$ (Horn 1/2 support beam) or
$220.5''$ (Target support beam). Both $L_b > L_c$.

• F_b - Section is compact but $L_b > L_c$. Set $C_b = 1$.

$$l/r_T = 203''/4.37'' = 46.5$$

$$l/r_T = 220.5''/4.37'' = 50.5$$

$$\sqrt{\frac{102 \times 10^3}{36}} = 53 > 46.5 \,/\, \doteq 50.5$$

$$\sqrt{\frac{510 \times 10^3}{36}} = 119 > 46.5 \,/\, > 50.5$$

• Eqn AISC F1-6,

$$F_b = \left[\frac{2}{3} - \frac{F_y (l/r_T)^2}{1530 \times 10^3}\right] F_y = \left[\frac{2}{3} - \frac{36(50.5)^2}{1{,}530{,}000}\right] F_y$$

$$= 0.6\, F_y = 0.6(36{,}000) = 21{,}600 \text{ psi}$$

• Eqn AISC F1-8,

$$F_b = \frac{12{,}000}{l\left(\frac{d}{A_f}\right)} = \frac{12{,}000}{220.5(0.64)} = \cancel{85} \text{ ksi} > 0.6\, F_y \;\text{N/A}$$

Conclusion: $F_b = 0.6\, F_y = 21{,}600$ psi

- F_v

$$\frac{h}{t_w} \overset{?}{\leq} \frac{380}{\sqrt{F_y}}$$ F_v formula selection criteria, AISC § F4.

$$12.9 \overset{?}{\leq} \frac{380}{\sqrt{36}}$$

$$12.9 < 63 \Rightarrow F_v = 0.4\ F_y = 0.4\,(36{,}000)$$

$$\underline{F_v = 14{,}400 \text{ psi}}$$

2.2 Grade 8 Bolts

The AISC code does not include Grade 8 bolts. Grade 8 bolts have the same proof load, yield strength, tensile strength, material and treatment as A490 Type 1 bolts. A490 bolts are in the AISC Code. Use the AISC code to analyze the Grade 8 bolts as if they are A490 bolts.

- Bearing-type connection

$F_v = 28{,}000$ psi $F_t = 54{,}000$ psi   AISC Table J3.2

2.3 Bearing

2.3.1 Bolt hole in hot rolled steel

$d \equiv$ bolt hole diameter

For edge distance > 1½d and center spacing > 3d,

$F_p = 1.2\ F_u = 1.2\,(50{,}000) = 60{,}000$ psi

2.3.2 Contact area

- Steel → $F_p = 0.9\,F_y$ per AISC Manual

Hot rolled steel: $F_p = 0.9(29{,}000\text{ psi}) = 26{,}100$ psi

A36: $F_p = 0.9(36{,}000\text{ psi}) = 32{,}400$ psi

- Aluminum → Tables in Aluminum Design Manual

1100: $F_p = 7{,}300$ psi

6061 T6: $F_p = 23{,}000$ psi

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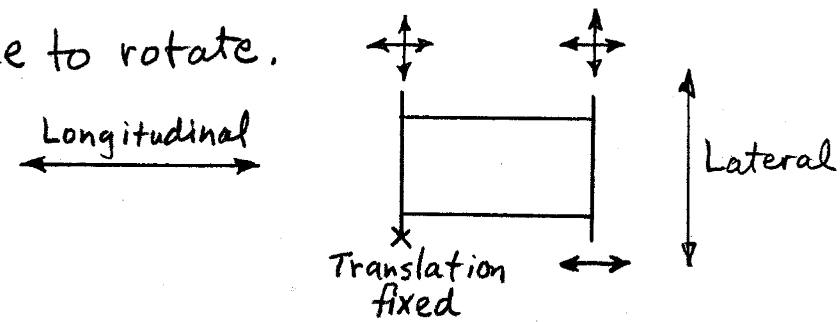
3.0 Expansion force

One carriage foot is fixed with respect to translation. The other 3 are free to translate as shown in the sketch.

Sketch reference: Dwg ME-427288 Rev 0.

The arrows indicate free translation directions.

All support feet are free to rotate.



Translation occurs after the expansion force overcomes the static friction force.

$F = \mu N$

$\mu = 0.75$ for mild steel on mild steel (dry)
$\mu = 0.61$ for mild steel on aluminum (dry)

Total design load on the carriage:

Total load from a Horn #1/#2 module = 56,290 Lbs. This value is taken from page A2 or A3 in App. A.

Total load from the target module = 17.06 tons = 34,120 Lbs. This value is taken from page B1 in Appendix B.

Crane capacity = 30 tons = 60,000 Lbs

Carriage weight ≐ 10 tons = 20,000 Lbs

Set the total design load on the carriage to 60,000 Lbs.

This design load is obviously excessive for the target carriage! However, this design load won't affect the results much and it covers higher loads that might be placed on the target carriage in the future.

$$F = \mu N$$

$$F = 0.75\,(60{,}000 + 20{,}000) = 60{,}000 \text{ Lbs}$$

$$F = 0.61\,(60{,}000 + 20{,}000) = 48{,}800 \text{ Lbs}$$

The 60,000 Lb expansion force is used to analyze the support beams, the cross beam, and elements in the support feet that are above the aluminum foot (§11.3). The 48,800 Lb expansion force is used to analyze the lower elements in the support feet. This is done so steel support feet can be used in the future.

4.0 Analysis plan for the support beam

Both ends of the support beam are free to rotate. Hence, it is analyzed as a simply supported beam in §5.0 & 6.0 to check the beam for maximum moment. In §7.0, the beam is analyzed with some degree of rotational restraint at the ends. The resulting bending moment at each end of the beam is used to check the design of the connection to the crossbeam.

The Horn #1/#2 support beam is analyzed in §5.0. The target support beam is analyzed in §6.0 and §7.0.

5.0 Horn #1/#2 support beam – Simply supported ends

The support beam is a W14 x 211.

Drawing ME-427282 Rev 0.

Applied loads are in Appendix A.

5.1 Expansion force

The expansion force causes axial compression and a bending moment because it is applied to the support beam at a flange.

One-half of the expansion force is applied to each of the two support beams.

∴ Compressive expansion force applied to one support beam = 60,000 Lbs/2 = 30,000 Lbs maximum

From § 3.0.

5.1.1 Axial compression

$$f_a = \frac{P}{A} = \frac{30{,}000 \text{ Lbs}}{62 \text{ in}^2} = 485 \text{ psi}$$

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} = \sqrt{\frac{2\pi^2 (29{,}000{,}000 \cancel{\text{psi}})}{36{,}000 \cancel{\text{psi}}}} = 126$$

Use the length of the target support beam so the calc doesn't have to be repeated for it.

$$\frac{Kl}{r} = \frac{1(220.5 \cancel{\text{in}})}{4.07 \cancel{\text{in}}} = 54 < 126$$

$$\therefore F_a = \frac{\left[1-\frac{(Kl/r)^2}{2C_c^2}\right]F_y}{\frac{5}{3}+\frac{3(Kl/r)}{8C_c}-\frac{(Kl/r)^3}{8C_c^3}} = \frac{\left[1-\frac{54^2}{2(126)^2}\right]\times 36{,}000}{\frac{5}{3}+\frac{3(54)}{8(126)}-\frac{(54)^3}{8(126)^3}}$$

$$\doteq 0.5\,F_y = 18{,}000\ \text{psi}$$

$$f_a = 485\ \text{psi} < 18{,}000\ \text{psi}\quad \underline{\underline{\text{OK}}}$$

5.1.2 Bending moment about x-axis

$M_{ef} = e$ (Expansion force)

$$e = \frac{\text{beam depth}}{2} + \text{spacer plate thickness} + \frac{\text{crossbeam flange thk}}{2}$$

$$= (15.72/2)\,\text{in} + (0.875+1.75)\,\text{in} + \frac{1.56}{2}\,\text{in} = 11.265\,\text{in}$$

$$M_{ef} = 11.265\,\text{in}\,(30{,}000\ \text{Lbs}) = 338{,}000\ \text{in-Lbs}$$

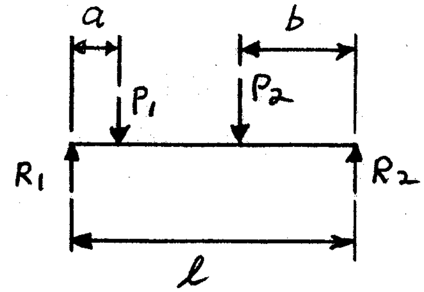
$$f_b = M/S = 338{,}000\ \cancel{\text{in}}\text{-Lbs}/338\ \text{in}^{\cancel{3}\,2} = 1{,}000\ \text{psi}$$

5.2 Simply supported beam with Appendix A loadings

5.2.1 Arm, 3-point support, other side

$P_1 = 13{,}900$ Lbs $P_2 = 18{,}700$ Lbs

$a = 27''$; $b = 77''$; $l = 218.75 - 15.75 = 203''$



$$R_1 = V_1 = \frac{P_1(l-a) + P_2 b}{l}\quad \text{max when } a<b$$

$$= (13{,}900\ \text{Lbs}\,(203-27)\,\text{in} + 18{,}700\ \text{Lbs}\,(77)\,\text{in})/203$$

$$= 19{,}145\ \text{Lbs}$$

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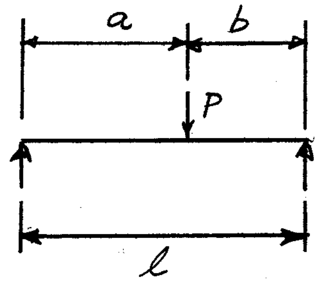
$R_2 = (13,900 + 18,700) - 19,145 = 32,600 - 19,145$

$= 13,455$ Lbs

M_2 (max when $R_2 < P_2$) $= R_2 b = 13,455$ Lbs $(77$ in$) = 1,036,035$ psi

5.2.2 Arm, 3-point support, strip line side



$P = 23,700$ Lbs $l = 203''$

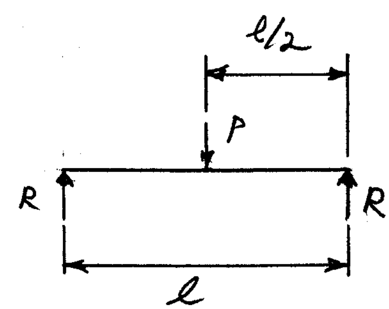
$b = 77''$ $a = 203 - 77 \cong 126''$

$R_1 = V_1 = \frac{Pb}{l} = \frac{23,700 \text{ Lbs } (77 \cancel{\text{in}})}{203 \cancel{\text{in}}} = 8,990$ Lbs

$R_2 = V_2 = \frac{Pa}{l} = \frac{23,700 \text{ Lbs } (126 \cancel{\text{in}})}{203 \cancel{\text{in}}} = 14,710$ Lbs

$M_{max} = \frac{Pab}{l} = 23,700 \text{ Lbs } \frac{(126 \text{ in})(77 \cancel{\text{in}})}{203 \cancel{\text{in}}} = 1,132,700$ in-Lbs

5.3 Simply supported beam with 30,000 Lbs ($\frac{1}{2}$ crane capacity (§3.0)) applied at mid-span



$P = 30,000$ Lbs $l = 203''$

$R = V = 30,000/2 = 15,000$ Lbs

M_{max} @ center $= \frac{Pl}{4} = \frac{30,000 \text{ Lbs } (203 \text{ in})}{4}$

$= 1,552,500$ in-lbs

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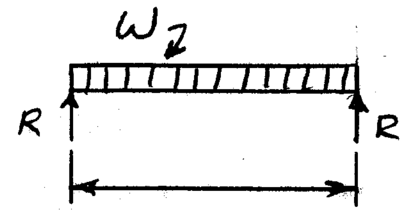
5.4 Beam weight



Beam weight $= 211 \frac{\text{Lbs}}{\cancel{ft}} * \frac{1 \cancel{ft}}{12 \text{ in}} = 17.6 \frac{\text{Lbs}}{\text{in}}$

$R = V = \frac{wl}{2} = 17.6 \frac{\text{Lbs}}{\cancel{in}} \times \frac{203 \cancel{in}}{2} = 1{,}787 \text{ Lbs}$

M_{max} @ center $= \frac{wl^2}{8} = 17.6 \frac{\text{Lbs}}{\cancel{in}}, \frac{(203)^2 \text{ in}^{\cancel{2}}}{8} = 90{,}660$ in-Lbs

5.5 Beam stresses

Use maximum loads in § 5.2 or § 5.3.

$f_a = 485$ psi $\quad F_a = 18{,}000$ psi $\quad$ (§5.1.1)

$M_{ef} = 338{,}000$ in-Lbs $\quad$ (§5.1.2)

$\Sigma V = \underset{(\S 5.2.1)}{19{,}145} + \underset{(\S 5.4)}{1{,}787} = 20{,}932$ Lbs

$M_{\text{concentrated loads}} = 1{,}552{,}500$ in-Lbs (§5.3)

$M_{\text{beam wt}} = 90{,}660$ in-Lbs (§5.4)

$\Sigma M = 338{,}000 + 1{,}552{,}500 + 90{,}660 \doteq 2{,}000{,}000$ in-Lbs

$A_c = 62 \text{ in}^2 \quad S = 338 \text{ in}^3$

$f_v = \Sigma V / A_c = 20{,}932 \text{ Lbs} / 62 \text{ in}^2 = 340 \text{ psi} < 14{,}400$ psi

$f_b = \frac{\Sigma M}{S} = \frac{2{,}000{,}000 \cancel{in}\text{-Lbs}}{338 \text{ in}^{\cancel{3}\,2}} = 5{,}920 \text{ psi} < 21{,}600$ psi ok

Check combined stresses for axial compression and bending:

$$\frac{f_a}{F_a} = \frac{485\ \cancel{psi}}{18{,}000\ \cancel{psi}} = 0.03 < 0.15$$

$$\therefore \quad \frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0$$

$$0.03 + \frac{5{,}920\ psi}{21{,}600\ psi} + 0 = 0.3 < 1.0 \quad \underline{\underline{OK}}$$

Conclusion of § 5.0: Axial, bending, and shear stresses check out OK for the Horn#1/#2 support beam with simply supported ends.

6.0 Target support beam – Simply supported ends

The support beam is a W14 x 211.

Drawing ME-427283 Rev 0.

6.1 Applied loads are in Appendix B. The total load applied to the target carriage, i.e., two support beams, is 17.06 tons. Assuming the load is carried equally by 3 supports yields a loading of approximately 17.06/3 = 5.7 tons = 11,400 Lbs on each support. For maximum flexibility in the future, use the Horn #1/#2 support beam loading in §5.3 for the target support beam.

Follow §5.3.

$P = 30{,}000$ Lbs $\quad \ell = 236.25'' - 15.75'' = 220.5''$

$R = V = 30{,}000/2 = 15{,}000$ Lbs

$$M_{max} \text{ @center} = \frac{P\ell}{4} = \frac{30{,}000 \text{ Lbs } (220.5 \text{ in})}{4} = 1{,}653{,}750 \text{ in-Lbs}$$

6.2 Beam weight

$$\text{Beam weight} = 211 \frac{\text{Lbs}}{\cancel{\text{ft}}} \times \frac{\cancel{\text{ft}}}{12 \text{ in}} = 17.6 \frac{\text{Lbs}}{\text{in}}$$

$$R = V = w\ell/2 = 17.6 \frac{\text{Lbs}}{\cancel{\text{in}}} \times \frac{220.5 \cancel{\text{in}}}{2} = 1{,}940 \text{ Lbs}$$

$$M_{max} \text{ @center} = \frac{w\ell^2}{8} = 17.6 \frac{\text{Lbs}}{\cancel{\text{in}}} \times \frac{(220.5)^2 \text{ in}^2}{8} = 106{,}965 \text{ in-Lbs}$$

6.3 Beam stresses

$f_a = 485$ psi $F_a = 18{,}000$ psi (§5.1.1)

$M_{ef} = 338{,}000$ in-Lbs (§5.1.2)

$\Sigma V = 15{,}000$ Lbs $+ 1{,}940$ Lbs $= 16{,}940$ Lbs
(§6.1) (§6.2)

$\Sigma M = 338{,}000 + 1{,}653{,}750 + 106{,}965 \doteq 2{,}100{,}000$ in-Lbs
(§5.1.2) (§6.1) (§6.2)

$A_c = 62\,in^2$ $S = 338\,in^3$

$f_v = \Sigma V/A_c = 16{,}940\ \text{Lbs}/62\,in^2 = 275\ \text{psi} < 14{,}400\ \text{psi}$ ok

$f_b = \Sigma M/S = \dfrac{2{,}100{,}000\ \text{in-Lbs}}{338\,in^3} = 6{,}215\ \text{psi} < 21{,}600\ \text{psi}$ ok

Check combined stresses for axial compression and bending

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1.0$$

$$\frac{485}{18{,}000} + \frac{6{,}215}{21{,}600} \le 1.0$$

$$0.03 + 0.29 = 0.32 < 1.0 \quad \text{ok}$$

Conclusion of 6.0: Axial, bending and shear stresses check out ok for target support beam with simply supported ends.

7.0 Target support beam – Fixed ends

l = larger of (203, 220.5) = 220.5 in

horn → 203; target sup't beam → 220.5

Note: Only the target support beam is analyzed because it is longer than the horn support beam.

7.1 Assume both ends are fully restrained.

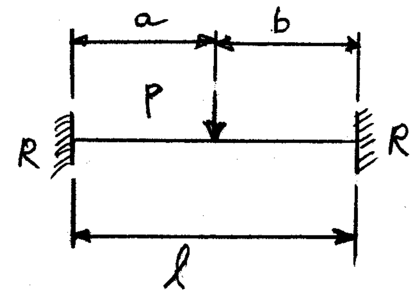
P = 30,000 Lbs applied at mid span (Same as §5.3 & §6.1.)

$\therefore a = b = l/2$

$R = V = P/2 = 30{,}000/2 = 15{,}000$ Lbs

M_{max} @ center & ends $= \dfrac{Pl}{8} = \dfrac{30{,}000 \text{ Lbs } (220.5 \text{ in})}{8}$

$= 826{,}875$ in-Lbs



7.2 Locate P to maximize the connection bolt load:

$a = 150.5''$ $\quad b = l - a = 220.5 - 150.5 = 70''$

$R_2 = V_2$ max when a>b $= \dfrac{Pa^2}{l^3}(a+3b) = \dfrac{30{,}000 \text{ Lbs } (150.5)^2 \cancel{in^2} (150.5 + 3*70) \cancel{in}}{220.5^3 \cancel{in^3}}$

$= 22{,}850$ Lbs

M_2 max when a>b $= \dfrac{Pa^2b}{l^2} = \dfrac{30{,}000 \text{ Lbs } (150.5)^2 \cancel{in^2} (70) \text{ in}}{(220.5)^2 \cancel{in^2}} = 978{,}310$ in-Lbs

7.3 Beam wt

$R = V = wl/2 = 1{,}940$ Lbs (§6.2)

M_{max} @ ends $= \dfrac{wl^2}{12} = \dfrac{17.6 \frac{\text{Lbs}}{\cancel{in}} (220.5)^2 \text{ in}^{\cancel{2}}}{12} = 71{,}310$ in-Lbs

7.4 Beam stresses

$f_a = 485$ psi $\quad F_a = 18,000$ (§5.1.1)

$M_{ef} = 338,000$ in-Lbs (§5.1.2)

$$\Sigma V = \underset{(\S 7.2)}{22,850} + \underset{(\S 7.3)}{1,940} = 24,790 \text{ Lbs}$$

$$\Sigma M = \underset{(\S 5.1.2)}{338,000} + \underset{(\S 7.2)}{978,310} + \underset{(\S 7.3)}{71,310} = 1,387,620 \text{ in-Lbs}$$

$A_c = 62 \text{ in}^2 \qquad S = 338 \text{ in}^3$

$f_v = \Sigma V / A_c = 24,790 \text{ Lbs}/62 = 400 \text{ psi} < 14,400 \text{ psi}$ OK

$f_b = \Sigma M / S = 1,387,620 \cancel{\text{in}}\text{-Lbs}/338 \text{ in}^3 = 4,105 \text{ psi} < 21,600 \text{ psi}$ OK

Check combined stresses for axial compression and bending

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1.0$$

$$\frac{485}{18,000} + \frac{4,105}{21,600} \le 1.0$$

$$0.03 + 0.19 = 0.22 < 1.0 \text{ OK}$$

Conclusion of 7.4: Axial, bending and shear stresses check out ok for target support beam with fixed ends.

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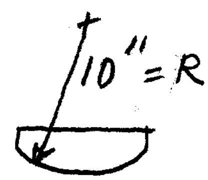
7.5 Degree of end restraint

The calcs in §7.1 and §7.2 assume both ends of the support beam are fully restrained from rotating. The support feet have a spherical bearing surface that allows rotation about all axes.* Estimate the frictional resistive end moment for a support foot.

Spherical foot drawing: ME-427267



$M_{sf} = (\mu N) R$

$\mu = 0.75$ for mild steel on mild steel

$N = 60{,}000/2 + 20{,}000/4 = 35{,}000$ Lbs (§3.0)

$M_{sf} = (0.75 \times 35{,}000 \text{ Lbs})(10 \text{ in}) = 262{,}500$ in-Lbs

Use $M_{sf} = 400{,}000$ in-Lbs $<$ 1,387,620 in-Lbs in §7.4 so beam stresses are ok.

* The support feet are located at the ends of the cross member.

8.0 Bolts between the support beam and the cross beam

8.1 Bolt tensile loads

Bolt tensile loads are calculated using §7.0 loads, as discussed in §4.0.

8.1.1 Vertical reaction at end of beam = 24,790 Lbs downward (§7.4)

Moment at end of beam = 400,000 in-Lbs (§7.5)

There are 2 pairs of bolts at each end of the beam.

The vertical reaction is shared equally by the four bolts.

Vertical reaction per bolt = 24,790/4 = 6,200 Lbs/bolt

Reaction force due to end moment = $\frac{\text{moment}}{\text{distance between bolts}}$

400,000 in-Lbs / 11.5 in ≐ 34,800 Lbs

Moment reaction force per bolt = 34,800/2 = 17,400 Lbs

Σ bolt tensile loads = 6,200 + 17,400 = 23,600 Lbs

8.1.2 Prying force

Follow AISC procedure on page 4-90.

T = 23,600 Lbs

Bolt $\phi = 1'' = d$

Nominal bolt cross sectional area = $\pi(1^2)/4 = 0.785\ in^2$

B = 54 ksi $(0.785\ in^2)$ = 42.4 kips

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$F_y = 36$ ksi

$p = b_f/2 = 15.8/2 = 7.9''$

$b = 5.75 - t_w/2 = 5.75 - 0.5 = 5.25''$

$a = (b_f/2) - (t_w/2) - b = 7.9 - 0.5 - 5.25 = 2.15''$

$d' = 1.125''$

$b' = b - d/2 = 5.25'' - (1/2)'' = 4.75''$

$a' = a + d/2 = 2.15 + (1/2) = 2.65''$

$\rho = b'/a' = 4.75/2.65 = 1.8$

$\delta = 1 - d'/p = 1 - 1.125/7.9 = 0.86$

$$t_c = \sqrt{\frac{8Bb'}{pF_y}} = \sqrt{\frac{8(42.4)(4.75)}{7.9(36)}} = 2.38 \text{ in}$$

$$\alpha = \frac{1}{\delta}\left[\frac{T/B}{(t/t_c)^2} - 1\right] = \frac{1}{0.86}\left[\frac{23.6/42.4}{(1.56/2.38)^2} - 1\right] = 0.34$$

$$Q = B\delta\alpha\rho\left(\frac{t}{t_c}\right)^2 = 42.4(0.86)(0.34)(1.8)\left(\frac{1.56}{2.38}\right)^2 \doteq 10 \text{ kips}$$

8.1.3 Bolt tensile load with prying force = 23,600 + 10,000 = <u>33,600 Lbs</u>

8.2 Bolt shear load

From § 5.0, the expansion force on each support beam is 30,000 Lbs. There are two pairs of bolts at each end of the beam. The shear load is shared equally by the four bolts.

Bolt shear load = 30,000/4 = 7,500 Lbs

8.3 Bolt stresses for bearing-type connection

$A_b \equiv$ Nominal bolt body area $= \pi \frac{d^2}{4} = \frac{\pi (1in)^2}{4} = 0.785\ in^2$

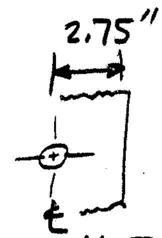
$f_v = 7{,}500\ Lbs / 0.785\ in^2 = 9{,}555\ psi < 28{,}000\ psi$ OK

Allowable tension stress considering the shear stress

$= \sqrt{54^2 - 3.75(f_v)^2} = \sqrt{54^2 - 3.75(9.555)^2} = 50.7\ Ksi$

$f_t = 33{,}600\ Lbs / 0.785\ in^2 = 42{,}800\ psi < 50{,}700\ psi$ OK

8.4 Bearing stress on bolt hole



Bolt hole edge distance = (17 − 11.5)/2 = 2.75"

bolt hole diameter = 1 1/8" = d; bolt hole spacing = 11.5"

$$\left. \begin{array}{l} 1\tfrac{1}{2} d = 1\tfrac{1}{2}(1\tfrac{1}{8}) = 1.7'' < 2.75'' \\ 3d = 3(1\tfrac{1}{8}) = 3.4'' < 11.5'' \end{array} \right\} \therefore F_p = 1.2 F_u$$

$f_p = \frac{\text{Bolt shear load}}{\text{Bolt bearing area}} = \frac{7{,}500\ Lbs}{1 in (0.75 in)} = 10{,}000\ psi < 60{,}000\ psi$ OK

9.0 Check AISC stiffener requirements for webs & flanges under concentrated forces per Chapter K and § F5.

9.1 Under the 30,000 Lb load at midpoint of the horn support beam:

<u>K1.2</u> Eqn. K1-1 does not apply.

<u>K1.3</u> ⓐ Eqn. K1-2

$$\frac{R}{t_w(N+5k)} = \frac{30{,}000 \text{ Lbs}}{0.98 \text{ in } (4+5(2.25)) \text{ in}} = 2{,}010 \text{ psi}$$

4 ← Minimum bearing length

2,010 psi < 0.6 F_y = 21,600 psi ⇒ Stiffeners not required.

<u>K1.4</u> ⓐ Eqn K1-4

$$R = 67.5\, t_w^2 \left[1 + 3\left(\frac{N}{d}\right)\left(\frac{t_w}{t_f}\right)^{1.5}\right]\sqrt{F_{yw} t_f / t_w}$$

$$= 67.5(0.98)^2 \text{ in}^2 \left[1 + 3\left(\frac{4 \text{ in}}{15.72 \cancel{\text{in}}}\right)\left(\frac{0.98 \cancel{\text{in}}}{1.56 \cancel{\text{in}}}\right)^{1.5}\right]\sqrt{\frac{36(1.56)}{0.98}}$$

= 677 kips > 30,000 Lbs ⇒ Stiffeners not req'd.

<u>K1.5</u> $$\frac{d_c}{t_w}\frac{b_f}{l} = \frac{d-2k}{t_w}\frac{b_f}{l} = \frac{(15.72-2(2.25))\cancel{\text{in}}}{0.98 \cancel{\text{in}}}\frac{15.8 \cancel{\text{in}}}{203 \cancel{\text{in}}}$$

= 0.9 < 1.7 ⇒ Must check eqn K1-7.

$$R = \frac{6{,}800\, t_w^3}{h}\left[0.4\left(\frac{d_c/t_w}{l/b_f}\right)^3\right] = \frac{6{,}800(0.98)^3}{12.6}\left[0.4(0.9)^3\right]$$

$h = d - 2t_f = 15.72 - 2(1.56) =$ 12.6

= 148 kips > 30,000 Lbs ⇒ Stiffeners not required.

K1.6 Eqn K1-8 does not apply.

K1.7 Not applicable.

K1.8 Not applicable. Eqn 1-9 does not apply.

F5. $\frac{h}{t_w} = 12.9$ (§2.1)

$\frac{h}{t_w} = 12.9 < 260 \Rightarrow$ Transverse stiffeners are not required.

Conclusion of §9.1: Transverse stiffeners are not req'd on the horn support beam under the 30,000 Lb concentrated load.

9.2 Check stiffener requirements under the 30,000 Lb load at midpoint of the target support beam (follow §9.1):

K1.2 Same as §9.1.

K1.3 "

K1.4 "

K1.5 $\frac{d_c}{t_w}\frac{b_f}{l} = \frac{d-2k}{t_w}\frac{b_f}{l} = \frac{(15.72-2(2.25)\cancel{in})}{0.98\cancel{in}}\frac{15.8\cancel{in}}{220.5\cancel{in}}$

$= 0.82 < 1.7 \Rightarrow$ Must check eqn K1-7.

$R = \frac{6{,}800\,t_w^3}{h}\left[0.4\left(\frac{d_c/t_w}{l/b_f}\right)^3\right] = \frac{6{,}800(0.98)^3}{12.6}\left[0.4(0.82)^3\right]$ ← §9.1

$= 112$ kips $> 30{,}000$ Lbs

$\Rightarrow$ Stiffeners not required.

K1.6 Same as § 9.1.

K1.7 "

K1.8 "

F5 "

Conclusion of §9.2: Transverse stiffeners are not required on the target support beam under the 30,000 Lb concentrated load.

9.3 For the reaction forces at the end of the horn support beam

Refer to § 8.1.1 → Maximum tensile load on a bolt = 23,600 Lbs

There are 2 bolts in tension in the same transverse plane across the beam.

∴ Force applied to the flange = 2 (23,600) = 47,200 Lbs

K1.2 Eqn K1-1

$$0.4\sqrt{\frac{P_{bf}}{F_{yc}}} = 0.4\sqrt{\frac{5/3\,(47{,}200)}{36{,}000}} = 0.6$$

$t_f = 1.56'' > 0.6 \Rightarrow$ Stiffeners not required

K1.3 (b) Eqn K1-3

$$\frac{R}{t_w(N+2.5k)} = \frac{47{,}200 \text{ Lbs}}{0.98\text{in}\,(4+2.5(2.25))\text{ in}}$$

Minimum bearing length, § 9.1.

$$= 5{,}005 \text{ psi}$$

$5{,}005$ psi $< 0.6\,F_y = 21{,}600$ psi

⇒ Stiffeners not required.

K1.4 (b) Eqn K1-5

$$R = 34 t_w^2 \left[1 + 3\left(\frac{N}{d}\right)\left(\frac{t_w}{t_f}\right)^{1.5}\right]\sqrt{F_{yw}\, t_f / t_w}$$

$$= 34(0.98)^2\left[1 + 3\left(\frac{4}{15.72}\right)\left(\frac{0.98}{1.56}\right)^{1.5}\right]\sqrt{\frac{36(1.56)}{0.98}}$$

$= 341$ kips $> 47{,}200$ Lbs $\Rightarrow$ Stiffeners not required.

K1.5 (b) Eqn K1-7

$R = 148$ kips (Same as for the 30,000 Lb load case, §9.1.)

$R = 148{,}000$ Lbs $> 47{,}200$ Lbs $\Rightarrow$ Stiffeners not required

K1.6 Eqn K1-8 does not apply.

K1.7 Not applicable.

K1.8 Not applicable. Eqn K1-9 does not apply.

F5. $\frac{h}{t_w} = 12.9$ (§2.1)

$\frac{h}{t_w} = 12.9 < 260 \Rightarrow$ Transverse stiffeners are not required.

Conclusion of §9.3: Transverse stiffeners are not required at the ends of the horn support beam.

9.4 For the reaction forces at the end of the target support beam (follow §9.3)

K1.2 Same as §9.3.

K1.3 "

K1.4 "

K1.5 R = 112 kips (Same as for the 30,000 Lb load case, §9.2.)

R = 112,000 Lbs > 47,200 Lbs ⇒ Stiffeners not required

K1.6 Same as §9.3.

K1.7 "

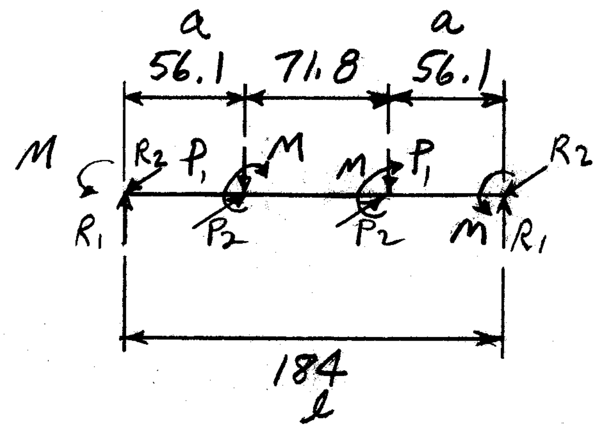
K1.8 "

F5. "

Conclusion of §9.4: Transverse stiffeners are not required at the ends of the target support beam.

10.0 Cross member Drawing ME-427280 Rev 0.

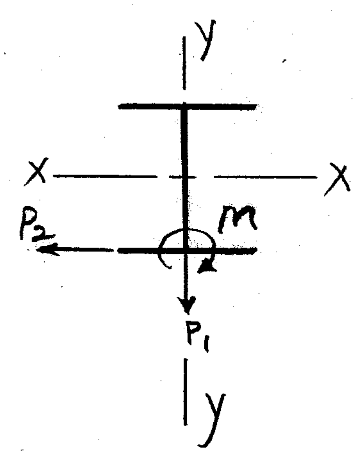
The cross member is the same for the horn #1, horn #2 and target carriage assemblies.



Cross member ends are simply supported.

Resistive end moment is estimated in §7.5.

The cross member is a W14X211, just like the support beams.



$P_1 = 24,790$ Lbs (§ 8.1.1)

$P_2 = 30,000$ Lbs (§5.1)

$M = 400,000$ in-Lbs (§8.1.1)

10.1 Shear and bending about X-X

- P1

$R_{1a} = V_{1a} = P_1 = 24,790$ Lbs

$M_{1a\,max}\Big|_{\text{between loads}} = Pa = 24,790 \text{ Lbs}(56.1 \text{ in}) = 1,390,719$ in-Lbs

$f_{v_x} = 24,790 \text{ Lbs}/13 \text{ in}^2 = 1,910 \text{ psi} < 14,400 \text{ psi}$ OK

$f_{b_x} = 1,390,719 \cancel{\text{in-}}\text{Lbs}/338 \text{ in}^3 = 4,115 \text{ psi} < 21,600 \text{ psi}$.

- Beam weight

Beam weight $= 211 \frac{Lbs}{\cancel{ft}} \cdot \frac{\cancel{ft}}{12 in} = 17.6 \frac{Lbs}{in}$

$R_{1b} = V_{1b} = wl/2 = 17.6 \frac{Lbs}{in} * \frac{184 \cancel{in}}{2} = 1,620$ Lbs

$M_{1b}max$ @ center $= \frac{wl^2}{8} = 17.6 \frac{Lbs}{in} * \frac{184^2 in^2}{8} = 74,500$ in-Lbs

$R_1 = R_{1a} + R_{1b} = 24,790 + 1,620 = 26,410$ Lbs

- Stresses

A flanges $= 49 \; in^2$

A web $= 13 \; in^2$

$\Sigma = 62 \; in^2$

$f_{vx} = (R_{1a} + R_{1b}) / A_{web} = (24,790 + 1,620)$ Lbs$/13 \; in^2$

$= 2,035$ psi $< 14,400$ psi OK

$f_{bx} = (M_{1a} + M_{1b}) / S_{xx} = (1,390,719 + 74,500)$ in-Lbs$/338 \; in^3$

$= 4,335$ psi $< 21,600$ psi OK

10.2 P_2 - Shear and bending about Y-Y

$R_2 = V_2 = P_2 = 30{,}000$ Lbs

$M_{2max}\big|_{\text{between loads}} = Pa = 30{,}000 \text{ Lbs } (56.1 \text{ in}) = 1{,}683{,}000 \text{ in-Lbs}$

$f_{v_y} = R_2 / A_{flanges} = 30{,}000 \text{ Lbs} / 49 \text{ in}^2 = 615 \text{ psi} < 14{,}400 \text{ psi}$ ok

$f_{by} = 1{,}683{,}000 \text{ in-Lbs} / 130 \text{ in}^3 = 12{,}950 \text{ psi} < 21{,}600 \text{ psi}$ ok

10.3 Torsion

Calculate torsional resistance of the W14 x211.

Reference: Design of Welded Structures - Blodgett, 1972

$$\text{I} = R_1 \,\square_{1}^{12.6} + 2\left(R_2 \,\square_{1.56}^{15\,3/4}\right)$$

$$R = \beta b d^3$$

R_1: $b = 12.6$, $d = 1$ $\quad b/d = 12.6 \Rightarrow \beta = 1/3$

$R_1 = 1/3\,(12.6)(1)^3 = 4.2 \text{ in}^4$

R_2: $b = 15.75$, $d = 1.56$ $\quad b/d = 10 \Rightarrow \beta = 0.313$

$R_2 = 0.313(15.75)(1.56)^3 = 18.7 \text{ in}^4$

$R = R_1 + 2R_2 = 4.2 + 2(18.7) = 41.6 \text{ in}^4$

AISC value for $R = 44.6 \text{ in}^4 = J$

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Use the AISC value.

$\therefore R = J = 44.6 \text{ in}^4$

$$f_{v\,torsion} = \frac{Tt}{R}$$

For a flange: $f_{v\,torsion} = \dfrac{400{,}000 \text{ in-Lbs} (1.56 \text{ in})}{44.6 \text{ in}^2}$

$= 14{,}000 \text{ psi} < 14{,}400 \text{ psi}$ ok

For the web: $f_{v\,torsion} = \dfrac{400{,}000 (1)}{44.6} = 8{,}970 \text{ psi}$

$< 14{,}400 \text{ psi}$ ok

10.4 Combined bending stresses

$$\frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0$$

$$\frac{4{,}335}{21{,}600} + \frac{12{,}950}{21{,}600} = 0.80 \leq 1.0 \quad \text{ok}$$

10.5 Combined shear stresses

The combined web shear stresses are ok by inspection.

Combined flange shear stresses:

Shear force $= SF = f_v t$

$$SF\Big|_{\substack{\text{bending}\\ \text{about}\\ Y\text{-}Y}} = 615\ \frac{\text{Lbs}}{\text{in}^{\cancel{2}}}\left(1.56\ \cancel{\text{in}}\right) = 959.4\ \frac{\text{Lbs}}{\text{in}}$$

$$SF\Big|_{\substack{\text{torsion}\\ \text{about}\\ X\text{-}X}} = 14{,}000\ \frac{\text{Lbs}}{\text{in}^{\cancel{2}}}\left(1.56\ \cancel{\text{in}}\right) = 21{,}840\ \text{Lbs/in}$$

$$\text{Resultant } SF = \sqrt{959.4^2 + 21{,}840^2} = 21{,}861\ \text{Lbs/in}$$

$$\text{Combined } f_v = 21{,}861\ \frac{\text{Lbs}}{\text{in}} \cdot \frac{1}{1.56\ \text{in}} = 14{,}015\ \text{psi} < 14{,}400\ \text{psi}$$

OK

10.6 AISC stiffener requirements

10.6.1 Where the support beam attaches to the flange of the cross beam.

The support beam is ok, § 9.3 and § 9.4, so the cross beam is ok since both beams are W14 x 211 and the cross beam is shorter than the support beam.

10.6.2 Cross beam ends

The cross beam ends are ok for the reasons given in § 10.6.1.

Conclusion of § 10.0: The cross beam checks out ok. No transverse stiffeners are required.

11.0 Support feet Dwg ME-427284 Rev 0.

11.1 Bearing in vertical direction

The spherical foot is the smallest bearing area for the vertical reactions.

$A_p \equiv$ bearing area

$A_p = \pi d^2/4 = \pi\, 6^2 in^2/4 = 28.25\ in^2$ minimum (Use projected area.)

Vertical reaction = 26,410 Lbs (§ 10.1)

$f_p = 26{,}410\ Lbs / 28.25\ in^2 = 935\ psi < 7{,}300\ psi$ OK

1100 alumimum is the metal in the bearing load path that has the lowest allowable bearing stress, $F_p = 7{,}300$ psi.

The vertical reaction ultimately bears on concrete.

$f'_c = 4{,}000$ psi minimum for the target pile pit

$F_p = 0.35\, f'_c = 0.35(4{,}000) = 1{,}400$ psi

935 psi < 1,400 psi OK

11.2 Weld between spherical foot and W14 x 211

- Weld: 1/4" equal leg fillet weld, E6011 electrode, all the way around the 6" ϕ spherical foot

Weld capacity $= 0.3(60{,}000 \frac{Lbs}{in^2})\frac{(0.25 \times 0.707)\,in\,(1\,in)}{in\ of\ weld}$

$= 3{,}180\ Lbs/in$ of weld

Weld length $= \pi d = \pi(6) = 18.8\ in$

Total load capacity of the weld $= 18.8\,in \times 3{,}180 \frac{Lbs}{in\ of\ weld}$

$= 59{,}784\ Lbs$

$R_2 = 30{,}000\ Lbs < 59{,}784\ Lbs$ ok

- The spherical foot is made with hot rolled steel. Check the base metal shear stress.

$F_y = 29{,}000$ psi for hot rolled steel, § 2.3.2

Use $F_v = 29{,}000\,(0.4) = 11{,}600$ psi

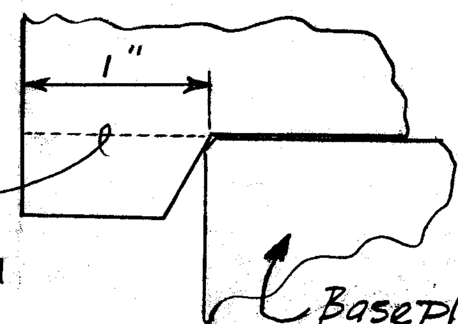
Base metal capacity $= 0.25\cancel{in}\,(18.8\cancel{in})(11{,}600\ Lbs/\cancel{in^2})$

$= 54{,}520\ Lbs > 30{,}000\ Lbs = R_2$ ok

11.3 Foot

The foot critical section is where the captured base plate bears against the protruding edges on the foot.

There are 2 protruding edges on each side of the foot.



$A_v = 2(1.5 \times 1) = 3\,in^2$ minimum

Friction will hold some of the load. Use half the coefficient of static friction to be on the safe side.

$\mu = 0.61$ coefficient of static friction, aluminum on mild steel.

Friction force $= \frac{\mu}{2} R_1 = \frac{0.61}{2}(26{,}410\ Lbs) \doteq 8{,}000\ Lbs$

$f_v = (R_2 - \text{friction force})/A_v = (30{,}000 - 8{,}000)\ Lbs/3\,in^2$

$= 7{,}350\ psi < 11{,}600\ psi$ OK

§11.2

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11.4 Shim capture blocks Dwg ME-427269, Part 2

As explained in §3.0, the calculations from this point on will use the 48,800 expansion force for the mild steel - aluminum sliding surfaces instead of the 60,000 Lb expansion force for mild steel - mild steel sliding surfaces that the rest of the carriage is designed for.

The aluminum shim pack is captured by four blocks. There is one block on each side of the rectangular shim pack.

Follow §5.1 to calculate the maximum expansion force applied to one support beam:

$$\frac{48,800}{2} = 24,400 \text{ Lbs}$$ (vs 30,000 Lbs used in all previous sections.)

Friction will hold some of the load. Use the resistive frictional force calculated in §11.3, 8,000 Lbs.

Force applied to the weld on a capture block

$= 24,400 \text{ Lbs} - 8,000 \text{ Lbs} = 16,400 \text{ Lbs}$

Length of weld $= 8''$

Unit weld load $= 16,400 \text{ Lbs} / 8 \text{ in} = 2,050$ Lbs/in of weld

The weld is a partial penetration groove weld with $S = 5/16''$. The effective throat $E = S - \frac{1}{8} = 5/16 - 1/8 = 3/16''$.

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Use E60XX electrode.

$$\text{Weld capacity} = \frac{3/16\,\cancel{in} \times 1\,\cancel{in}}{\text{in of weld}} \times 0.3\left(60{,}000\,\frac{Lbs}{\cancel{in^2}}\right)$$

$$= 3{,}375\,\frac{Lbs}{\text{in of weld}} > 2{,}050\,\frac{Lbs}{\text{in of weld}} \quad \underline{\underline{OK}}$$

The capture blocks and plate they're welded to are made with hot rolled steel. Check the base metal shear stress.

$$\text{Base metal capacity} = (3/16\,in)(8\,in)(11{,}600\,Lbs/in^2)$$

from § 11.2

$$= 17{,}400\,Lbs > 16{,}400\,Lbs \quad \underline{\underline{OK}}$$

SUBJECT: 11.5 Guide pins & Threaded rods

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11.5.1 Guide pins (Drill rod)

- Friction between the slide top plate and the slide base should keep the top plate from moving and bearing on the pins and rods. To start, assume only the four pins hold, as a bearing load, the net expansion force calculated in §11.4.

Net expansion force = 16,400 Lbs (§11.4)

Neglect any rod clamping force. See §11.5.2 for clamping force estimate.

Load per pin = 16,400/4 = 4,100 Lbs

- Calculate the bearing area with a pin:

The top slide plate is hot rolled steel, 1/2" thick. $F_y = 29{,}000$ psi.

$$A_p = 4{,}100\ \cancel{Lbs} \times \frac{in^2}{29{,}000\ \cancel{Lbs}} = 0.14\ in^2$$

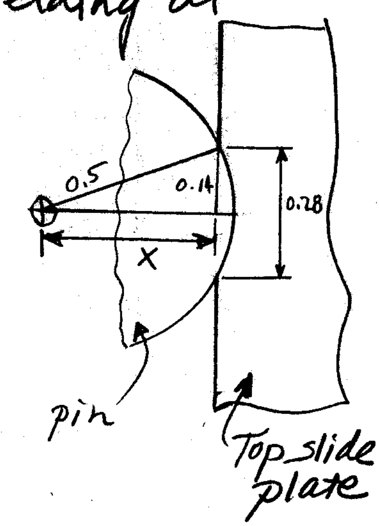
Depth of bearing = 0.5"

Width of bearing area = 0.14 in²/0.5 in = 0.28 in

Plate movement resulting from local yielding at each of the four pins –

$x^2 + 0.14^2 = 0.5^2 \Rightarrow x = 0.48$ in

Plate movement = depth of impression
= 0.5 − x = 0.5 − 0.48
= 0.02" ok



• Check pin stresses –

Pin material: Drill rod stock (not heat treated to full hardness)

Hardness = B94 to B100 $\Rightarrow F_{TU} \doteq 50{,}000$ psi,
Use $F_y \doteq 25{,}000$ psi

Use: $F_b = 0.6(25{,}000) = 15{,}000$ psi
$F_v = 15{,}000/2 = 7{,}500$ psi

$A_c = \pi d^2/4 = \pi(1\,in^2)/4 = 0.785\,in^2$

$f_v = 4{,}100\,Lbs/0.785\,in^2 = 5{,}225\,psi < 7{,}500\,psi$ ok

$S = \pi d^3/32 = \pi(1in)^3/32 = 0.098\,in^3$

Bending moment on pin = $Pe = 4{,}100\,Lbs\left(\frac{0.5}{2}\right)in$

$= 1{,}025$ in-Lbs

$f_b = M/S = 1{,}025\,in\text{-}Lbs/0.098\,in^3 = 10{,}500\,psi < 15{,}000\,psi$ ok

Conclusion: Both the pin and its hole will deform until enough contact area is attained to stop the materials from yielding. The estimated deformation is acceptable. Pin stresses are ok.

11.5.2 Threaded rods

- The two, 1/8", 1/2" long welds at the end of the rod are only there to keep the threaded rod in the plate during shipping and installation. The welds will break when the nut is tightened.

- Estimate rod preload based on load capacity of the internal threads

Rod nominal diameter = 1"

Effective thread engagement length = 1/2"

Plate material: hot rolled steel

$$\text{Thread capacity} = 2.33\ \frac{in^2}{\cancel{\text{in engagement}}} * \tfrac{1}{2}\ \cancel{\text{in engagement}}$$

$$* \underbrace{11{,}600}_{\S 11.2}\ \frac{Lbs}{in^2} = 13{,}500\ Lbs$$

- Rod material allowable stresses

$F_u = 125{,}000$ psi minimum Hardness = 28-32 Rc

$F_y = 105{,}000$ psi minimum

$F_v = 0.17\ F_u$ When threads are not excluded from shear planes. Based on untheaded nominal body area.

$F_v = 0.17(125{,}000\ psi) = 21{,}250\ psi$

$F_T = F_u/3 = 125{,}000/3 = 41{,}600\ psi$

- Calculate slip resistance of the 1"ϕ rod with the 13,500 Lb preload:

Follow Allowable Stress Design Specification for Structural Joints Using ASTM A325 or A490 Bolts in the AISC Manual of Steel Construction.

$P_s \equiv$ Allowable slip resistance

$P_s = F_s A_b N_b N_s$

$F_s = 15{,}000$ psi (Slip load per unit of bolt area, Table 3)

$A_b = \pi d^2/4 = \pi (1)^2/4 = 0.785 \text{ in}^2$

$N_b = 1$ bolt

$N_s = 1$ slip plane

$$P_s\Big|_{A325} = 15{,}000 \frac{Lb}{\cancel{in^2}} * 0.785 \cancel{in^2} * 1 * 1 = 11{,}775 \text{ Lbs}$$

The preload on a A325 bolt is 51,000 Lbs minimum

$$P_s\Big|_{F_i = 13{,}500 \text{ Lbs}} = (11{,}775 \text{ Lbs}) \frac{13{,}500}{51{,}000} \doteq 3{,}000 \text{ Lbs}$$

∴ Conclusion: Each 1"ϕ B7 rod will hold about 3,000 Lbs of lateral force.

- Check rod stresses

Net expansion force = 16,400 Lbs (§ 11.4)

Load per rod = (16,400/2) - 3,000 = 5,200 Lbs

$A_c = \pi d^2/4 = \pi (1 in)^2/4 = 0.785 in^2$

$f_v = 5,200 \text{ Lbs} / 0.785 in^2 = 6,625 \text{ psi} < 21,250 \text{ psi}$ OK

Adjust F_T for f_v. Use the AISC formula for A325 bolts since its F_u, 120,000 psi, is close to the F_u of the rod material.

$F_T' = \sqrt{(F_T)^2 - 4.39 f_v^2} = \sqrt{(41.6 ksi)^2 - 4.39(6.625 ksi)^2}$

$F_T' = 39,200 \text{ psi}$

Axial stress due to the preload force $= \dfrac{13,500 \text{ Lbs}}{0.785 in^2}$

$f_a = 17,200 \text{ psi}$

Bending moment on rod $= Pe = 5,200 \text{ Lbs} (0.5/2) in$

$= 1,300 \text{ in-Lbs}$

$S = \pi d^3/32 = \pi (1 in)^3/32 = 0.098 in^3$

$f_b = M/S = 1,300 \text{ in-Lbs} / 0.098 in^3 = 13,265 \text{ psi}$

Σ axial stresses = 17,200 + 13,265 = 30,465 psi < 39,2.. psi OK

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- Calculate the bearing area with a rod:

The top slide plate is hot rolled steel, 1/2 thick. $F_y = 29{,}000$ psi.

$$A_p = 8{,}200\ \text{lbs} \times \frac{\text{in}^2}{29{,}000\ \text{lbs}} = 0.28\ \text{in}^2$$

Depth of bearing = 0.5"

Width of bearing area = $0.28\ \text{in}^2 / 0.5\ \text{in} = 0.56\ \text{in}$

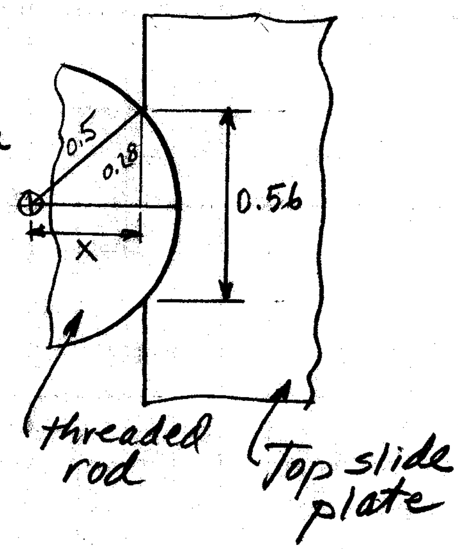
Plate movement resulting from local yielding at each of the two rods –

$x^2 + 0.28^2 = 0.5^2 \Rightarrow x = 0.4$ in

Plate movement = depth of impression

$= 0.5 - x = 0.5 - 0.4$

$= 0.1$ in OK



Conclusion: The hole will deform until enough contact area is attained to stop the plate from yielding. The estimated deformation is acceptable. Rod stresses are ok.

11.6 Slide base & Expansion foot base welds

The minimum weld length on each of these bases is 8".

As discussed in § 11.5.1, friction should keep these plates from sliding. But check the weld for the net expansion force.

Net expansion force = 16,400 Lbs (§ 11.4)

Load per inch of weld $= \frac{16{,}400 \text{ Lbs}}{8 \text{ in of weld}} = 2{,}050 \frac{\text{Lbs}}{\text{in of weld}}$

Use E60XX electrode. 3/8" equal leg fillet weld.

Weld capacity $= \frac{0.375 \cancel{\text{in}} (0.707) \times 1 \cancel{\text{in}}}{\text{in of weld}} * 0.3 \left(60{,}000 \frac{\text{Lbf}}{\cancel{\text{in}^2}}\right)$

$= 4{,}770 \frac{\text{Lbs}}{\text{in of weld}} > 2{,}050 \frac{\text{Lbs}}{\text{in of weld}}$ OK

Base metal capacity $= \frac{0.375 \cancel{\text{in}} * 1 \cancel{\text{in}}}{\text{in of weld}} * \frac{11{,}600 \text{ Lbs}}{\cancel{\text{in}^2}}$

$= 4{,}350 \frac{\text{Lbs}}{\text{in of weld}} > 2{,}050 \frac{\text{Lbs}}{\text{in of weld}}$ OK

Conclusion: The welds are sufficient.

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11.7 Welds between the base plate and the angles embedded in the target hall concrete pit liner

The minimum weld length on each of the base plates is 8". The weld is a 3/8" equal leg fillet weld.

The weld size, length, and loading are the same as checked in §11.6.

Conclusion: The welds are sufficient.

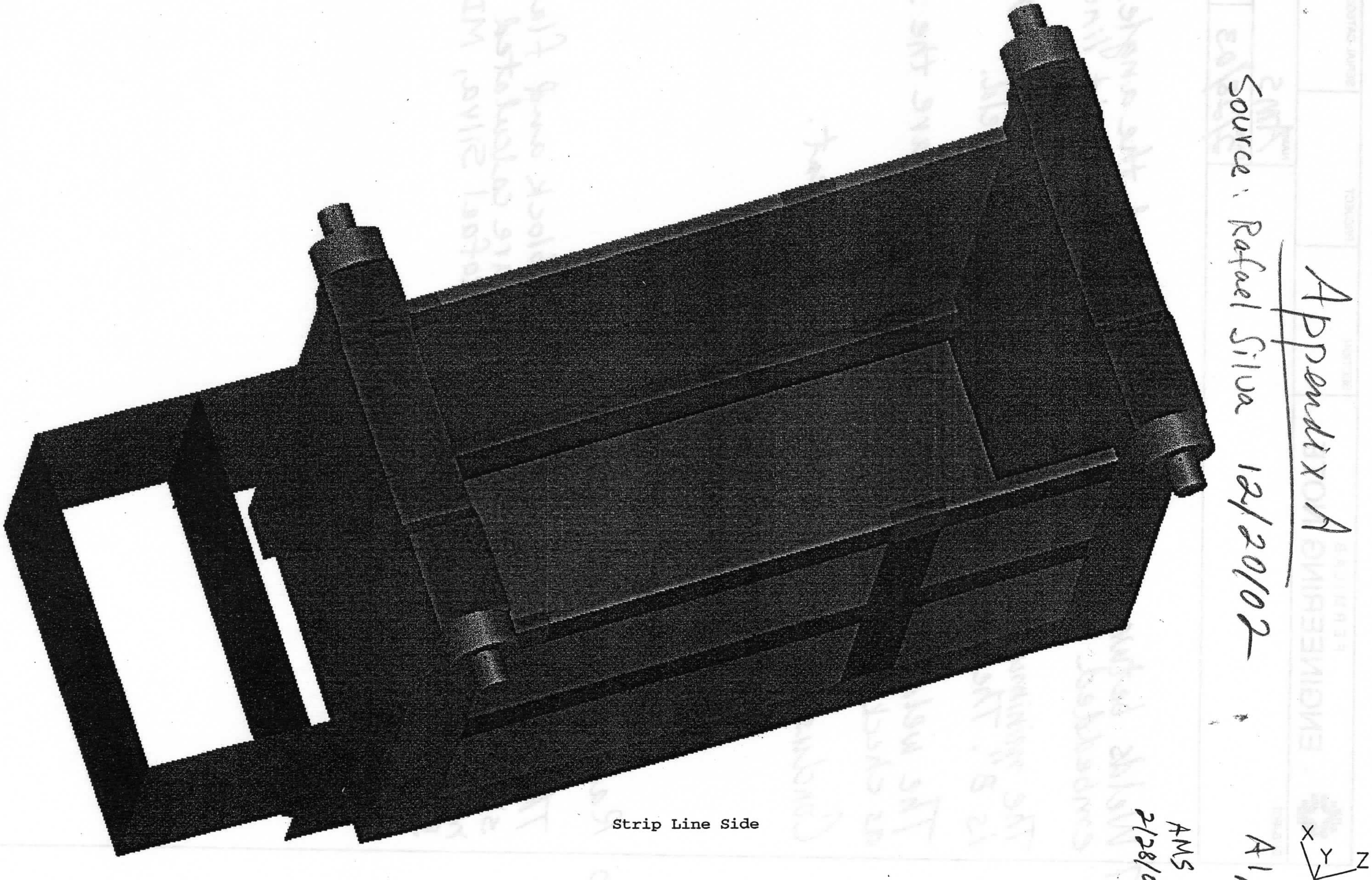
12.0 Rails - Dwg MC 427272

The module support pads (V-block and flat plate) sit on the rail. Rail stresses are calculated in the module engineering note by Rafael Silva, MD-ENG-012, §11.0.

I-DEAS 8 m4: PARTICLE PHYSICS DIVISION : USER.rafael : /cadwhs/server03/ms_ra 10-Dec-01 15:24:41

Database: /cadwhs/server03/ms_rafael/horn1_module.mf1 Units : IN
View : VIEW1 Display : No stored Option
Task : Post Processing Model/Part Bin: Main
Model: module_w_ss_slb Active Study: DEFAULT FE STUDY Parent Part: module_w_ss_slb

module_w_ss_slb



Appendix A

Source: Rafael Silva 12/20/02

AMS
2/28/03

A1/3

Plotted by rafael on 10-Dec-01 , File: horn1_module_shade.pff

To analyze the connections, another model was used. For that, the original model was copied and the 10-inch plates were coated with a 3/8" thick shell providing means of obtaining the moments at these locations.

A2/3

AMS
2/28/03

2.2.2. Parameters Used

- Program: SDRC I-DEAS v. 8m4 / Simulation.
- Analysis: Linear Statics
- Material properties -

  All elements are the default generic isotropic steel:

  density = 7.317372×10^{-4} lbf.sec^2/in^4

  η = 0.29

  Shell elements have E = 2.99938×10^7 psi (default)

  Solid elements have E = 2.0×10^7 psi
- Elements:

  Solids: solid parabolic tetrahedron with 4" average mesh size.

  Shells: parabolic quad shell with 4" average mesh size.

2.2.3. Boundary Conditions

The operational load is estimated to be:

- Module main frame: 30,100 lb
- Components: 5,100 lb
- Horn 1: 1,000 lb
- Tank (full): 1,100 lb
- Strip line: 13,500 lb
- Total: 50,800 lb

Just for reference, the estimated weight for the large module stand is 3,200 lb and for the lifting fixture is 1,500 lb.

For the model, the loads were:

- Weight of modeled steel parts = 32,580 lb (own weight)
- Contingency (by using g = 400 in/sec^2) = 1,125 lb (extra)
- Total force on top of the strip line box = 13,520 lb (strip line)
- Total force inside the sidewalls = 1,885 lb (grout and steel)
- Total force on top of 10-inch plates = 7,200 lb (horn, components, tank)

The total vertical reaction is 56,290 lb and the reaction from the lateral load is 5,739lb.

The module may be supported by its arms or by its lifting hooks. It may be possible to support or lift the module through 3 points only but, because of the position of the center of gravity, 2 of the 3 points have to be located downstream.

A3/3
AMS
2/28/03

2.2.4. Results

The maximum Von Mises and shear stress (ksi) and overall deflections (in) are indicated in the table bellow. For the linear buckling cases, the buckling load factor is indicated instead. Reactions are in kips.

Support Member	Number of Support Points	Linear Analysis Type	Boundary Conditions Set	Load Set	Restraint Set	Maximum Von Mises Peak Stress	Maximum Shear Peak Stresses	Maximum Deflection
Arm	4	Static	1	operational	1	7.96	4.27	0.011
	3	Static	2	operational	2	9.95	5.13	0.072
	3	Buckling	3	operational	2	BLF = 53.3		
Hook	4	Static	4	operational	3	2.15	1.13	0.008
	3	Static	5	operational	4	3.55	1.91	0.038
	3	Buckling	6	operational	4	BLF = 91.0		

Support Member	Number of Support Points	Upstream						Downstream						Total		
		Strip Line Side			Other Side			Strip Line Side			Other Side					
		Rx	Ry	Rz	Rx	Ry	Rz	Rx	Ry	Rz	Rx	Ry	Rz	Rx	Ry	Rz
Arm	4		9.7			4.5			13.6	3.4	5.4	28.5	-3.4	5.4	56.3	0.0
	3					13.9			23.7	3.3	5.4	18.7	-3.3	5.4	56.3	0.0
Hook	4		14.1			3.0			10.4	4.1	5.4	28.8	-4.1	5.4	56.3	0.0
	3					15.0			24.5	4.0	5.4	16.8	-4.0	5.4	56.3	0.0

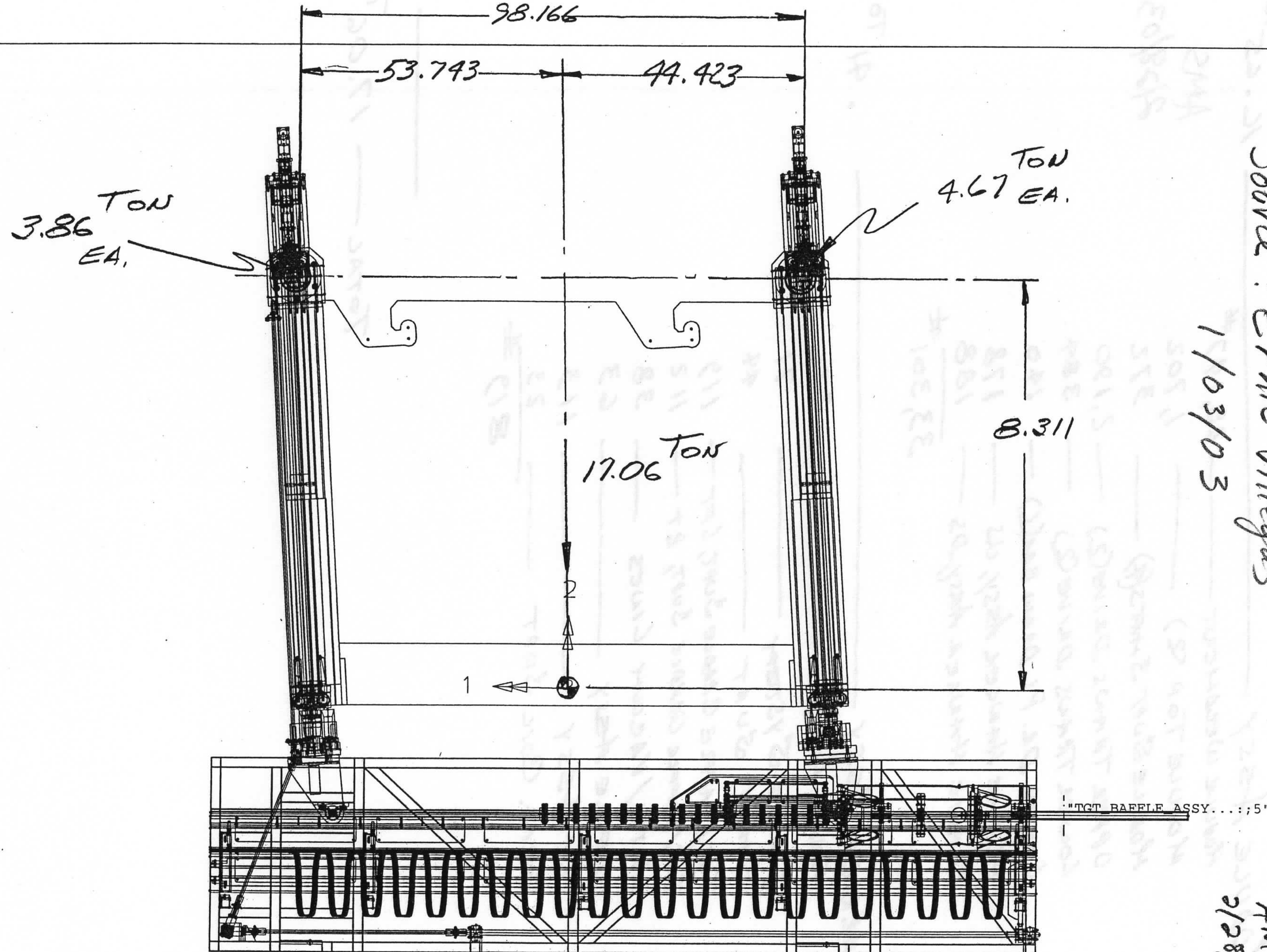
As can be seen on the plots attached, only a few spots of the structure reach stresses above 1 ksi, which indicates concentration of stresses in those spots.

- Maximum peak Von Mises stresses < 10.7 ksi
- Maximum peak shear stresses < 5.3 ksi

Hence, the structure is ***OK***.

Appendix B

Source: Ernie Villegas 1/03/03



B1/2

AMS 2/28/03

Y
Z X

Plotted by villegas on 03-Jan-03 , File: generic.pff

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
			B2/2

SUBJECT: TGT/BAFFLE ASSY WEIGHTS

NAME: E.M. Villegas

DATE: 1/03/02

REVISION DATE:

MODULE ASSY		16.65 TON
MODULE WELDMENT	28,147#	
MODULE TOP (2)	1,702	
MODULE SUPT SHAFTS (4)	372	
UPPER TRANS DRIVE (2)	2,190	
LOWER TRANS DRIVE (2)	384	
LOWER DR. PL DRAW BAR (6)	140	
FRAME HANGER ASSY, US	178	
FRAME HANGER ASSY, DS	188	
	33,301#	

AMS
2/28/03

CARRIER ASSY		.41 TON
FRAME ASSY	236	
DRIVE SYSTEM	71	
SHAFT SUPT	44	
TGT/BAFFLE CRADLE SUPT, LFT	119	
TGT/BAFFLE CRADLE SUPT, RT	112	
WATER/VACUUM LINES	38	
BAFFLE ASSY	63	
TGT ASSY	113	
HORIZ. COIL SUPT	23	
	819#	

TOTAL — 17.06 TON