

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab	
Calculation No.: NE-EO-2011-003	Revision Number: 2

CALCULATION COVER SHEET

Supersedes Calculation No.:	Total Number of Attachments:	
Analyzed System: E906 Station 3 & 4 Detector Support Structure		
Purpose of Revision: Added Hilti anchor design requirements		
PREPARER		
P. Strons & R. Fischer, NE-EO		
_____ Print Name	_____ Signature	_____ Date
REVIEWER		
_____ Print Name	_____ Signature	_____ Date
VENDOR APPROVER (if vendor-supplied calculation)		
n.a.		
_____ Print Name	_____ Signature	_____ Date
FINAL APPROVER		
_____ Print Name	_____ Signature	_____ Date

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab	
Calculation No.: NE-EO-2011-003	Revision Number: 2

TABLE OF CONTENTS

COVER SHEET..... 1

TABLE OF CONTENTS..... 2

LIST OF EFFECTIVE PAGES 3

1 Objectives 4

2 Limitations 6

3 Acceptance Criteria..... 6

4 Methodology 6

5 Assumptions..... 6

6. Calculation 10

7 Conclusions..... 22

8 References..... 22

9 Computer Software Specifications 22

APPENDICES

Appendix A-G – Calculation back-up and Commercial reference

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2

LIST OF EFFECTIVE PAGES

Pages	Revision
1 to 20	0
1 to 32	1
1 to 32	2

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003
--

Revision Number: 2

1 Objectives

The purpose of this note is to document the FEA confirming that the design of E906 Stations 3 & 4 Support Frame (see Figure 11) meets requirements of Allowable Strength Design (ASD) as defined by The AISC Steel Construction Manual, 13th Edition.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab	
Calculation No.: NE-EO-2011-003	Revision Number: 2

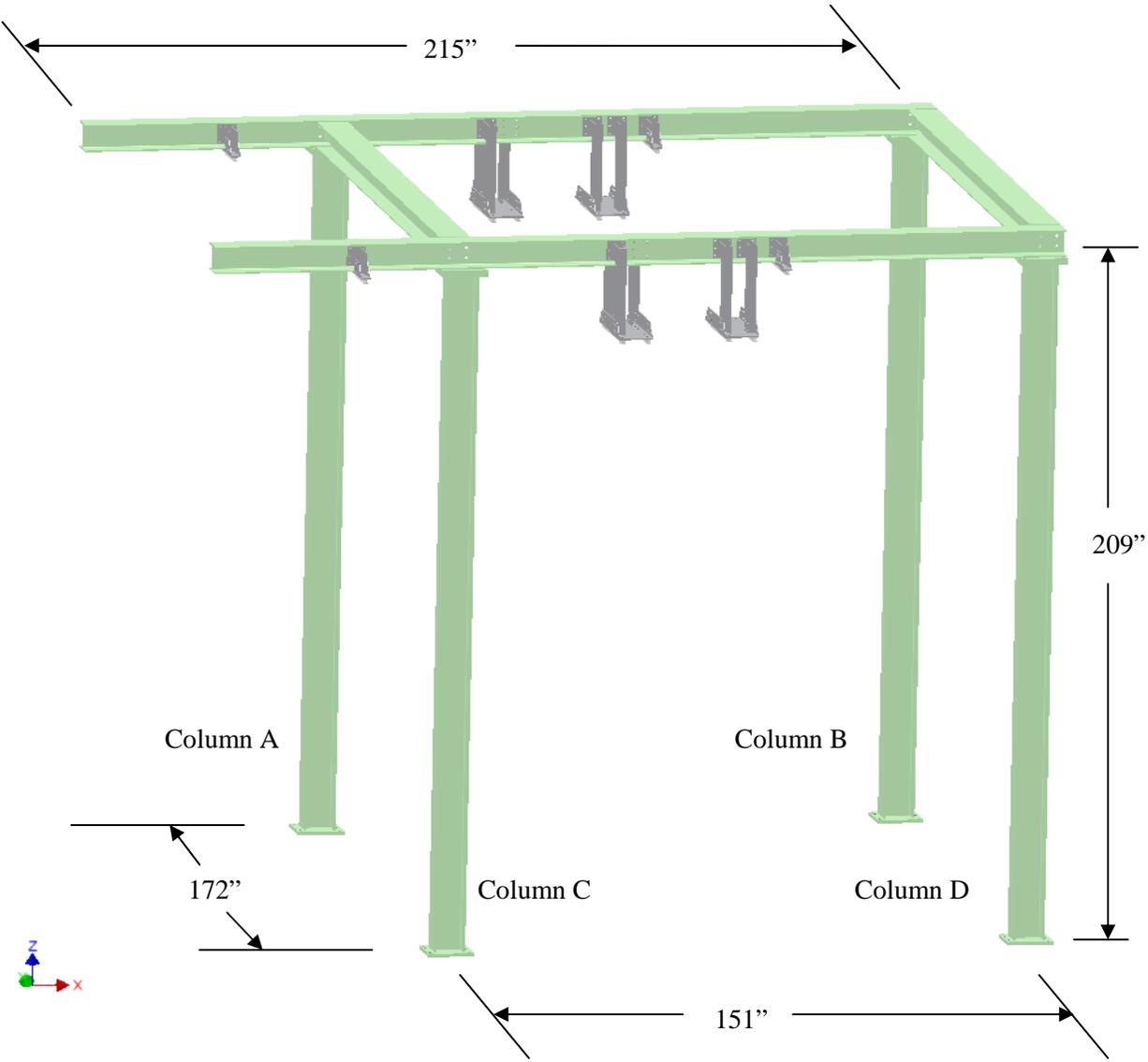


Figure 1 E906 Station 3 &4 Support Frame structural members (shown in light green) are AISC size W8x31 wide-flange I-beams. The drop connectors (shown in gray) connect the detectors to the structure.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab	
Calculation No.: NE-EO-2011-003	Revision Number: 2

2 Limitations

This analysis is limited to the Support Frame structure. The analysis is contingent upon the use meeting the assumptions specified in section 5.

3 Acceptance Criteria

The acceptance criteria are to meet the requirements of the AISC Steel Construction Manual 13th Edition, using ASD (Note that in the 13th Edition, unlike previous editions, that ASD is Allowable Strength Design instead of Allowable Stress Design, where strength is intended to mean maximum applied load). The requirements are defined in Part 16, Specifications and Codes.

4 Methodology

The methodology of calculation was based on static elastic FEA, which was verified by following the AISC Steel Construction Manual code to determine the allowable loading in the structure.

5 Assumptions

The following assumptions are made with regard to the construction of the Support Frame structure:

- The material used for construction of the structure is A36 steel with linear elastic behavior
- The A36 steel has a Young's Modulus of 29e6 psi and poisson's ratio of 0.30
- The design of the Support Frame structure is described by the file Station_3_and_4_Layout_for Kevin.stp.
- All members have rigid, moment transferring connections to one another
- All columns are fixed in all degrees of freedom at their bases

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003
--

Revision Number: 2

5.1 Support Frame applied loads

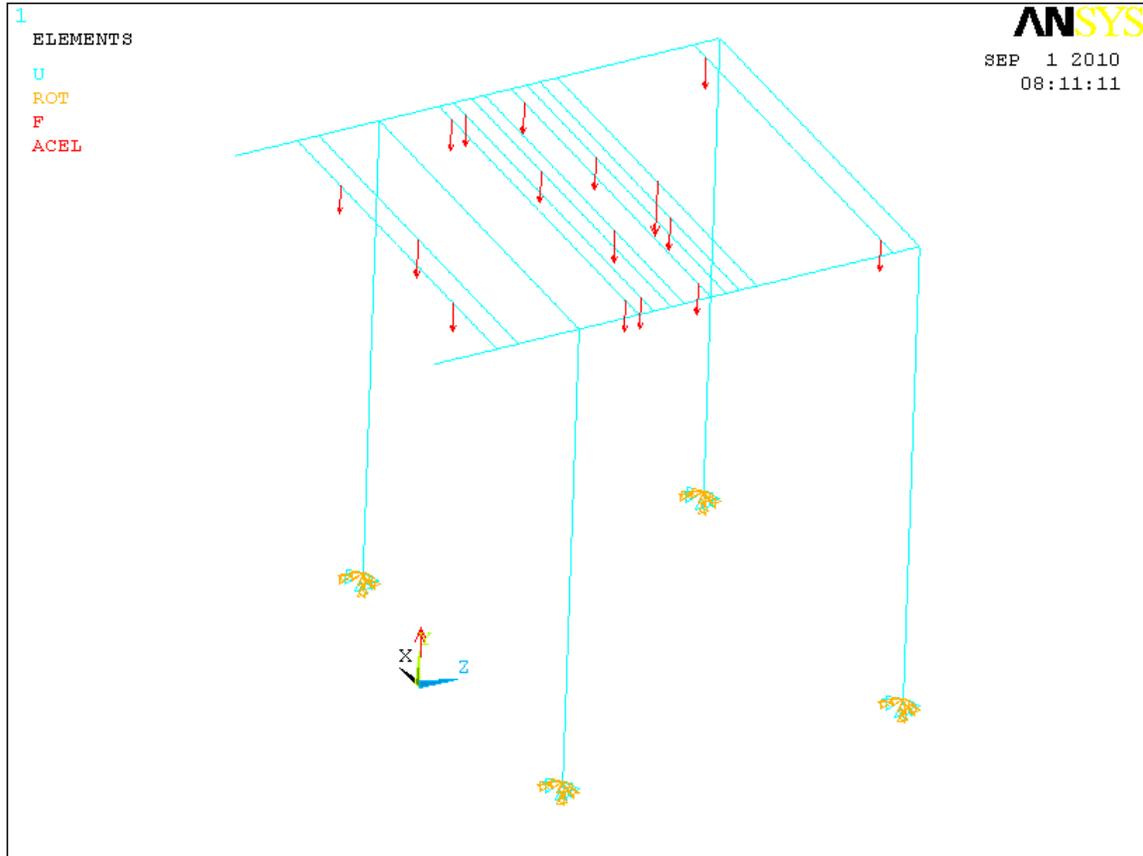
There are three load cases in this FEA:

- Load Case #1 models the detectors in place plus gravitational loading from the mass of the structural members (See Fig. 2)
- Load Case #2 models the effect of moving detectors out for service plus gravitational loading from the mass of the structural members (See Fig. 3)
- Load Case #3 has the loads from Load Case #1 plus an additional seismic load (See Fig. 4)

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2



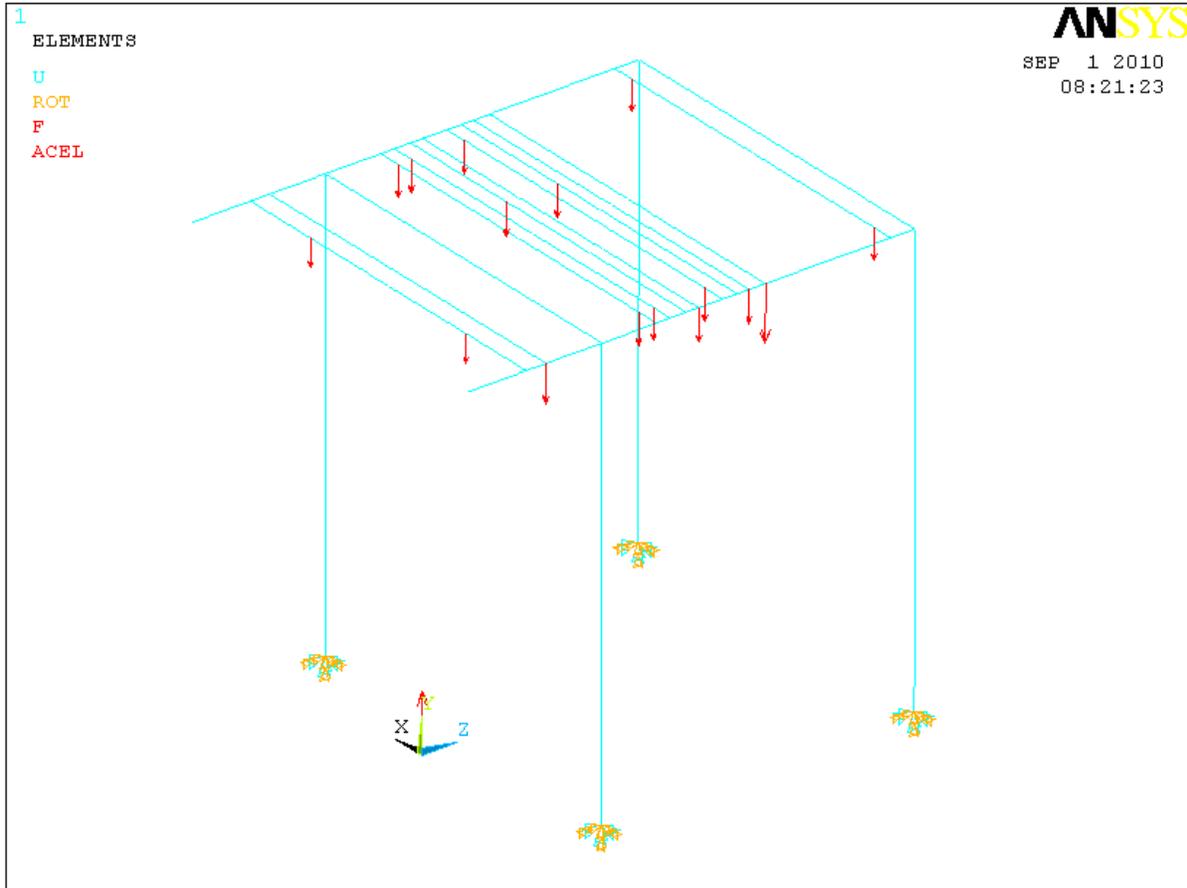
	CAD_load Xeast	CAD_load Xwest	Cross Beam No.	CAD_load_ z	Total Weight	Detector Type
Chamber 3 Lower			1	-44.403		
Chamber 3 Upper	-48.629	48.629	2	-16.773	770	fixed
Hodo 3x	-46.5	46.5	3	-7.31	540	sliding
Iron Wall	0	0	4	19.6	0	
Station 4a prop tube X	-75	75	5	46.06	870	fixed
Station 4a Prop tube Y	-75.5	75.5	6	52.68	870	fixed
Station 4Ya1 Hodo	-15	67.25	7	60.44	450	sliding
Station 4Ya2 Hodo	-67.25	15	8	66.31	450	sliding
Station 4bx Prop tubes	-75	75	9	78.06	870	fixed
Station 4BY1 Hodo	-15	67.25	10	84.88	450	sliding
Station 4BY2 Hodo	-67.25	15	11	90.75	450	sliding
Stations 4BX Hodo	-62.5	62.5	12	98.5	775	sliding
Station 4by Prop tubes	-75.5	75.5	13	159	870	fixed

Figure 2: Load Case #1, Detectors in place, Gravity load.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2



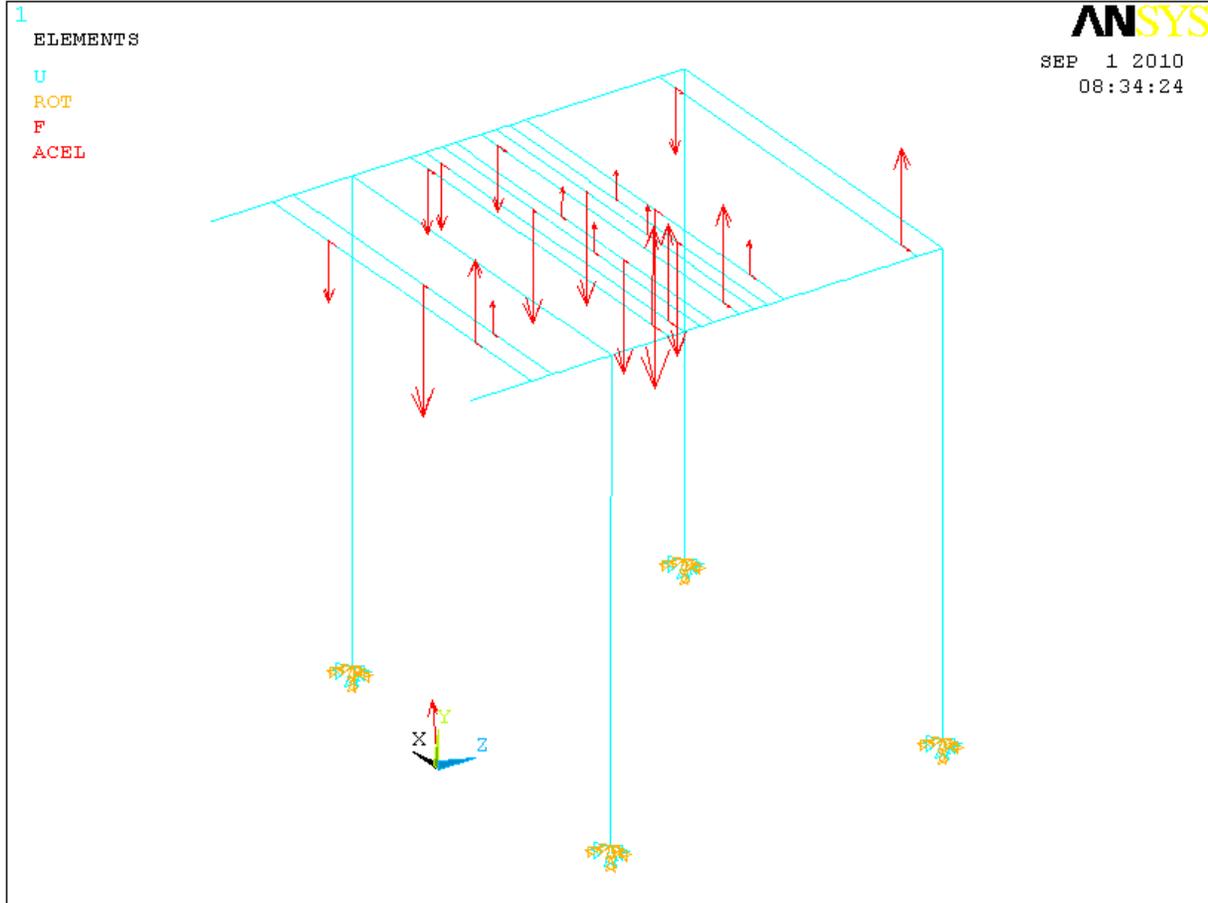
	CAD_load Xeast	CAD_load Xwest	Cross Beam No.	CAD_load_ z	Total Weight	Detector Type
Chamber 3 Lower			1	-44.403		
Chamber 3 Upper	-48.629	48.629	2	-16.773	770	fixed
Hodo 3x	-46.5	46.5	3	-7.31	540	sliding
Iron Wall	0	0	4	19.6	0	
Station 4a prop tube X	-75	75	5	46.06	870	fixed
Station 4a Prop tube Y	-75.5	75.5	6	52.68	870	fixed
Station 4Ya1 Hodo	-15	67.25	7	60.44	450	sliding
Station 4Ya2 Hodo	-67.25	15	8	66.31	450	sliding
Station 4bx Prop tubes	-75	75	9	78.06	870	fixed
Station 4BY1 Hodo	-15	67.25	10	84.88	450	sliding
Station 4BY2 Hodo	-67.25	15	11	90.75	450	sliding
Stations 4BX Hodo	-62.5	62.5	12	98.5	775	sliding
Station 4by Prop tubes	-75.5	75.5	13	159	870	fixed

Figure 3: Load Case #2, Detectors rolled out, Gravity load.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2



	CAD_load Xeast	CAD_load Xwest		CAD_load_ z	Total Weight		Seismic Loads			
Chamber 3 Lower			1	-44.403			Ly	Ry	Lx	Rx
Chamber 3 Upper	-48.629	48.629	2	-16.773	770	fixed	444	326	57.75	57.75
Hodo 3x	-46.5	46.5	3	-7.31	540	sliding	168	-708	40.5	40.5
Iron Wall	0	0	4	19.6	0					
Station 4a prop tube X	-75	75	5	46.06	870	fixed	520	350	65.25	65.25
Station 4a Prop tube Y	-75.5	75.5	6	52.68	870	fixed	519	351	65.25	65.25
Station 4Ya1 Hodo	-15	67.25	7	60.44	450	sliding	158	-608	33.75	33.75
Station 4Ya2 Hodo	-67.25	15	8	66.31	450	sliding	158	-608	33.75	33.75
Station 4bx Prop tubes	-75	75	9	78.06	870	fixed	520	350	65.25	65.25
Station 4BY1 Hodo	-15	67.25	10	84.88	450	sliding	158	-608	33.75	33.75
Station 4BY2 Hodo	-67.25	15	11	90.75	450	sliding	158	-608	33.75	33.75
Stations 4BX Hodo	-62.5	62.5	12	98.5	775	sliding	182	-957	58.125	58.125
Station 4by Prop tubes	-75.5	75.5	13	159	870	fixed	519	351	65.25	65.25

Figure 4: Load Case #3, Detectors in place, Gravity load, Seismic X load.

6. Calculation

6.1 FEA Load Case #1 Results

Load Case #1 is the standard configuration with loading applied from each detector. In Fig. 5, the bending stress combined with the direct stress is shown in psi. The maximum combined stress (2139 psi)

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

is in the W8X31 beams located at the top on either side of the beamline. The minimum stress is found in the same beams with a value of -2241 psi.

In Fig. 6, the deflection in the vertical direction is shown. The ends of the W8X31 beams on the sides deflect up by 0.016 inches. Near the midpoint of the same beams, the deflection is down by 0.044 inches.

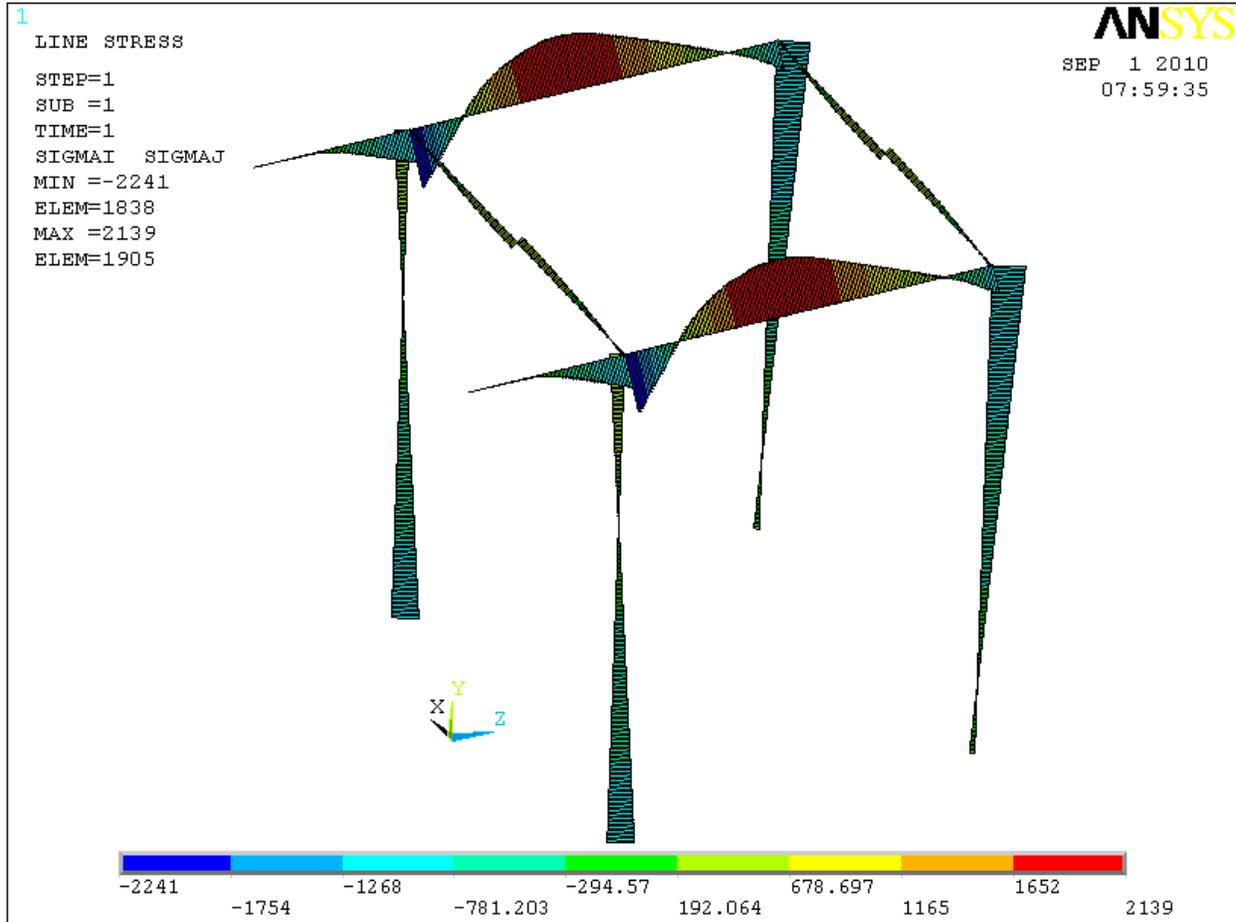


Figure 5 Bending + Direct Stress plot for Load Case #1.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

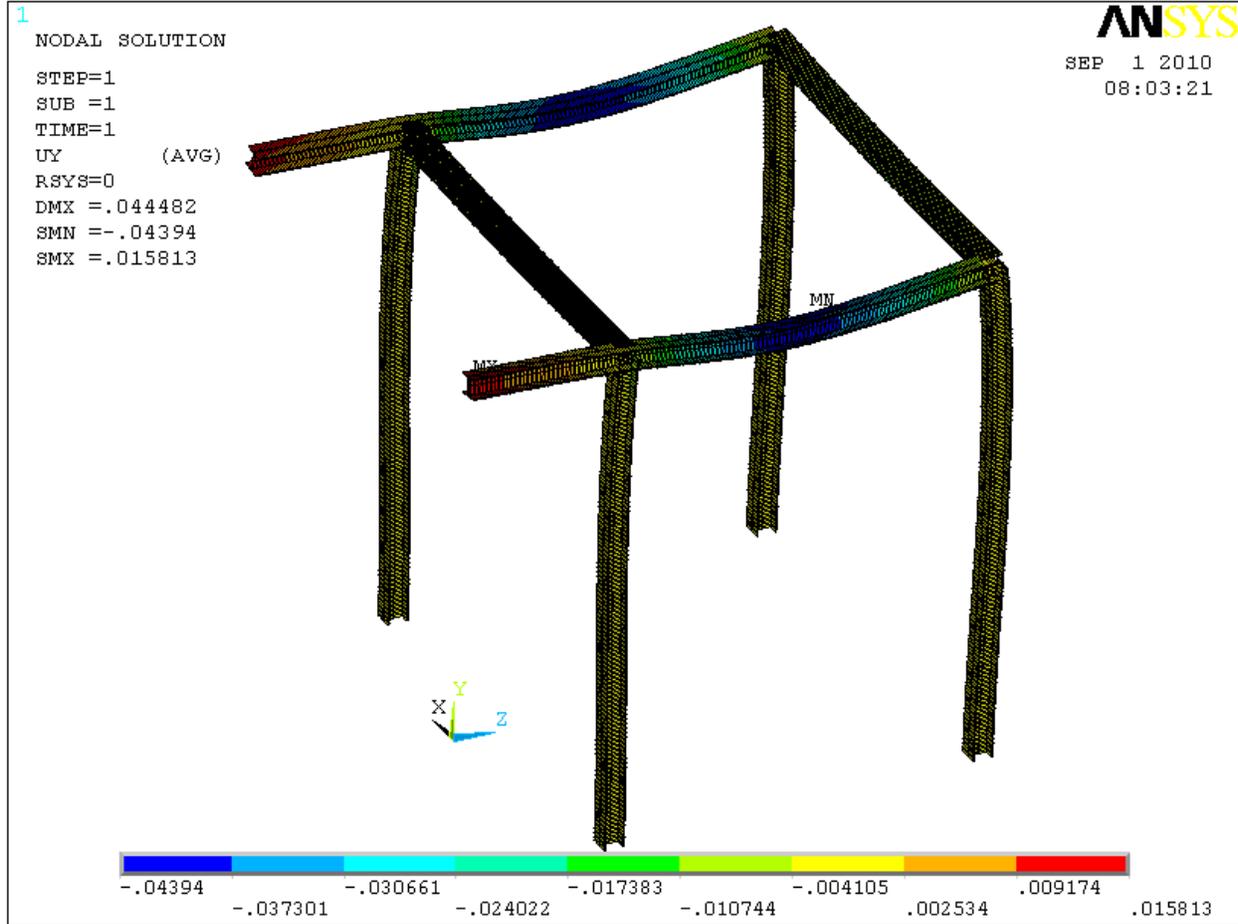


Figure 6 Y Deflection plot for Load Case #1

Table 1: Reaction at column bases, Load Case #1

COLUMN	A	B	C	D
FX	-17.218	-16.912	17.079	17.051
FY	4702.4	2495.4	4691.1	2506.7
FZ	199.33	-199.21	200.07	-200.19
MX	14344.	-12921.	14417.	-12965.
MY	0.24502E-01	0.33351E-01	0.25160E-01	0.15094E-01
MZ	1199.7	1172.4	-1184.0	-1188.1

6.2 FEA Load Case #2 Results

Load Case #2 is the configuration with loading applied from each detector, but detectors that are able to slide out for maintenance apply their loads to just one side of the structure. In Fig. 7, the bending stress combined with the direct stress is shown in psi. The maximum combined stress (2629 psi) is in the W8X31 beam located at the top on the side of the beamline where detectors are slid out for maintenance. The minimum stress is found in the same beam with a value of -2679 psi.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

In Fig. 8, the deflection in the vertical direction is shown. The end of the W8X31 beam on the maintenance side deflects up by 0.018 inches. Near the midpoint of the same beam, the deflection is down by 0.050 inches.

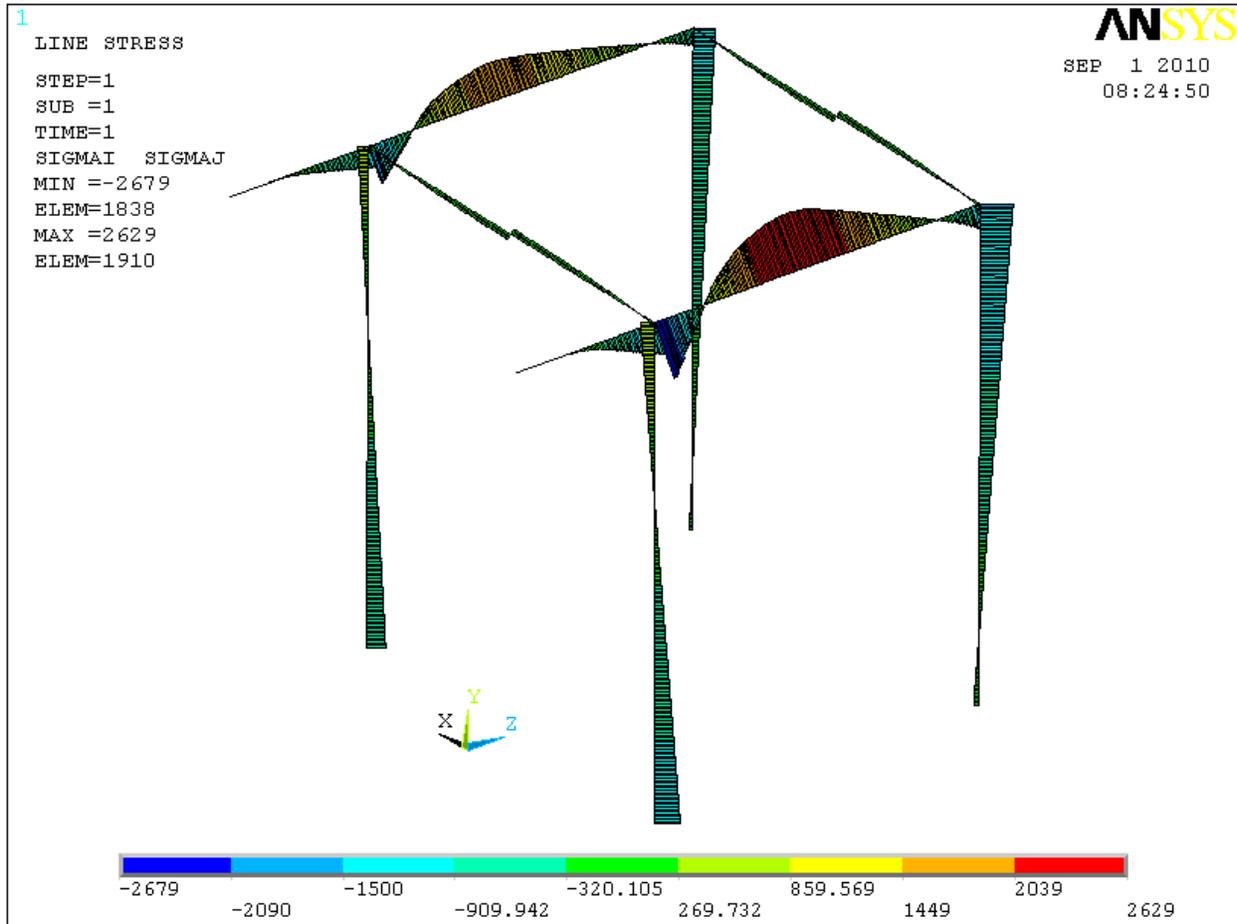


Figure 7 Bending + Direct Stress plot for Load Case #2.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

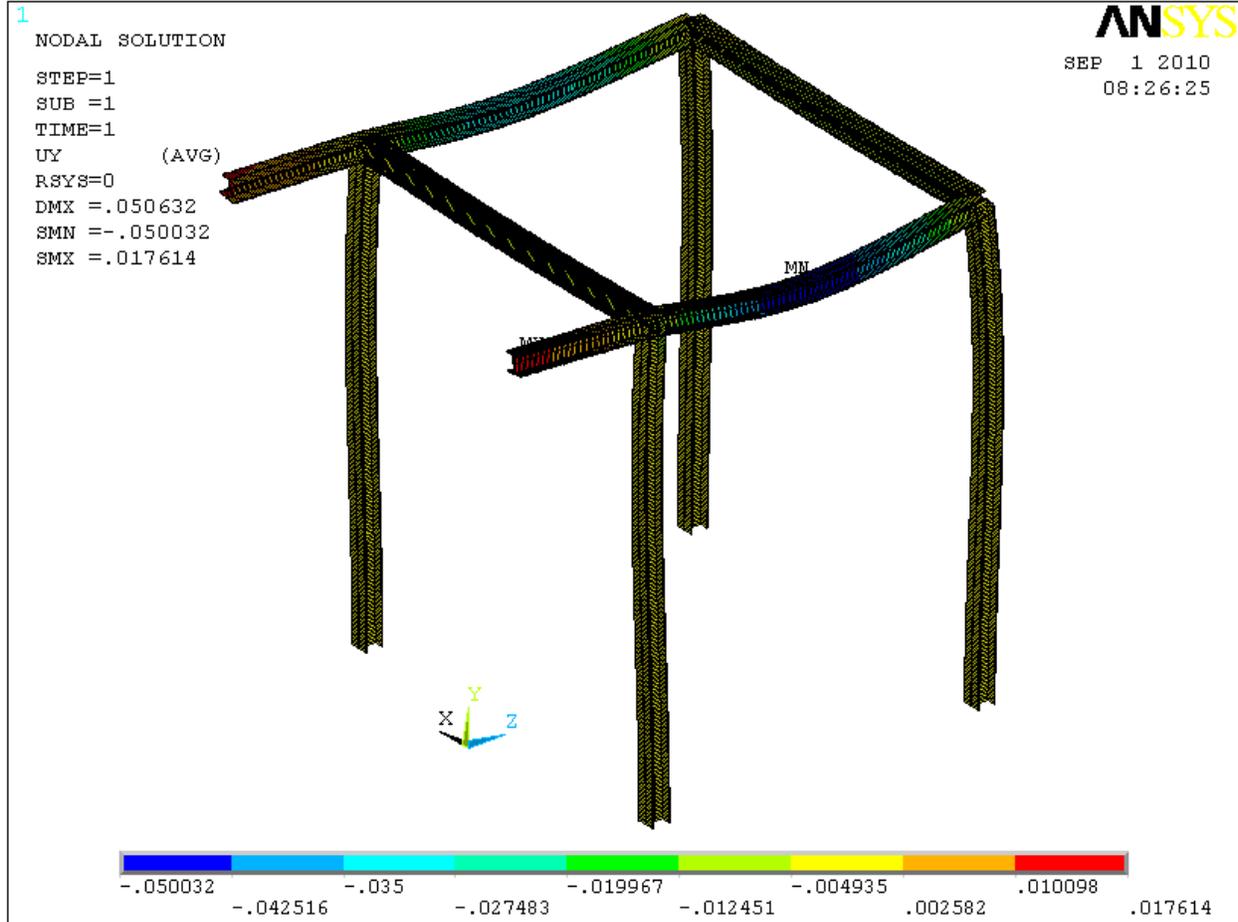


Figure 8 Y Deflection plot for Load Case #2.

Table 2: Reaction at column bases, Load Case #2

COLUMN	A	B	C	D
FX	-20.697	-16.522	16.353	20.866
FY	3986.0	2178.7	5344.1	2761.6
FZ	176.81	-172.99	256.21	-260.03
MX	11822.	-10681.	17530.	-15680.
MY	0.58606	0.58113	0.58681	0.55981
MZ	1407.1	986.26	-1019.3	-1462.2

6.3 FEA Load Case #3 Results

For a seismic event, Load Case #3 has loading applied from each detector in its normal position, but a horizontal load is added. The horizontal load is 0.15 times the load of the detector split between the two support points. (Value of 0.15g provided by Dave Pushka.) In Fig. 9, the bending stress combined with the direct stress is shown in psi. The maximum combined stress (983 psi) is in the W8X31 beam located at the front top in between the two detector support beams. The minimum stress is found in the same beam with a value of -2286 psi.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

In Fig. 10, the deflection in the vertical direction is shown. The end of the W8X31 beam on one side deflects up by 0.012 inches. Near the midpoint of the same beam, the deflection is down by 0.041 inches.

In Fig. 11, the deflection in the horizontal direction is shown. The highest magnitude deflection in X is 0.474 inches.

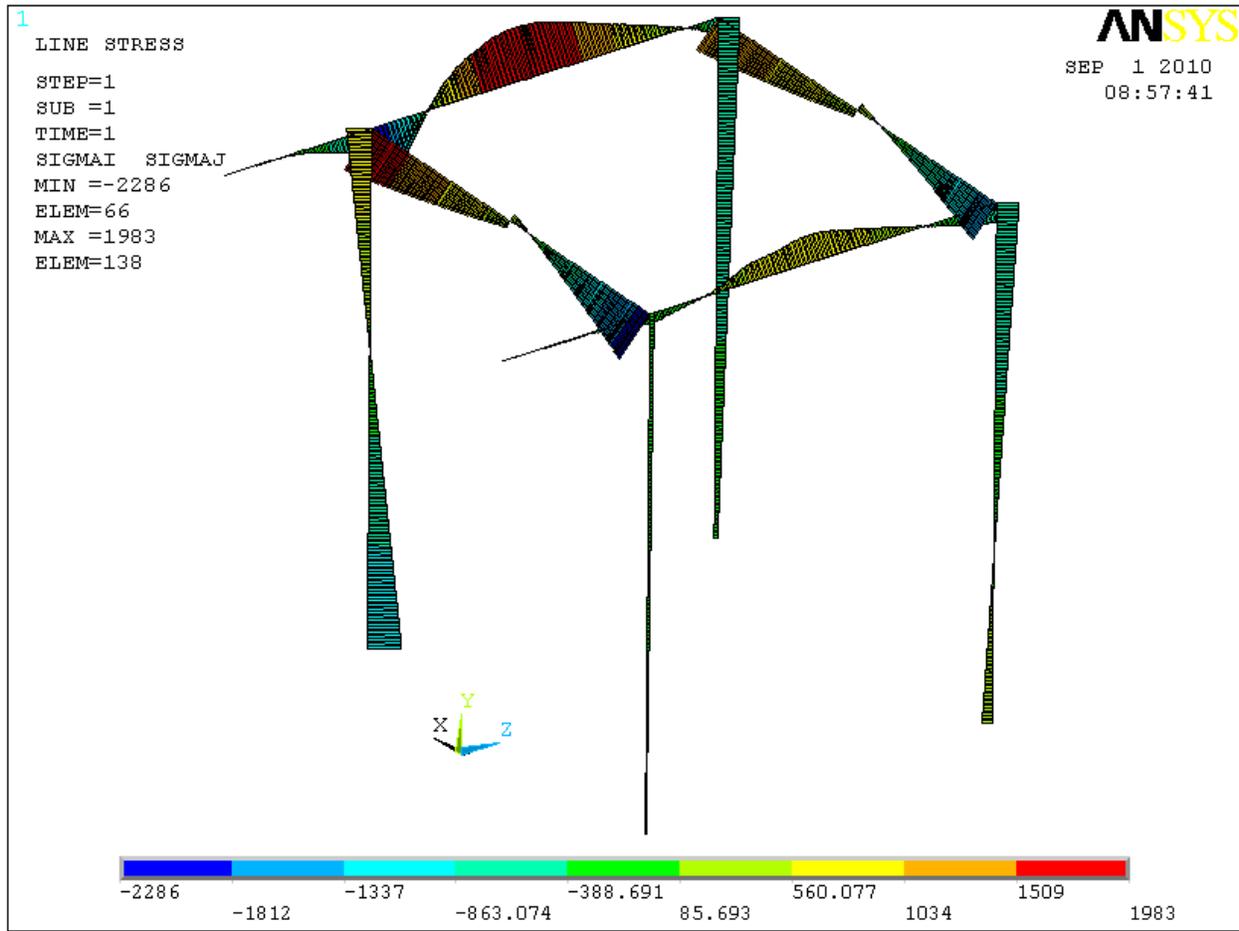


Figure 9 Bending + Direct Stress plot for Load Case #3.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

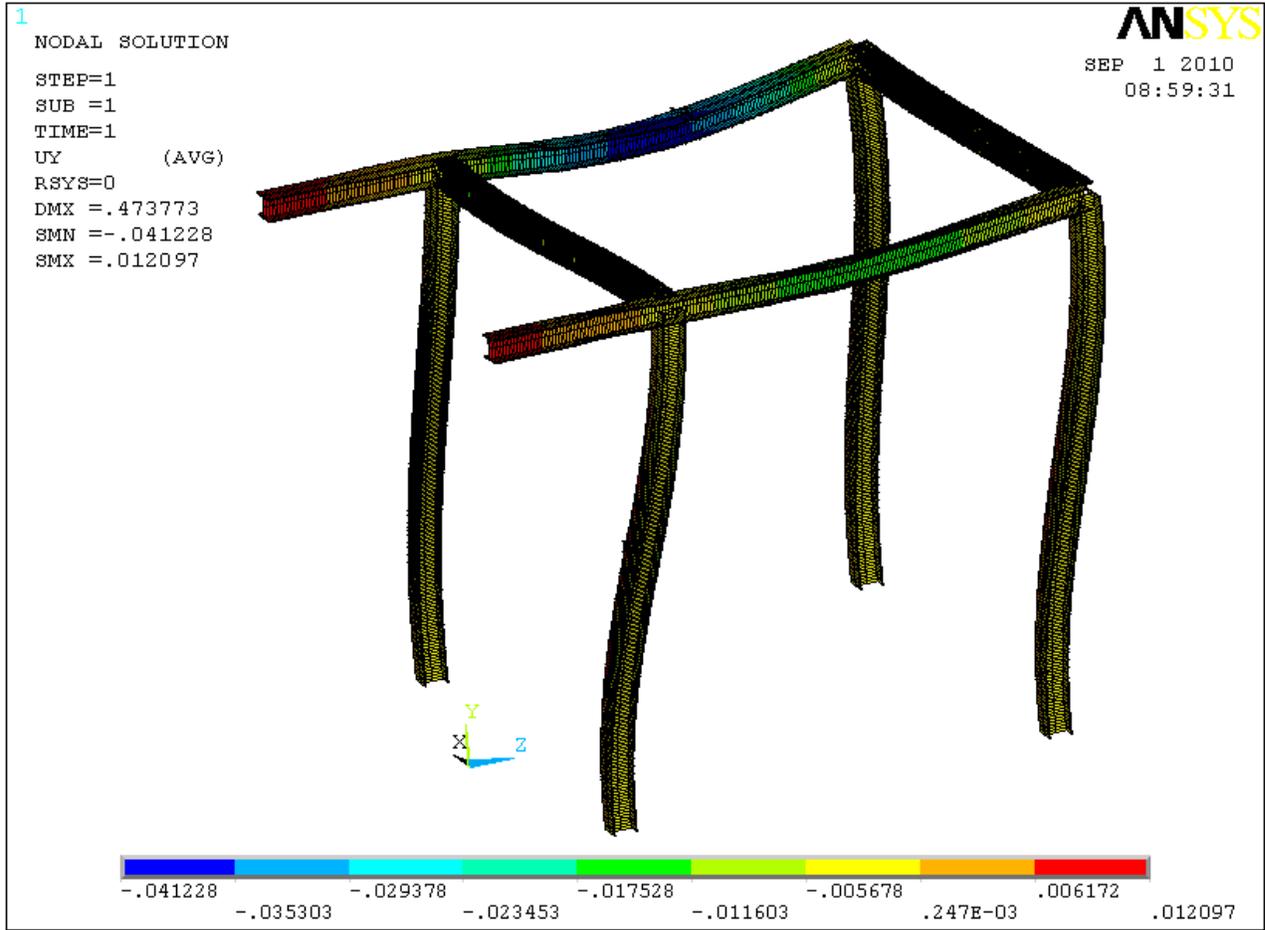


Figure 10 Vertical deflection plot for Load Case #3.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

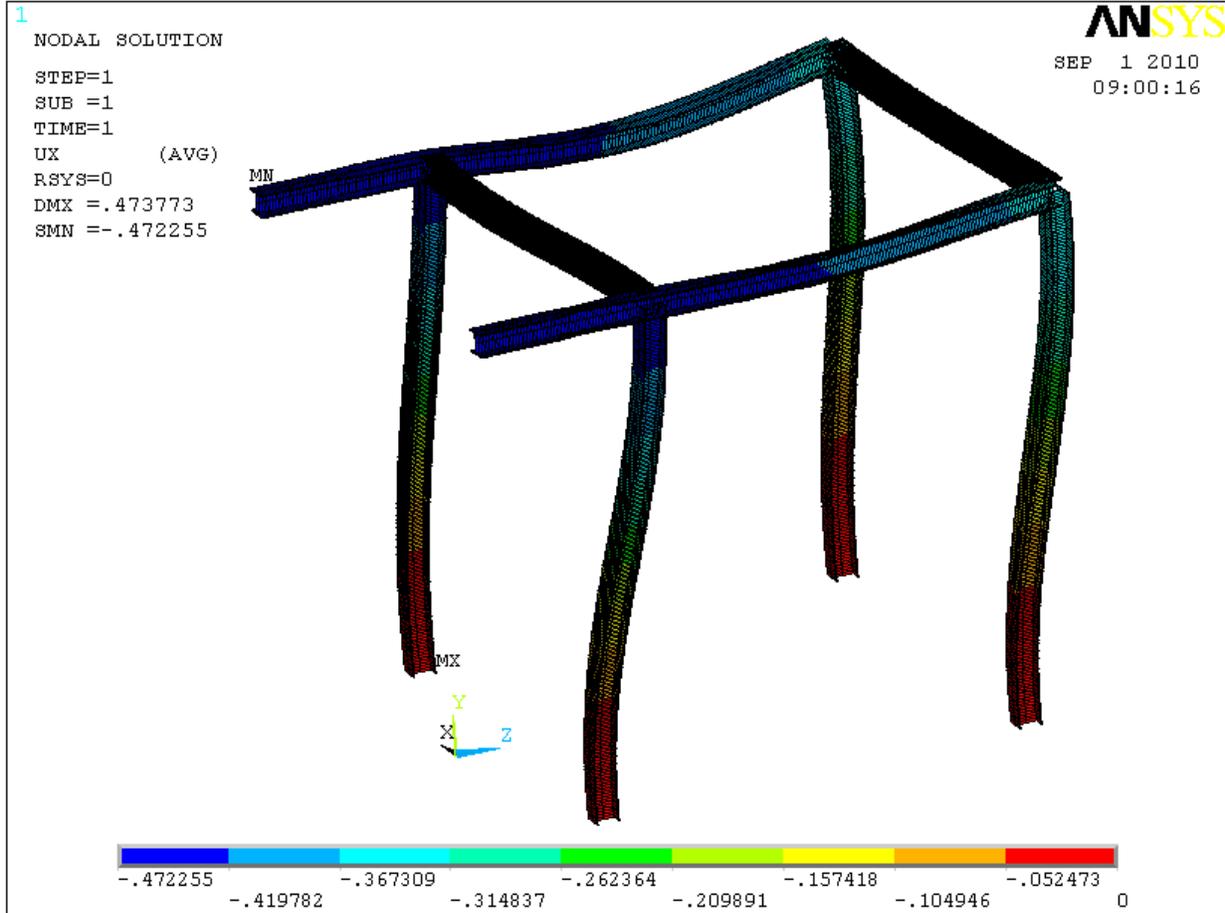


Figure 11 Horizontal deflection plot for Load Case #3.

Table 3: Reaction at column bases, Load Case #3

COLUMN	A	B	C	D
FX	578.67	467.35	612.69	500.63
FY	3682.5	1719.1	2229.4	1720.6
FZ	287.70	-94.753	-24.661	-168.29
MX	24799.	-1360.2	-5801.7	-15632.
MY	-10.328	-18.045	-10.333	-18.068
MZ	-60828.	-48669.	-63192.	-50982.

6.4 Compressive Strength of the Column

The highest compressive force (taken from reaction force data in the FEA results) on any column from all load cases is 5344 lbf in Load Case #2. According to Section E3 of the Steel Construction Manual, the nominal compressive strength for a W8X31 column is 135,000 lbf. With the ASD safety factor of 1.67, the allowable compressive strength is 80,000 lbf. Since the load of 5344 lbf is less than the allowable, the columns are strong enough to resist buckling.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab
Calculation No.: NE-EO-2011-003 Revision Number: 2

6.5 Combined flexure and compression in column

The highest combination of compressive force and bending moment is found in Load Case #3. The compressive load is 5297 lbf, and the moment is 73,773 in-lbf. Section H1 of the Steel Construction Manual gives Eqn. H1-1b, which combines the ratios of applied load to allowable load. The combination must be less than or equal to 1.0. For the case of the W8X31 column, the combination of ratios is 0.149, well below 1.0.

6.6 Connections to floor and between members

Calculations for the following values are to be found in appendices C – H. The allowable strengths for these portions of the structure are all far greater than the applied loads.

6.6.1 Base plate and anchors

The columns are welded all around to 1" thick base plates that are 12" square. The leg of the weld is 3/8". See Figure 12 below. Since the weld has greater area and greater moments of inertia than the column section, it is strong enough by inspection.

The plates are bolted to the floor with 3/4" diameter Hilti anchors. The anchors have a total shear force of 647 lbf, whereas the recommended maximum shear force is 5161 lbf. The highest tensile load in any one threaded rod is 3139 lbf, but the recommended maximum load is 4196 lbf. Checking the combined effects of tension and shear reveals that there are no problems. (See Appendix D) The allowable bearing strength for the bolt holes 32,000 lbf.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

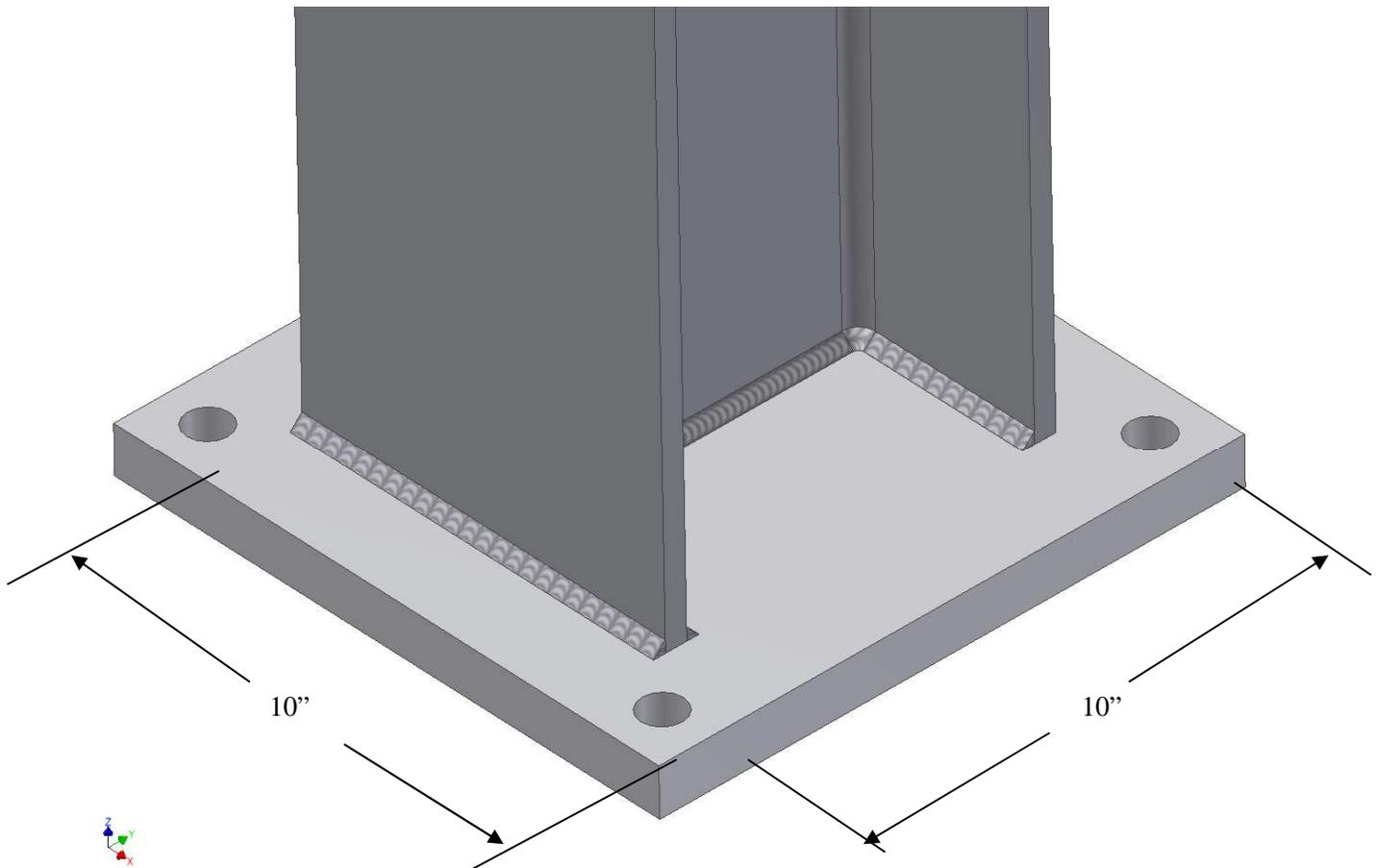


Figure 12 Base plate geometry. The column is has a 3/8" fillet weld all around. The plate is connected to the floor with 3/4" Hilti anchors.

6.6.2 Column to beam

The joint between column and beam is similar to the base plate that connects the column to the floor. See Figure 13 below. From the base plate calculations, we know that the bolted connection is strong enough. The allowable shear strength of the weld from beam to column is 76,368 lbf.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2



Figure 13 Photo of the connection between column and beam. Design is similar to that of the column base plate.

6.6.3 Beam to beam connection

The beam to beam connections are shown in Figure 14 below. Assuming the bolt diameter to be 0.5", the allowable shear load on the bolts is 18,850 lbf.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2



Figure 14 Photo of the beam to beam connection.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003
--

Revision Number: 2

7 Conclusions

- 7.1 The E906 Detector Support Frame design analyzed within this document under the assumptions presented in section 5 meets the requirements as set out in the acceptance criteria in section 3.
- 7.2 Maintenance loading and Seismic loading do not cause any of the columns to buckle.
- 7.3 Connections are strong enough to handle much higher loads than what this structure is likely to encounter.

8 References

1. AISC Steel Construction Manual 13th Edition
2. 2011 North American Product Technical Guide Volume 2: Anchor Fastening Technical Guide

9 Computer Software Specifications

ANSYS R12.1 by ANSYS, Inc.

Mathcad 14.0 M020 (14.0.2.5) by Parametric Technology Corporation

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2

APPENDIX 1
GENERAL CHECKING CRITERIA SHEET

CALCULATION CHECKLIST	Yes	No	N/A	Comments
1. Are analytical methods appropriate?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
2. Are assumptions appropriate?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
3. Is the calculation complete?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
4. Is the calculation mathematically accurate?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
5. Do calculation parameters comply with design criteria/dimensions?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
6. Were input data appropriate?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
7. Does the calculation reference or list applicable assumptions and major equation sources?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
COMPUTER CODE CHECKLIST	Yes	No	N/A	Comments
1. Was an applicable and valid computer program used?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
2. Are the input assumptions appropriate?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
3. Was the input entered correctly?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
4. Do the input results seem reasonable?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2

APPENDIX 1
GENERAL CHECKING CRITERIA SHEET

ADDITIONAL COMMENTS		
Number	Comment	Resolution
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

Appendices A-G

Calculation back-up

See following pages.

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab
Calculation No.: NE-EO-2011-003 Revision Number: 2

A. Compressive strength for flexural buckling of members without slender elements (Section E3)

This calculation evaluates the strength of the W8x31 columns in the service beam support structure.

$$b_f := 8.00\text{-in} \quad t_f := 0.435\text{-in} \quad \text{flange dimensions}$$

$$\lambda := \frac{b_f}{2 \cdot t_f} = 9.195 \quad \text{width - thickness ratio of member}$$

$$E := 29000\text{-ksi} \quad F_y := 36\text{-ksi} \quad \text{material properties of A36 steel}$$

$$\lambda_p := 0.38 \cdot \sqrt{\frac{E}{F_y}} = 10.785 \quad \text{limit for compact sections (Table B4.1)}$$

$$\lambda < \lambda_p \quad \text{therefore section is considered compact}$$

$$k := 1 \quad \text{effective length factor determined in accordance with Section C2}$$

$$L := 197\text{-in} \quad \text{laterally unbraced length of member}$$

$$r := 3.47\text{-in} \quad \text{governing radius of gyration, taken from Table 1-1}$$

$$\frac{k \cdot L}{r} = 56.772 \quad \text{column slenderness ratio}$$

$$4.71 \cdot \sqrt{\frac{E}{F_y}} = 133.681 \quad \text{when slenderness ratio is less than this value, Equation E3-2 applies}$$

$$F_e := \frac{\pi^2 \cdot E}{\left(\frac{k \cdot L}{r}\right)^2} = 88.802\text{-ksi} \quad \text{first determine elastic critical buckling stress from Equation E3-4}$$

$$F_{Cr} := \left(0.658 \frac{F_y}{F_e}\right) \cdot F_y = 30.382\text{-ksi} \quad \text{flexural buckling stress Equation E3-3}$$

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2

$$A_g := 4.43 \cdot \text{in}^2 \quad \text{gross cross sectional area of member from Table 1-1}$$

$$P_n := F_{cr} \cdot A_g = 134.591 \times 10^3 \cdot \text{lb} \cdot \text{f} \quad \text{nominal compressive strength}$$

$$\Omega_c := 1.67 \quad \text{ASD Safety Factor}$$

$$\frac{P_n}{\Omega_c} = 8.059 \times 10^4 \cdot \text{lb} \cdot \text{f} \quad \text{allowable strength of column}$$

$$P := 5344 \cdot \text{lb} \cdot \text{f} \quad \text{applied load to column from FEA Case #2 results}$$

$$P < \frac{P_n}{\Omega_c} \quad \text{therefore, column has adequate strength}$$

B. Doubly symmetric members in Flexure and Compression (Sect. H1.1):

$$I_{yc} := \frac{b_f^3 \cdot t_f}{12} = 18.56 \cdot \text{in}^4 \quad \text{moment of inertia about y-axis referred to the compression flange}$$

$$I_y := 37.1 \cdot \text{in}^4 \quad \text{from Table 1-1}$$

$$\frac{I_{yc}}{I_y} = 0.5 \quad \text{this value must be between 0.1 and 0.9 for Eqns. H1-1a and H1-1b to apply}$$

$$P_r := 5297 \cdot \text{lb} \cdot \text{f} \quad \text{required axial compressive strength from FEA Case #3 results}$$

$$P_c := \frac{P_n}{\Omega_c} = 8.059 \times 10^4 \cdot \text{lb} \cdot \text{f} \quad \text{available compressive strength from previous calculation}$$

$$\frac{P_r}{P_c} = 0.066 \quad \text{For } \frac{P_r}{P_c} < 0.2 \quad \text{Eqn H1-1b applies}$$

To compute Eqn H1-1b, required flexural strength and available flexural strength must be determined for both x-axis and y-axis from Chapter F

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

$$\lambda := \frac{b_f}{2 \cdot t_f} = 9.195 \quad \text{width - thickness ratio}$$

$\lambda < \lambda_p$ therefore section is compact according to Table B4.1

The nominal flexural strength shall be the lower value according to the limit states of yielding and lateral-torsional buckling.

$L := 197 \cdot \text{in}$ length of beam

$M_{IX} := 73773 \cdot \text{in} \cdot \text{lbf} = 6.148 \times 10^3 \cdot \text{ft} \cdot \text{lbf}$ applied moment on column from FEA case #3 results

Section F2.1 Yielding:

$Z_x := 30.4 \cdot \text{in}^3$ plastic section modulus about x-axis, from Table 1-1

$F_y = 36 \cdot \text{ksi}$ minimum yield stress of A36 steel

$M_p := F_y \cdot Z_x = 9.12 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$ plastic moment

$M_n := M_p$ nominal flexural strength

$\Omega_b := 1.67$ ASD Safety Factor

$M_a := \frac{M_n}{\Omega_b} = 5.461 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$

Section F2.2 Lateral-torsional buckling (LTB):

$L_b := L = 197 \cdot \text{in}$ unbraced length of beam

$r = 3.47 \cdot \text{in}$ radius of gyration in x-axis, from Table 1-1

$L_p := 1.76 \cdot r \cdot \sqrt{\frac{E}{F_y}} = 173.336 \cdot \text{in}$ lower limit for LTB

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

The next row of parameters are needed to determine L_r , and are taken from Table 1-1

$$S_x := 27.5 \cdot \text{in}^3 \quad r_{ts} := 2.26 \cdot \text{in} \quad J := 0.536 \cdot \text{in}^4 \quad h_o := 7.57 \cdot \text{in}$$

$$c := 1 \quad \text{from (F2-8a)}$$

$$L_r := 1.95 \cdot r_{ts} \cdot \frac{E}{0.7 \cdot F_y} \cdot \sqrt{\frac{J \cdot c}{S_x \cdot h_o}} \cdot \sqrt{1 + \sqrt{1 + 6.76 \cdot \left(\frac{0.7 \cdot F_y}{E} \cdot \frac{S_x \cdot h_o}{J \cdot c} \right)}} = 431.495 \cdot \text{in}$$

$L_p < L_b < L_r$ therefore nominal flexural strength for LTB determined by Equation F2-2

$$C_b := 1 \quad \text{permitted to be conservatively taken as 1.0 for all cases}$$

$$M_n := C_b \left[M_p - (M_p - 0.7 \cdot F_y \cdot S_x) \cdot \left(\frac{L - L_p}{L_r - L_p} \right) \right] = 8.813 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$$

$$M_a := \frac{M_n}{\Omega_b} = 5.277 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$$

$$M_{cx} := M_a = 5.277 \times 10^4 \cdot \text{ft} \cdot \text{lbf} \quad \text{the lesser of the two values for } M_a$$

Section F6.1 Yielding in members bent about minor axis

$$Z_y := 14.1 \cdot \text{in}^3 \quad S_y := 9.27 \cdot \text{in}^3 \quad \text{parameters from Table 1-1}$$

$$M_p := F_y \cdot Z_y = 4.23 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$$

$$\text{which must be less than } 1.6 \cdot F_y \cdot S_y = 4.45 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$$

$$M_n := M_p \quad M_{cy} := \frac{M_n}{\Omega_c} = 2.533 \times 10^4 \cdot \text{ft} \cdot \text{lbf}$$

$$M_{ry} := 17 \cdot \text{in} \cdot \text{lbf} = 1.417 \cdot \text{ft} \cdot \text{lbf}$$

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: NE-EO-2011-003

Revision Number: 2

So, now Eqn H1-1b can be checked

$$\frac{P_r}{2 \cdot P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) = 0.149 \quad \text{which must be less than 1.0}$$

C. Welded connection of column to base plate:

$$\begin{aligned} F_x &:= 579 \cdot \text{lbf} & F_y &:= 3683 \cdot \text{lbf} & F_z &:= 288 \cdot \text{lbf} & \text{reactions at base of} \\ & & & & & & \text{column} \\ M_x &:= 24800 \cdot \text{in} \cdot \text{lbf} & M_y &:= -10 \cdot \text{in} \cdot \text{lbf} & M_z &:= 60830 \cdot \text{in} \cdot \text{lbf} \end{aligned}$$

$$\text{leg} := 0.375 \cdot \text{in} \quad \text{throat} := \frac{\text{leg}}{\sqrt{2}} = 0.265 \cdot \text{in} \quad \text{size of weld and throat}$$

total length of weld:

$$\text{length}_{\text{weld}} := 2 \cdot 7.995 \cdot \text{in} + 2 \cdot (7.995 \cdot \text{in} - 0.435 \cdot \text{in}) + 2 \cdot (8 \cdot \text{in} - 2 \cdot 0.435 \cdot \text{in}) = 45.37 \cdot \text{in}$$

$$\text{area}_{\text{weld}} := \text{length}_{\text{weld}} \cdot \text{throat} = 12.031 \cdot \text{in}^2$$

Weld has greater area and moment of inertia than the column

D. Allowable combined tension & shear on bolts for the base plate (Hilti Tech. Guide):

Determine shear force:

$$V_d := \sqrt{F_x^2 + F_z^2} = 646.672 \cdot \text{lbf} \quad \text{Sum of shear forces}$$

Determine maximum tensile force on bolts for the base plate:

$$n := 1 \quad \text{number of bolts} \quad d := 0.75 \cdot \text{in} \quad \text{nominal bolt diameter}$$

$$A_b := n \cdot \left(\frac{\pi}{4} \cdot d^2 \right) = 0.442 \cdot \text{in}^2 \quad \text{area of bolts}$$

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab

Calculation No.: **NE-EO-2011-003**

Revision Number: 2

$$I_{xx} := 60.25 \cdot \text{in}^4 \quad I_{yy} := I_{xx} \quad \text{moments of inertia for bolt pattern}$$

$$c := 5 \cdot \text{in} \quad \text{distance of bolt from neutral axis}$$

Stress in bolt from X-moment and Z-moment:

$$\sigma_{x_x} := \frac{M_x \cdot c}{I_{xx}} = 2.058 \times 10^3 \cdot \text{psi} \quad \sigma_{z_z} := \frac{M_z \cdot c}{I_{yy}} = 5.048 \times 10^3 \cdot \text{psi}$$

$$\sigma := \sigma_{x_x} + \sigma_{z_z} = 7.106 \times 10^3 \cdot \text{psi}$$

$$N_d := \sigma \cdot A_b = 3.139 \times 10^3 \cdot \text{lbf} \quad \text{equivalent tensile force on bolt:}$$

Hilti design requirements:

$$N_{\text{allow}} := 4065 \cdot \text{lbf} \quad \text{allowable tensile force (Section 3.3.9, Table 2 of Hilti Tech Guide)}$$

$$V_{\text{allow}} := 5000 \cdot \text{lbf} \quad \text{allowable shear force (Section 3.3.9, Table 2 of Hilti Tech Guide)}$$

$$f_A := 0.88 \quad \text{load adjustment factor for anchor spacing}$$

$$f_{\text{seismic}} := 1.333 \quad \text{load adjustment factor for seismic loading}$$

$$N_{\text{rec}} := N_{\text{allow}} \cdot f_A \cdot f_A \cdot f_{\text{seismic}} = 4.196 \times 10^3 \cdot \text{lbf} \quad \text{Recommended tensile load}$$

$$V_{\text{rec}} := V_{\text{allow}} \cdot f_A \cdot f_A \cdot f_{\text{seismic}} = 5.161 \times 10^3 \cdot \text{lbf} \quad \text{Recommended shear load}$$

$$\left(\frac{V_d}{V_{\text{rec}}} \right)^{\frac{5}{3}} + \left(\frac{N_d}{N_{\text{rec}}} \right)^{\frac{5}{3}} = 0.648 \quad \text{This result must less than or equal to 1}$$

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab
Calculation No.: NE-EO-2011-003 Revision Number: 2

E. Bearing strength at base plate bolt holes (Section J3.10):

$$F_u := 58 \cdot \text{ksi} \quad \text{minimum tensile strength of the material}$$

$$L_c := \frac{9}{16} \cdot \text{in} \quad \text{clear distance from edge of hole to edge of material}$$

$$t := 1 \cdot \text{in} \quad \text{thickness of material}$$

$$R_n := 1.0 \cdot L_c \cdot t \cdot F_u = 32.625 \times 10^3 \cdot \text{lbf} \quad \text{nominal bearing strength, Equation (J3-6c)}$$

$$\Omega := 2.00 \quad \text{ASD safety factor}$$

$$R_a := \frac{R_n}{\Omega} = 16.312 \times 10^3 \cdot \text{lbf} \quad \text{allowable bearing strength}$$

F. Weld shear strength in weld between beam and column:

(From photo and measurements, appears to be 3/8" fillet, 8" in length, both sides)

$$\text{throat} := \frac{0.375 \cdot \text{in}}{\sqrt{2}} = 0.265 \cdot \text{in} \quad \text{throat of 3/8" fillet weld}$$

$$A_w := (\text{throat} \cdot 8 \cdot \text{in}) \cdot 2 = 4.243 \cdot \text{in}^2 \quad \text{area of weld}$$

$$F_{EXX} := 60 \cdot \text{ksi} \quad \text{Ultimate tensile strength of filler metal}$$

$$F_w := 0.60 \cdot F_{EXX} = 36.000 \times 10^3 \cdot \text{psi} \quad \text{Nominal tensile strength of filler metal}$$

$$R_n := F_w \cdot A_w = 152.735 \times 10^3 \cdot \text{lbf} \quad \text{Nominal strength of weld}$$

$$\Omega := 2.00 \quad \text{ASD Safety Factor}$$

$$R_a := \frac{R_n}{\Omega} = 76.368 \times 10^3 \cdot \text{lbf} \quad \text{Allowable shear strength of fillet weld}$$

Title: Finite Element Analysis of E906 Station 3 & 4 Detector Support Structure at Fermilab
Calculation No.: NE-EO-2011-003 Revision Number: 2

G. Allowable shear on bolts (Section J3.6) for the beam to beam connection:

$$F_{nv} := 48 \cdot \text{ksi} \quad \text{nominal shear stress from Table J3.2}$$

$$n := 4 \quad \text{number of bolts} \quad d := 0.5 \cdot \text{in} \quad \text{nominal bolt diameter}$$

$$A_b := n \cdot \left(\frac{\pi}{4} \cdot d^2 \right) = 0.785 \cdot \text{in}^2 \quad \text{area of bolts}$$

$$R_n := F_{nv} \cdot A_b = 37.699 \times 10^3 \cdot \text{lb} \quad \text{nominal shear strength of bolted connection (J3-1)}$$

$$\Omega := 2.00 \quad \text{ASD safety factor}$$

$$R_a := \frac{R_n}{\Omega} = 18.85 \times 10^3 \cdot \text{lb} \quad \text{allowable shear strength}$$