ARRAY TECHNOLOGIES

Summary Of DuraTrack® HZ Solar Tracker

DTHZ v3 CHSM66M-DG-F-BH655-56 Projects for Sea Oak Capital
Madison, Document # 17897-902
Madison, CT
ASCE_7-16 115 mph-C Wind Load, 30 psf Snow Load

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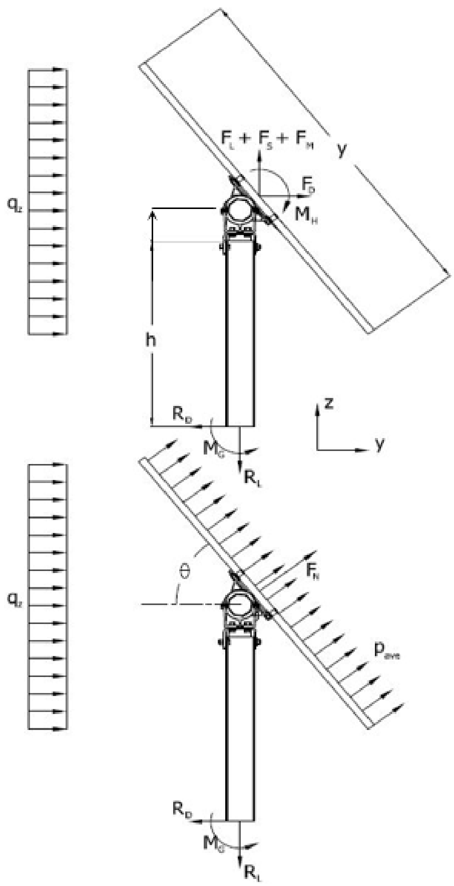
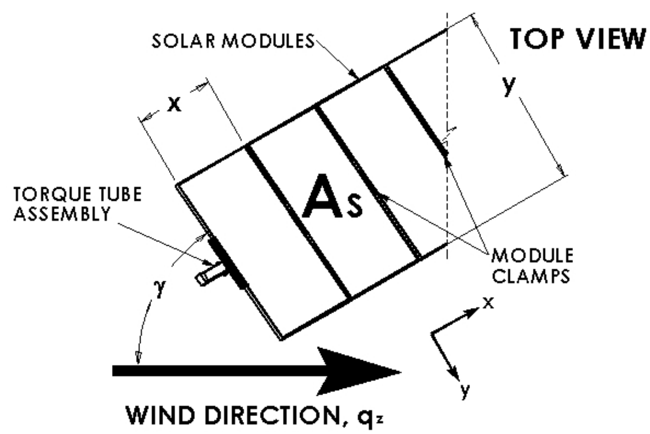
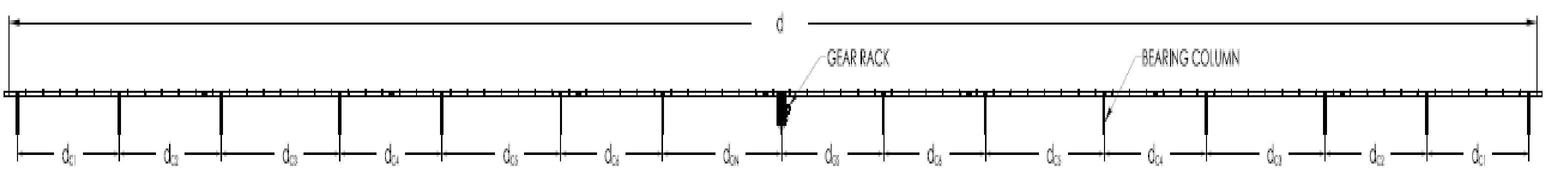


General Tracker Dimensions:	
d, Tracker Length (module to module)	242.0'
x, Module Width	51.30” = 4.27’
y, Module Length	93.86" = 7.82’
X, Module Assembly Width	51.87” = 4.32’
Y, Module Assembly Length	93.86" = 7.82’
n, Total Number of Modules	56
h, Max. Tracker Height	90” =7.50’
Max. open area	4.00 × 7.82’ = 31.28’; GCR=0.50



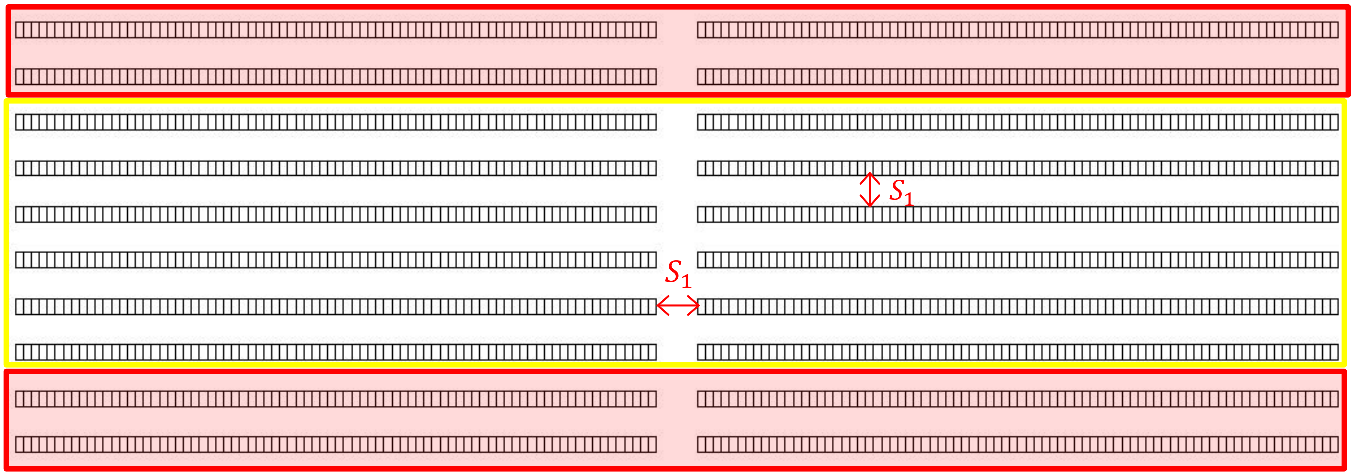


Other Symbols	
A$_S$, Module Surface Tributary Area for Column	**dc or dg,** Column Spacing
M$_H$, Hinge Moment due to wind loading	**F$_D$,** Drag Force due to wind loading
M$_G$, Total Ground Moment Reaction	**F$_L$,** Lift Force due to wind loading
R$_D$, Ground Drag Reaction	**F$_S$,** Lift Force due to snow loading
R$_L$, Ground Lift Reaction	**F$_M$,** Force due to module weight
θ, Tracker Angle from y-axis	**q$_z$,** Dynamic Velocity Pressure of wind
	γ, Yaw Angle of Wind from the y-axis

Note: The diagram is for demonstrational purposes only. For actual individual column spacing dimensions, refer to the assembly drawing package, document # 17897-901.

Column Definition and Spacing

The site is comprised of two row types, exterior and interior, to create an optimized structural design for the site; the wind tunnel report provided by RWDI for Array Technologies is used as the basis for the row optimization.



$S_1 \leq 4.00\ x\ Row\ Width$

= Exterior Columns

= Interior Columns

It is assumed that each column absorbs half of the load of the adjacent spans. Exterior rows are defined as the first two rows in any portion of the field where the max open area of 31.28' is exceeded in any direction.

Column Spans		Interior Row		Exterior Row	
Dimensions in Inches		North of GR	South of GR	North of GR	South of GR
Bearing Span 1	d_{c1}	201	201	201	201
Bearing Span 2	d_{c2}	207	207	207	207
Bearing Span 3	d_{c3}	207	207	207	207
Bearing Span 4	d_{c4}	259	259	207	207
Bearing Span 5	d_{c5}	259	259	207	207
Bearing Span 6	d_{c6}	NA	NA	207	207
GR North Span	d_{gn}	292	NA	188	NA
GR South Span	d_{gs}	NA	292	NA	188

Note: GR is abbreviated for gear rack.

Design Loads

Dead

Tube dead load (f_t): 5.25 lb/ft
Module dead load (f_{mo}): 83.78 lb
Clamp dead load (f_c): 9.15 lb
Width of one module assembly (w_{ma}): 4.32'
Row Width (y): 7.82'

The dead load applied to the tube can be approximated as a pressure:

$$f_m = \left(f_t + \frac{f_{mo} + f_c}{w_{ma}}\right)\left(\frac{1}{y}\right) = \left(5.25\ \text{lb/ft} + \frac{(83.78 + 9.15)\text{lb}}{4.32'}\right)\left(\frac{1}{7.82'}\right) = 3.42\ \text{PSF}$$

Wind

The wind load is a 115 mph 3 second gust, exposure C, evaluated using a combination of the ASCE code and the RWDI wind loading testing done on the DuraTrack HZ system. All maximums were found at $\gamma = 0^{\circ}$. To properly determine design forces, a dynamic/velocity pressure, q_z, was determined to be:

$$qz = 0.00256 K_z K_{zt} K_d V^2 K_e = 0.00256(0.85)(1.00)(0.85)(115)^2(1.00) = 24.46\ \text{PSF}$$

The design wind load and moment are determined using the following equations, similar to those found in ASCE 7. Diagrams showing how these loads are applied can be seen on page 1. C_D, C_L, and C_M refer to the coefficients of drag, lift, and moment respectively. These coefficients were experimentally determined from RWDI wind loading tests. A_S refers to the applicable surface area of the portion of the tracker being analyzed and G refers to the gust effect factor,

$$F_D = q_z G C_D A_S, \quad F_L = q_z G C_L A_S, \quad M_H = q_z G C_M A_S y$$

Snow load $p_g = 30\ psf$

If p_g is less than 20psf $\Longrightarrow p_f$ will be the max. of $0.7 C_e C_t C_s p_g I\ or\ p_g I$
If p_g is more than 20psf $\Longrightarrow p_f$ will be the max. of $0.7 C_e C_t C_s p_g I\ or\ 20 \times I$

For tilt angles less than 15 degrees:
$For\ P_g \leq 20psf\ \ p_f = I \times p_g \times \cos\emptyset = 0.80 \times 30\text{psf} \times \cos\emptyset = 24.00\text{psf} \times \cos\emptyset$
$For\ P_g > 20psf\ p_f = I \times 20 \times \cos\emptyset = 0.80 \times 20\text{psf} \times \cos\emptyset = 16.00\text{psf} \times \cos\emptyset$
$p_f = 0.7 C_e C_t p_g I = (0.7)(0.90)(1.2)(30\text{psf})(0.80)\cos\emptyset = 18.14\text{psf} \times \cos\emptyset$

For tilt angles greater than or equal to 15 degrees:

$$p_f = 0.7 C_e C_t C_s p_g I = (0.7)(0.90)(1.2)(C_s)(30\text{psf})(0.80)\cos\emptyset = 18.14\text{psf} \times C_s \times \cos\emptyset$$

Tracker Component Analysis

(1) Bushing Housing:

Exterior Row Analysis:

The bushing housing will resist the normal load as well as an induced torsion from the locking mechanisms. The maximum load this system will need to resist will happen when the tracker is in the 52 degree position. The loads below are for a single column.

$\bar{d}_b$ = 162"

$A'_S = \bar{d}_b y = (162/12)(93.86''/12) = 105.59\ \text{ft}^2$

For the drag force F_D, $GC_D = 1.207\times 1.03 = 1.24$:
$V_U = F_D = q_z GC_D A_S = (24.46\ \text{PSF})(1.24)(105.59\ \text{ft}^2) = 3.20\ \text{k}$

For the lift force F_L, $GC_L = 0.983\times 1.03 = 1.01$:
$P_U = F_L = q_z GC_L A_S = (24.46\ \text{PSF})(1.01)(105.59\ \text{ft}^2) = 2.61\ \text{k}$

For the torque, $T_M, GC_M = 0.189 \times 1.03 = 0.19$
$T_U = T_M = q_z GC_M A_S L = (24.46\ \text{PSF})(\ 0.19)(105.59\ \text{ft}^2)(7.82') = 3.84\ \text{k-ft}$

The controlling aspect of the bushing housing and bracket assembly are, torsion on the bearing stop, housing reaction, and slip of the connection of bracket to the I-beam in terms of uplift. Following are the checks with applied load vs capacities:

1. Torque Check:

Check that the ultimate bearing torque load does not exceed the allowable torque load of bearing stop.

The Ultimate Bearing Torque Load = 3.84 k-ft ≤ 4.3 k-ft

2. Housing Reaction Force Check:

Check that when the ultimate input loads are resolved to the reaction force in the bearing housing bolt location, this resolved force does not exceed the capacity.

$$\left[\frac{1}{2}(2.61 kips) + \frac{3.84\ k-ft}{0.2567\ ft} + \frac{3.20\ kips \times 5.125''}{3.08''}\right] \times 1.00 = 21.59 \leq 24.4\ \text{Kips}$$

3. Slip Plane Force Check:

Check that the resolved service load at the bracket to pile slip plane does not exceed the allowable slip resistance.

$$\left[\frac{1}{2}(2.61 kips) + \frac{3.84\ k - ft}{0.5\ ft} + \frac{3.20\ kips \times 8.2"}{6"}\right] \times 0.60 = 8.02 \leq 13.289 \text{ kips}$$

4.3 k-ft is the allowable torque capacity of bearing stop, 24.4 kips is the allowable reaction force of bearing, and 13.289 kips is the allowable slip resistance of 3/4" diameter bolt connecting bracket and I beam, refer to the bushing housing product calculation in the appendix for a detailed analysis.

Interior Row Analysis:

The bushing housing will resist the normal load as well as an induced torsion from the locking mechanisms. The maximum load this system will need to resist will happen when the tracker is in the 52 degree position. The loads below are for a single column.

$\bar{d}_b$ = 162"

$A_S' = \bar{d}_b y = (162/12)(93.86"/12) = 105.59 \text{ ft}^2$

For the drag force F_D, $GC_D = 1.070 \times 1.03 = 1.10$:
$V_U = F_D = q_z GC_D A_S = (24.46 \text{ PSF})(1.10)(105.59 \text{ ft}^2) = 2.84 \text{ k}$

For the lift force F_L, $GC_L = 0.876 \times 1.03 = 0.90$:
$P_U = F_L = q_z GC_L A_S = (24.46 \text{ PSF})(0.90)(105.59 \text{ ft}^2) = 2.32 \text{ k}$

For the torque, T_M, $GC_M = 0.176 \times 1.03 = 0.18$
$T_U = T_M = q_z GC_M A_S L = (24.46 \text{ PSF})(0.18)(105.59 \text{ ft}^2)(7.82') = 3.64 \text{ k-ft}$

The controlling aspect of the bushing housing and bracket assembly are, torsion on the bearing stop, housing reaction, and slip of the connection of bracket to the I-beam in terms of uplift. Following are the checks with applied load vs allowable loads:

1. Torque Check:

Check that the ultimate bearing torque load does not exceed the allowable torque load of bearing stop.

The Ultimate Bearing Torque Load = 3.64 k-ft ≤ 4.3 k-ft

2. Housing Reaction Force Check:

Check that when the ultimate input loads are resolved to the reaction force in the bearing housing bolt location, this resolved force does not exceed the capacity.

$$\left[\frac{1}{2}(2.32kips)+\frac{3.64\ k-ft}{0.2567\ ft}+\frac{2.84\ kips\times 5.125"}{3.08"}\right]\times 1.00=20.07\leq 24.4\ \text{Kips}$$

3. Slip Plane Force Check:

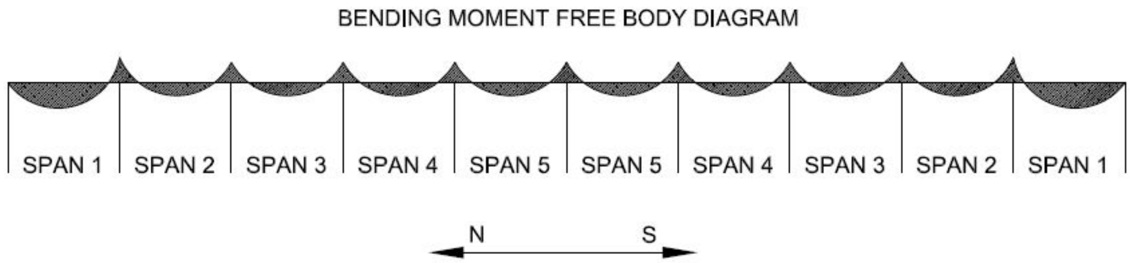
Check that the resolved service load at the bracket to pile slip plane does not exceed the allowable slip resistance.

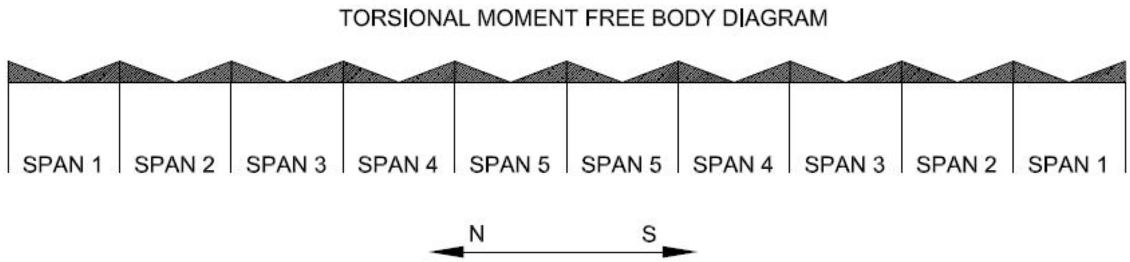
$$\left[\frac{1}{2}(2.32kips)+\frac{3.64\ k-ft}{0.5\ ft}+\frac{2.84\ kips\times 8.2"}{6"}\right]\times 0.60=7.39\leq 13.289\ \text{kips}$$

4.3 k-ft is the allowable torque capacity of bearing stop, 24.4 kips is the allowable reaction force of bearing, and 13.289 kips is the allowable slip resistance of 3/4" diameter bolt connecting bracket and I beam, refer to the bushing housing product calculation in the appendix for a detailed analysis.

(2) Torque Tube:

The free body diagram below shows the moment distribution for bending and torsion as well as identified the spans that are referenced in the calculations that follow. The spans identified are for the interior row and exterior row. This figure is representative of the row, additional spans may be required and would follow the numbering pattern. The bending moment is analyzed per table 3-23 figure 42 of the AISC Manual.





When the torque tube goes into the stow position the torsion is resisted at the individual columns. The tributary area is half of the span for the torsional load on the torque tube. In this scenario the section GC_M is used in lieu of the row.

When the row torque limiter has slipped, and the row is in the locked position the span becomes a fixed – fixed end condition for torsion. When the tracker is fixed at the ends the frequency will increase great enough to prevent any harmonic motion with the wind. Therefore, dynamic effects are not considered in the slipped condition.

The maximum slip capacity on the torque limiter is 3.50 k-ft, which is higher than the ultimate torque in the slipped position. But, due to the end conditions when the tracker is in tracking mode, only fixed for torsion at the torque limiter, the necessary wind speed to reach 3.50 k-ft is approximately 50 MPH. The torsion and bending interaction at 50 MPH is much less than the bending and torsion interaction at design wind speeds. The following analysis is for when the tracker is at 52 degrees at max design conditions.

Interior Span 1: 201"

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.61)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.78)(24.46\text{ psf})\right)^2}$$

$= 28.26$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.107 p_{combo} y\, \mathrm{d}_{b1}^2 = \frac{0.107(28.26\text{ PSF})(93.86)(201)^2}{1000 \times 144} = 79.63\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\, PSF)(0.18)(\frac{201"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 2.26\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 28.26\, PSF \times \frac{93.86" \times 201"}{144 \times 2} = 1.85\, k$$

AISC Equation H3-6

$$\left(\frac{79.63}{138.7}\right) + \left(\frac{2.26}{10.06} + \frac{1.85}{27.03}\right)^2 = 0.65 \leq 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0D + 0.60W

Max. p_{combo} – For service loading

$$= \sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.61)(24.46\text{ psf})\right)^2 + \left((0.60)(0.78)(24.46\text{ psf})\right)^2}$$

$= 16.86$ PSF

$$\Delta = \frac{0.0065\, p_{combo} y l^4}{EI} = \frac{0.0065(16.86\, psf)(93.86")(201")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.90 in$$

Interior Span 2: 207”

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\ psf) + (1.00)(0.38)(24.46\ psf) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.49)(24.46\ psf)\right)^2}$$

$$= 19.38 \text{ PSF}$$

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.107 p_{combo} y\, d_{b1}^2 = \frac{0.107(\ 19.38\ \text{PSF})(93.86)(207)^2}{1000 \times 144} = 57.92 \text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\ PSF)(0.13)(\frac{207"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 1.68 \text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 19.38\ PSF\ \times \frac{93.86" \times 207"}{144 \times 2} = 1.31\ k$$

AISC Equation H3-6

$$\left(\frac{57.92}{138.7}\right) + \left(\frac{1.68}{10.06} + \frac{1.31}{27.03}\right)^2 = 0.46\ \le 1.0\ \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42 \text{ psf}) + (0.60)(0.38)(24.46 \text{ psf})\right)^2 + \left((0.60)(0.49)(24.46 \text{ psf})\right)^2}$$
$$= 11.52 \text{ PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(11.52 psf)(93.86")(207")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.28\ in$$

Interior Span 3: 207”

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.35)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.45)(24.46\text{ psf})\right)^2}$$
$$= 18.20\text{ PSF}$$

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\, d_{b1}^2 = \frac{0.0894(18.20\text{ PSF})(93.86)(207)^2}{1000 \times 144} = 45.44\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\,PSF)(0.11)\left(\frac{207"}{2} \times 93.86"\right)(93.86") \times 1.00 \div 1728 = 1.42\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 18.20\,PSF \times \frac{93.86" \times 207"}{144 \times 2} = 1.23\,k$$

AISC Equation H3-6

$$\left(\frac{45.44}{138.7}\right) + \left(\frac{1.42}{10.06} + \frac{1.23}{27.03}\right)^2 = 0.36 \le 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.35)(24.46\text{ psf})\right)^2 + \left((0.60)(0.45)(24.46\text{ psf})\right)^2}$$
$$= 10.81\text{ PSF}$$

$$\Delta = \frac{0.0026\, p_{combo} y l^4}{EI} = \frac{0.0026(10.81 psf)(93.86")(207")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.26\,in$$

<u>Interior Span 4: 259”</u>

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

$$= \sqrt{\begin{array}{c}\left((1.20)(3.42\text{ psf}) + (1.00)(0.34)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \\ \left((1.00)(0.43)(24.46\text{ psf})\right)^2\end{array}}$$

$= 17.71\text{ PSF}$

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\, d_{b1}^2 = \frac{0.0894(17.71\text{ PSF})(93.86)(259)^2}{1000 \times 144} = 69.23\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$

$$= (24.46\ PSF)(0.11)(\frac{259"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 1.78\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 17.71\ PSF\ \times \frac{93.86" \times 259"}{144 \times 2} = 1.49\ k$$

AISC Equation H3-6

$$\left(\frac{69.23}{138.7}\right) + \left(\frac{1.78}{10.06} + \frac{1.49}{27.03}\right)^2 = 0.55\ \leq 1.0\ \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.34)(24.46\text{ psf})\right)^2 + \left((0.60)(0.43)(24.46\text{ psf})\right)^2}$$
$$= 10.51\text{ PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(10.51 psf)(93.86")(259")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.62\ in$$

<u>Interior Span 5: 259”</u>

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

$$= \sqrt{\begin{array}{c}\left((1.20)(3.42\text{ psf}) + (1.00)(0.34)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \\ \left((1.00)(0.43)(24.46\text{ psf})\right)^2\end{array}}$$

$= 17.71$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\ \mathrm{d}_{b1}^2 = \frac{0.0894(17.71\text{ PSF})(93.86)(259)^2}{1000 \times 144} = 69.23\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$

$$= (24.46\ PSF)(0.11)(\frac{259"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 1.78\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 17.71\ PSF\ \times \frac{93.86" \times 259"}{144 \times 2} = 1.49\ k$$

AISC Equation H3-6

$$\left(\frac{69.23}{138.7}\right) + \left(\frac{1.78}{10.06} + \frac{1.49}{27.03}\right)^2 = 0.55\ \leq 1.0\ \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (1.00)(0.34)(24.46\text{ psf})\right)^2 + \left((1.00)(0.43)(24.46\text{ psf})\right)^2} = 10.51\text{ PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(10.51 psf)(93.86")(259")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.62\ in$$

Interior Span 6: 292"

Using load combination: 1.20D + 1.00W + 0.50S
Bending Moment:

$$= \sqrt{\begin{array}{c}\left((1.20)(3.42\text{ psf}) + (1.00)(0.31)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \\ \left((1.00)(0.40)(24.46\text{ psf})\right)^2\end{array}}$$

$= 16.68$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y \, d_{b1}^2 = \frac{0.0894(16.68\text{ PSF})(93.86)(292)^2}{1000 \times 144}$$

$= 82.87$ k-in

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$

$$= (24.46\,PSF)(0.11)(\frac{292"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 2.00 \text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 16.68\,PSF \times \frac{93.86" \times 292"}{144 \times 2} = 1.59\,k$$

AISC Equation H3-6

$$\left(\frac{82.87}{138.7}\right) + \left(\frac{2.00}{10.06} + \frac{1.59}{27.03}\right)^2 = 0.66 \leq 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.31)(24.46\text{ psf})\right)^2 + \left((0.60)(0.40)(24.46\text{ psf})\right)^2}$$

$= 9.90$ PSF

$$\Delta = \frac{0.0026\, p_{combo} y l^4}{EI} = \frac{0.0026(9.90psf)(93.86")(292")^4}{29000ksi(4.46in^4)(144)(1000)}$$

$= 0.94\,in$

Exterior Span 1: 201”

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.77)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.98)(24.46\text{ psf})\right)^2}$$

$$= 34.46\text{ PSF}$$

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.107 p_{combo} y\, d_{b1}^2 = \frac{0.107(34.46\text{ PSF})(93.86)(201)^2}{1000 \times 144} = 97.10\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$

$$= (24.46\ PSF)(0.19)(\frac{201"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 2.38\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 34.46\ PSF\ \times \frac{93.86" \times 201"}{144 \times 2} = 2.26\ k$$

AISC Equation H3-6

$$\left(\frac{97.10}{138.7}\right) + \left(\frac{2.38}{10.06} + \frac{2.26}{27.03}\right)^2 = 0.80\ \leq 1.0\ \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.77)(24.46\text{ psf})\right)^2 + \left((0.60)(0.98)(24.46\text{ psf})\right)^2} = 20.58\text{ PSF}$$

$$\Delta = \frac{0.0065\ p_{combo} y l^4}{EI} = \frac{0.0065(20.58psf)(93.86")(201")^4}{29000ksi(4.46in^4)(144)(1000)} = 1.10\ in$$

Exterior Span 2: 207"

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.61)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.78)(24.46\text{ psf})\right)^2}$$
$$= 28.26\text{ PSF}$$

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.107 p_{combo} y\, d_{b1}^2 = \frac{0.107(28.26\text{ PSF})(93.86)(207)^2}{1000 \times 144} = 84.45\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\,PSF)(0.15)(\frac{207"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 1.94\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 28.26\,PSF \times \frac{93.86" \times 207"}{144 \times 2} = 1.91\,k$$

AISC Equation H3-6

$$\left(\frac{84.45}{138.7}\right) + \left(\frac{1.94}{10.06} + \frac{1.91}{27.03}\right)^2 = 0.68 \le 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.61)(24.46\text{ psf})\right)^2 + \left((0.60)(0.78)(24.46\text{ psf})\right)^2} = 16.86\text{ PSF}$$

$$\Delta = \frac{0.0026\,p_{combo} y l^4}{EI} = \frac{0.0026(16.86\,psf)(93.86")(207")^4}{29000ksi(4.46in^4)(144)(1000)} = 0.41\,in$$

Exterior Span 3: 207"

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.59)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.76)(24.46\text{ psf})\right)^2}$$

$= 27.57$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\, d_{b1}^2 = \frac{0.0894(27.57\text{ PSF})(93.86)(207)^2}{1000 \times 144} = 68.84\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\ PSF)(0.12)\left(\frac{207''}{2} \times 93.86''\right)(93.86'') \times 1.00 \div 1728 = 1.55\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 27.57\ PSF \times \frac{93.86'' \times 207''}{144 \times 2} = 1.86\ k$$

AISC Equation H3-6

$$\left(\frac{68.84}{138.7}\right) + \left(\frac{1.55}{10.06} + \frac{1.86}{27.03}\right)^2 = 0.55 \le 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.59)(24.46\text{ psf})\right)^2 + \left((0.60)(0.76)(24.46\text{ psf})\right)^2} = 16.44\text{ PSF}$$

$$\Delta = \frac{0.0026\, p_{combo} y l^4}{EI} = \frac{0.0026(16.44\ psf)(93.86'')(207'')^4}{29000ksi(4.46in^4)(144)(1000)} = 0.40\ in$$

Exterior Span 4: 207"

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\text{ psf}) + (1.00)(0.59)(24.46\text{ psf}) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.76)(24.46\text{ psf})\right)^2}$$

$= 27.57$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\, d_{b1}^2 = \frac{0.0894(27.57\text{ PSF})(93.86)(207)^2}{1000 \times 144} = 68.84\text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\, PSF)(0.12)\left(\frac{207"}{2} \times 93.86"\right)(93.86") \times 1.00 \div 1728 = 1.55\text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 27.57\, PSF \times \frac{93.86" \times 207"}{144 \times 2} = 1.86k$$

AISC Equation H3-6

$$\left(\frac{68.84}{138.7}\right) + \left(\frac{1.55}{10.06} + \frac{1.86}{27.03}\right)^2 = 0.55 \leq 1.0 \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\text{ psf}) + (0.60)(0.59)(24.46\text{ psf})\right)^2 + \left((0.60)(0.76)(24.46\text{ psf})\right)^2} = 16.44\text{ PSF}$$

$$\Delta = \frac{0.0026\, p_{combo} y l^4}{EI} = \frac{0.0026(16.44psf)(93.86")(207")^4}{29000ksi(4.46in^4)(144)(1000)} = 0.40\, in$$

Exterior Span 5: 207"

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\ psf) + (1.00)(0.59)(24.46\ psf) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.76)(24.46\ psf)\right)^2}$$

= 27.57 PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\ d_{b1}^2 = \frac{0.0894(\ 27.57\ \text{PSF})(93.86)(207)^2}{1000 \times 144} = 68.84 \text{ k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$
$$= (24.46\ PSF)(0.12)\left(\frac{207"}{2} \times 93.86"\right)(93.86") \times 1.00 \div 1728 = 1.55 \text{ k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 27.57\ PSF\ \times \frac{93.86" \times 207"}{144 \times 2} = 1.86\ k$$

AISC Equation H3-6

$$\left(\frac{68.84}{138.7}\right) + \left(\frac{1.55}{10.06} + \frac{1.86}{27.03}\right)^2 = 0.55\ \leq 1.0\ \Rightarrow \underline{\textbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\ \text{psf}) + (0.60)(0.59)(24.46\ \text{psf})\right)^2 + \left((0.60)(0.76)(24.46\ \text{psf})\right)^2}$$
$$= 16.44\ \text{PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(16.44 psf)(93.86")(207")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.40\ in$$

Exterior Span 6: 207”

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:

Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\ psf) + (1.00)(0.60)(24.46\ psf) + (0.50)(5.94)(\cos 52)\right)^2 + \left((1.00)(0.77)(24.46\ psf)\right)^2}$$

$= 27.92$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\ \mathrm{d}_{b1}^2 = \frac{0.0894(27.92\ \mathrm{PSF})(93.86)(207)^2}{1000 \times 144} = 69.71\ \text{k-in}$$

Torsional Moment:

$$T_u = q_z G C_M A_S y \times 1.00$$

$$= (24.46\ PSF)(0.12)\left(\frac{207"}{2} \times 93.86"\right)(93.86") \times 1.00 \div 1728 = 1.55\ \text{k-ft}$$

Shear:

$$V_u = p_{combo} \times \frac{A}{2} = 27.92\ PSF \times \frac{93.86" \times 207"}{144 \times 2} = 1.88\ k$$

AISC Equation H3-6

$$\left(\frac{69.71}{138.7}\right) + \left(\frac{1.55}{10.06} + \frac{1.88}{27.03}\right)^2 = 0.55 \leq 1.0 \Rightarrow \underline{\mathbf{OK}}$$

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\ \mathrm{psf}) + (0.60)(0.60)(24.46\ \mathrm{psf})\right)^2 + \left((0.60)(0.77)(24.46\ \mathrm{psf})\right)^2} = 16.65\ \mathrm{PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(16.65 psf)(93.86")(207")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.40\ \text{in}$$

Exterior Span 7: 188”

Using load combination: 1.20D + 1.00W + 0.50S

Bending Moment:
Max. p_{combo}

$$= \sqrt{\left((1.20)(3.42\ psf) + (1.00)(0.66)(24.46\ psf) + (0.50)(5.94)(cos\ 52)\right)^2 + \left((1.00)(0.84)(24.46\ psf)\right)^2}$$

$= 30.16$ PSF

Due to the continuous beam action the bending moment is as follows:

$$M_u = 0.0894 p_{combo} y\ d_{b1}^2 = \frac{0.0894(30.16\ \text{PSF})(93.86)(188)^2}{1000 \times 144}$$

$= 62.12$ k-in

Torsional Moment:

$T_u = q_z G C_M A_S y \times 1.00$

$= (24.46\ PSF)(0.12)(\frac{188"}{2} \times 93.86")(93.86") \times 1.00 \div 1728 = 1.41$ k-ft

Shear:

$V_u = p_{combo} \times \frac{A}{2} = 30.16\ PSF \times \frac{93.86" \times 188"}{144 \times 2} = 1.85\ k$

AISC Equation H3-6

$\left(\frac{62.12}{138.7}\right) + \left(\frac{1.41}{10.06} + \frac{1.85}{27.03}\right)^2 = 0.49 \leq 1.0 \Rightarrow$ **OK**

Maximum Deflection –

Using load combination 1.0DL + 0.60W

Max. p_{combo} – For service loading

$$\sqrt{\left((1.0)(3.42\ \text{psf}) + (0.60)(0.66)(24.46\ \text{psf})\right)^2 + \left((0.60)(0.84)(24.46\ \text{psf})\right)^2} = 18.00\ \text{PSF}$$

$$\Delta = \frac{0.0026\ p_{combo} y l^4}{EI} = \frac{0.0026(18.00 psf)(93.86")(188")^4}{29000 ksi(4.46 in^4)(144)(1000)} = 0.29\ \text{in}$$

(3) Center Structure Assembly:

The Center Structure assembly is limited by bending loads when subjected to maximum wind loads at maximum tilt. (See the appendix for detailed analysis.) The maximum allowable moment at the bottom of the Center Structure Assembly is:

$$M_a = F_D h_{CS} + M = (2739\ lb)\left(\frac{32.71}{12}\ ft\right) + (3090\ lbft) = 10556\ lbft$$

The design loads are:

$$F_D = q_z(GC_D)(l)(y)$$
$$M_H = q_z(GC_M)(l)(y^2)$$

Using load combination 1.00W:

$$M_u = 1.00(F_D h_{CS} + M_H) = 1.00(q_z)(l)(y)\big((GC_D)(h_{CS}) + (GC_M)(y)\big)$$

Interior rows

$$M_u = 1.00\left(24.46\ \frac{\text{lb}}{ft^2}\right)\left(\frac{262.0}{12}\ \text{ft}\right)\left(\frac{93.86}{12}\ \text{ft}\right)\left((0.402)\left(\frac{32.71}{12}\ \text{ft}\right) + (0.101)\left(\frac{93.86}{12}\ \text{ft}\right)\right)$$

$$7877 < 10556\ lbft \Rightarrow OK$$

Exterior rows

$$M_u = 1.00\left(24.46\ \frac{\text{lb}}{ft^2}\right)\left(\frac{158.0}{12}\ \text{ft}\right)\left(\frac{93.86}{12}\ \text{ft}\right)\left((0.864)\left(\frac{32.71}{12}\ \text{ft}\right) + (0.126)\left(\frac{93.86}{12}\ \text{ft}\right)\right)$$

$$8415 < 10556 lbft \Rightarrow OK$$

(4) Clamps:

According to the component calculation the max allowable normal pressure for 12" clamp is, $\psi p_{normal} < 110$ PSF

$\psi p_{normal} = 1.00 P_{wind} + 0.50 P_{snow} + 1.20 P_{dead}$

= 1.00(2.10×24.46 PSF)+(0.50×18.14 PSF)+(1.20×3.42 PSF)

Note: 2.10 is the maximum strip GC_p from the RWDI study.

= 64.54 PSF < 110 PSF (OK)

(5) Modules:

Maximum local pressure acting on the module is:

$\psi p_{local} = q_z \times GC_P$
$=24.46$ PSF $\times 2.10 \times 0.60 = 30.82$ PSF = 1476 Pa < 2400 Pa (OK)

Note: 2.10 is the maximum strip GC_p from the RWDI study.

N-S Loading Due to Tracker Weight

N-S wind loading is negligible, and N-S loads on the tracker are mostly due to the weight of tracker and seismic loading. Seismic loading is described next on this document. N-S loading due to tracker weight is W Sin (N-S slope in degrees) where W is the weight of tracker and N-S slope is assumed maximum as 4 degrees. For higher slopes, Array should be notified as loads may be affected.

N-S load due to tracker weight = 6919 lbs x Sin (4°) = 0.48 kips.

N-S loads due to tracker weight is equally shared by gear rack column and seismic columns as described in seismic loading in the following section.

Seismic Loading – North / South Direction (Weak-Axis)

According to ASCE code, Considering tracker as an inverted pendulum. The equivalent lateral force is as follows:

$V_s = C_s W$, $C_S = \frac{S_{DS}}{(\frac{R}{I_e})}$, Where R=2.0 , for an inverted pendulum and

I_e = 1.0 for occupancy Category I - Low Risk in accordance with ASCE code.

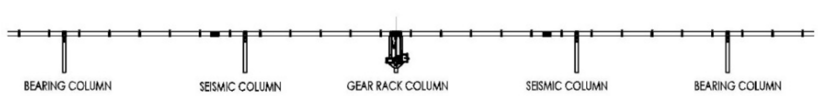
$S_{DS} = 0.22\text{g}$ and $C_S = \frac{0.22\text{g}}{2.0} = 0.11g$

The effective seismic weight of one row, W = 6919 lbs excluding all the columns.
The total lateral seismic force acting on the array, in any horizontal direction, is:

$$V_s = (0.11g)\left(\frac{6919\text{ lb}}{g}\right) = 0.76\text{ k}$$

The gear rack center structure and the seismic columns with the set screw bearing housings restrains the tracker in N/S direction and share the loads equally. The moment on the north south seismic resisting system is as follows:

<u>Seismic Shear Per Column:</u>



$V_{per\ column} = \frac{1}{3}[V_s] = \frac{1}{3}[0.76\text{k}] = 0.25\text{ kips}$

(Note: Seismic shear can be distributed to additional columns to lower shear per column)

$M_{sc} = \frac{1}{3}[V_s] \times h$

$$M_{sc} = \frac{1}{3}[0.76\text{k}](7.50') \times 12\text{ in/ft} = 22.83\text{ k-in}$$

Seismic Loading – East / West Direction (Strong-Axis)

In the east-west direction, the load is equally shared among all columns.

$$V_s = \frac{0.76\ \text{k}}{13} = 0.06\ \text{kips per column}$$

$$M_s = 0.06\text{k}\ (7.50') \times 12\ \text{in/ft}=5.40\ \text{k-in}$$

When comparing the seismic load in the east-west direction to the wind load, the seismic load is substantially lower and can be deemed negligible. For more detailed information on structural loading, please contact Rebecca Troske.

References:

1. American Institute of Steel Construction, 2010, *Steel Construction Manual*, AISC, Chicago, IL.

2. American Society of Civil Engineers, 2006, *Minimum Design Loads for Buildings and Other Structures*, ASCE, Reston, VA

3. Array Technologies Inc. and RWDI, 2012, *Ground Mounted Tracking System - Wind Loading Report*, Document # 1202342

Bearing Assembly Design Record

This document provides the design limits for the bearing assembly and the required checks to be performed for each application of this assembly.

1. Design Limits

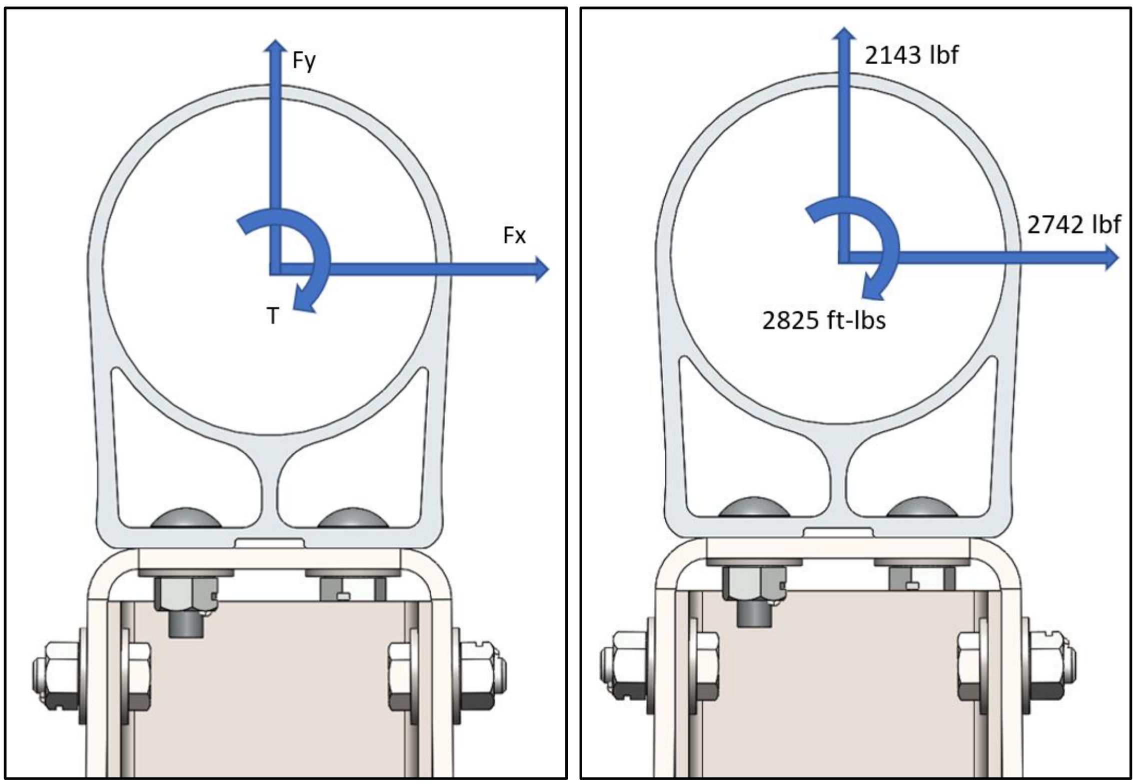


Figure 1: Standard Bearing Assembly Design Limits

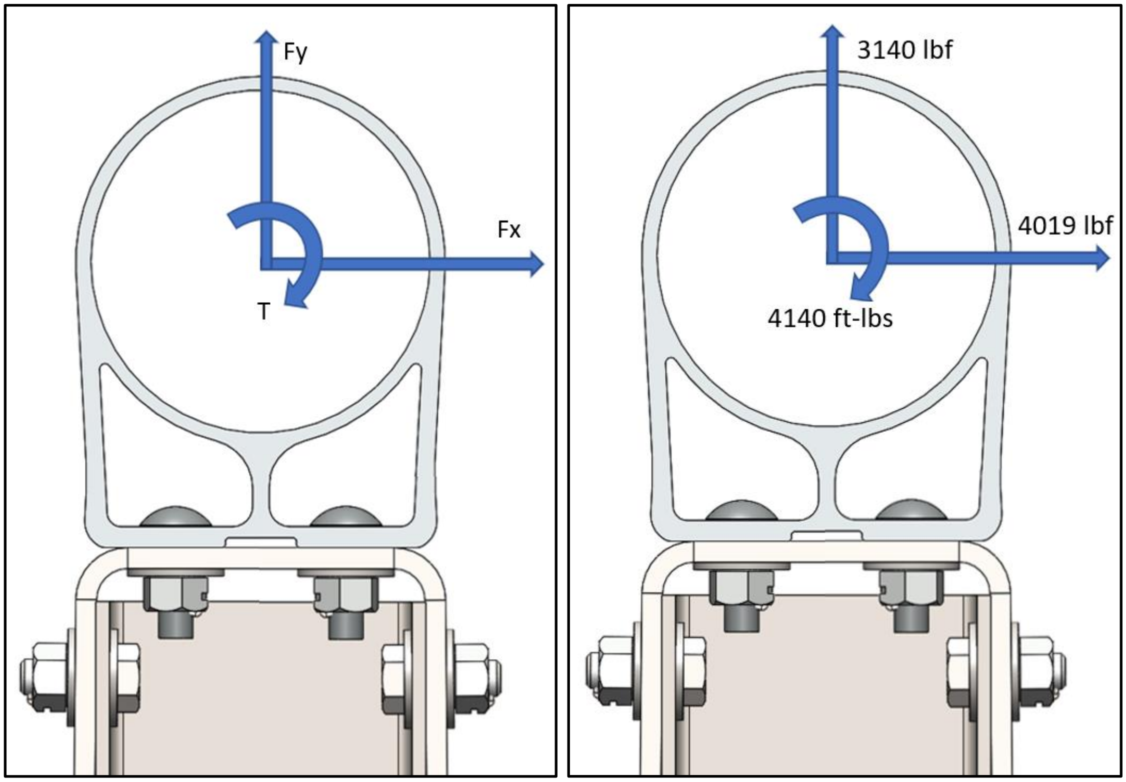


Figure 2: High Load Bearing Assembly Design Limits

2. Required Checks per Project

The tested capacity of the standard load bearing can be found in the test reports listed in Section 7. Inspection of these test reports will show variation in the limiting failure mode. In some instances, the interface between the u-bracket and the pile is slipping prior to any visual deformation in the aluminum housing. In other cases, there is visual deformation occurring in the aluminum housing before the u-bracket slips, or deformation occurs at the load which causes the bracket to slip.

The design limits provided in Section 1 have been determined as the load combination that can be endured by the bearing housing without failure to the aluminum housing. To account for the fact that these load components vary from application to application, three checks must be performed to verify if application loads are within the design limits. These three checks are as follows:

Required Checks

- Torque Check: Check that the ultimate bearing torque load does not exceed the allowable torque load of 4300 ft-lbs (See Figure 3)
  - This check ensures that the strength of the aluminum bearing stop is not exceeded.
  - Maximum allowable torque demonstrated by DVT tests listed in Section 7 [3] [4].
- Housing Reaction Force Check: Check that when the ultimate input loads are resolved to the reaction force in the bearing housing bolt, this resolved force does not exceed $Ry1_{Max}$ as shown in Section 4 (See Ry1 in Figure 4).
  - This check ensures that the strength of the aluminum housing is not exceeded.
  - Input site specific design loads as shown in Section 4.
- Slip Plane Force Check – RCSC Section 5.4: Check that the resolved service load at the u-bracket to pile slip plane does not exceed the allowable slip resistance established by the RCSC calculation as shown in Section 5.
  - Slip plane threshold demonstrated by DVT tests listed in Section 7 [2].

3. Torque Check

For both standard load and high load applications, ensure that the ultimate bearing torque load does not exceed 4300 ft-lbs.

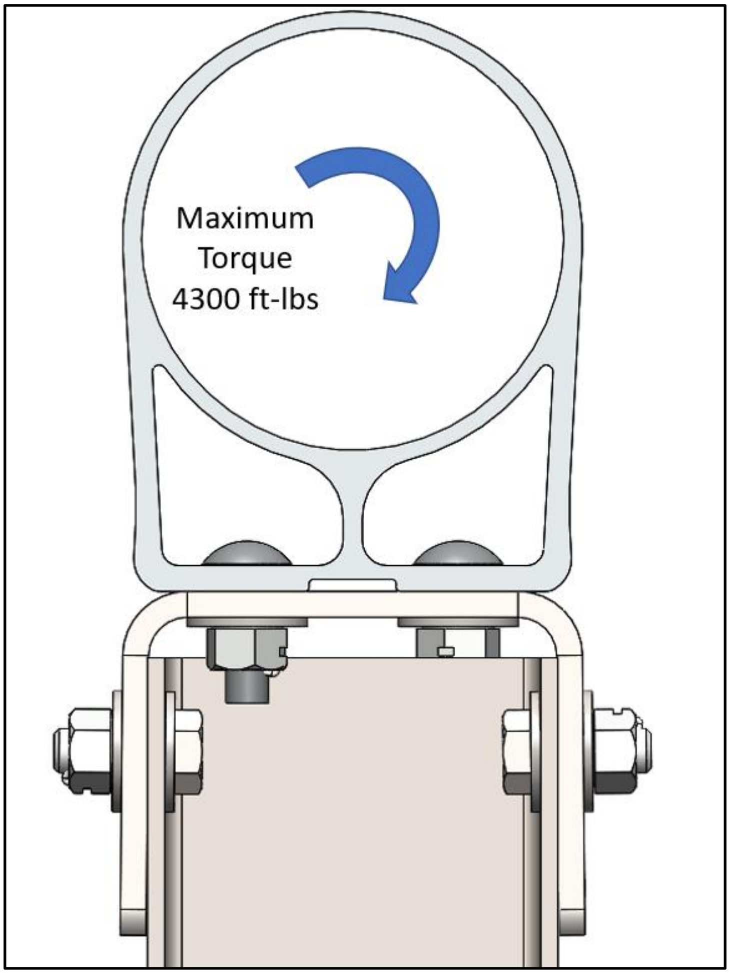


Figure 3: Ultimate Bearing Torque Limit

4. Housing Reaction Force Check

Assumptions/Knowns:

- The bolts are 3.08” apart in the E/W direction
- System loads act 5.125” above the bolt interface
- Thermal loads neglected
- Axial loads neglected

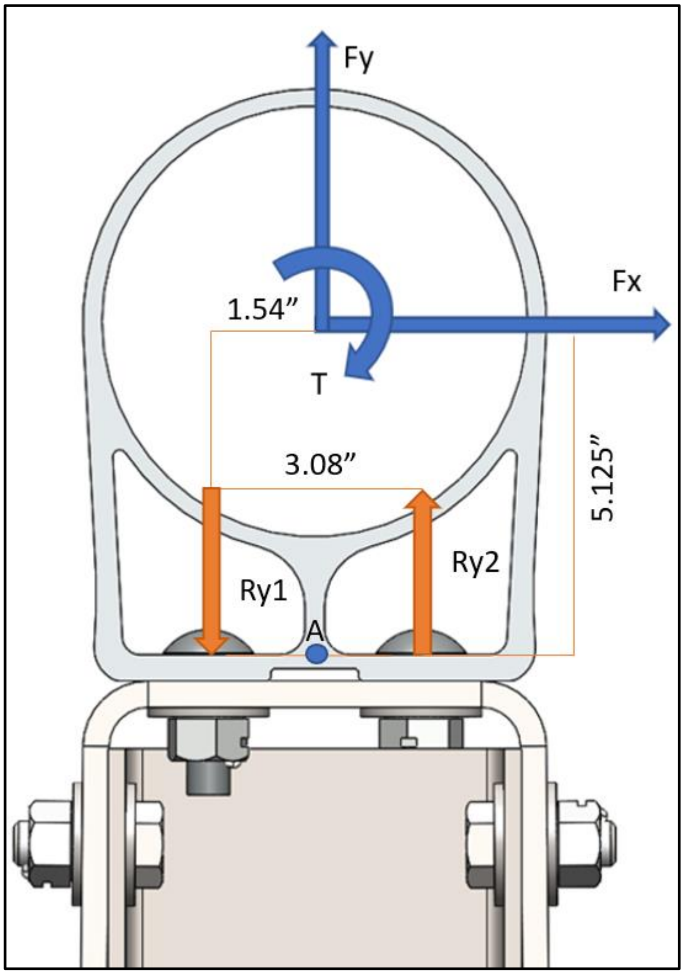


Figure 4: Housing Interface Reaction Forces

Reaction Force Check – Solving for Ry1

$$\sum F_{Y\,direction} = 0; \quad 0 = F_y + R_{y2} - R_{y1}; \quad R_{y2} = R_{y1} - F_y$$

$$\sum M_A = 0; \quad 0 = T * \frac{12"}{1ft} + F_x * 5.125" - 1.54" * R_{y1} - 1.54" * R_{y2}$$

$$T * \frac{12"}{1ft} + F_x * 5.125" = 1.54" * (\mathrm{R_{y1}} + R_{y2})$$

$$T * \frac{12"}{1ft} + F_x * 5.125" = 1.54" * (\mathrm{R_{y1}} + R_{y1} - F_y)$$

$$T * \frac{12"}{1ft} + F_x * 5.125" = 1.54" * (2*\mathrm{R_{y1}} - F_y)$$

$$\frac{T * \frac{12"}{1ft}}{1.54"} + \frac{F_x * 5.125"}{1.54"} = (2*\mathrm{R_{y1}} - F_y)$$

$$F_y + \frac{T * \frac{12"}{1ft}}{1.54"} + \frac{F_x * 5.125"}{1.54"} = 2*\mathrm{R_{y1}}$$

$$R_{y1} = \frac{F_y}{2} + \frac{T * \frac{12"}{1ft}}{2 * 1.54"} + \frac{F_x * 5.125"}{2 * 1.54"}$$

$$R_{y1} = 0.5 * F_y + 3.896 * T + 1.664 * F_x$$

Reaction Force at Design Limits

Standard Load Solution:

$$F_y = 2143\ lbf;\ T = 2825\ ft\ lbs;\ Fx = 2742\ lbf$$

$$R_{y1\,Max} = 0.5 * 2143 + 3.896 * 2825 + 1.664 * 2742$$

$$R_{y1\,Max} = 1072 + 11006 + 4563$$

$$R_{y1\,Max} = 16.6\ kips$$

High Load Solution:

$$F_y = 3140\ lbf;\ T = 4140\ ft\ lbs;\ Fx = 4019\ lbf$$

$$R_{y1\,Max} = 0.5 * 3140 + 3.896 * 4140 + 1.664 * 4019$$

$$R_{y1\,Max} = 1570 + 16129 + 6688$$

$$R_{y1\,Max} = 24.4\ kips$$

Reaction Force at Site Specific Loads

$$R_{y1} = 0.5 * F_y + 3.896 * T + 1.664 * F_x$$

Where:

$F_y =$ ________ lbf; $T =$ ________ $ft\ lbs$; $Fx =$ ________ lbf

$R_{y1} =$ ______________ < 16.6 kips (Standard Load Bearing Assembly)

$R_{y1} =$ ______________ < 24.4 kips (High Load Bearing Assembly)

5. Slip Plane Force Check – RCSC Section 5.4

Assumptions/Knowns:

- RCSC Slip Resistance Method Used – Link
- Thermal loads neglected
- Axial loads neglected
- Bolt K-factor = 0.12
- Standard load Assumptions
    - Nominal Torque of 125 ft-lbs applied
    - Bolt Diameter = 0.625”
    - Tb = 19,000 lbf (RCSC Table 8.1) for 5/8” Diameter Bolt
- High Load Assumptions
    - Nominal Torque of 210 ft-lbs applied
    - Bolt Diameter = 0.75”
    - Tb = 28,000 lbf (RCSC Table 8.1) for 3/4” Diameter Bolt
- Tu=0 [1]
- System loads act 8.2” above the bolt interface (the center of the bracket’s slot is used)

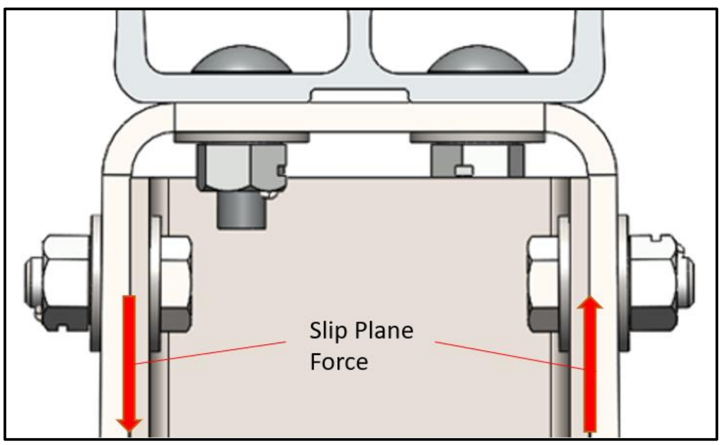


Figure 5: Slip Plane Force Loads

Slip Check

$$R_n = \mu D_u h_f T_b n_s k_{sc}$$

For long-slotted holes
$\phi = 0.70$ (LRFD)

$u = 0.3$ (Slip Coefficient)

$D_u = 1.13$ (multiplier)

$h_f = 1$ (factor for fillers – no fillers used)

$n_s = 1$ (Number of slip planes required to permit the connection to slip)

$k_{sc} = 1 - \frac{T_u}{D_u T_b n_b}$

$k_{sc} = 1 - \frac{0}{1.13 * T_b * 1} = 1$

$\varphi = 0.70$

$$R_n = [R_n]_{bolt\ 1} + [R_n]_{bolt\ 2}$$

$$R_n = 2 * \left[u * D_u * h_f * T_b * n_s * k_{sc}\right]$$

$$R_{n\ \frac{5}{8}"} = 2 * [0.3 * 1.13 * 1 * 19{,}000 * 1 * 1] = 12{,}882\ lbf$$

$$R_{n\ \frac{3}{4}"} = 2 * [0.3 * 1.13 * 1 * 28{,}000 * 1 * 1] = 18{,}984\ lbf$$

$$Slip\ Resistance = \varphi R_n = 0.7 * R_n$$

$$Slip\ Resistance\ \left(\frac{5}{8}"\ Bolt\right) = \varphi R_n = 0.7 * 12{,}882 = 9{,}017\ lbf$$

$$Slip\ Resistance\ \left(\frac{3}{4}"\ Bolt\right) = \varphi R_n = 0.7 * 18{,}984 = 13{,}289\ lbf$$

Standard Load Bearing Assembly Slip Check:

If Slip Plane Force < 9,017 lbf *Passes slip check*

If Slip Plane Force > 9,017 lbf *Fails slip check*

High Load Bearing Assembly Slip Check:

If Slip Plane Force < 13,289 lbf *Passes slip check*

If Slip Plane Force > 13,289 lbf *Fails slip check*

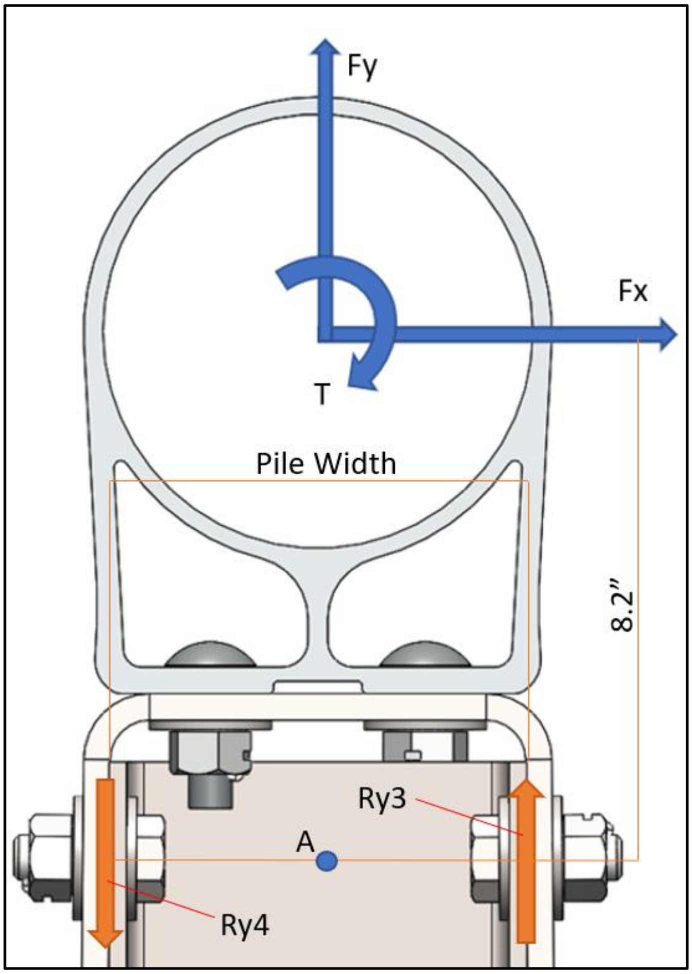


Figure 6: Pile Interface Reaction Forces

Reaction Force Check – Solving for Ry4

$$\sum F_{Y\ direction} = 0; \quad 0 = F_y + R_{y3} - R_{y4}; \quad R_{y3} = R_{y4} - F_y$$

$$\sum M_A = 0; \quad 0 = R_{y4} * \frac{Pile\ Width}{2} + R_{y3} * \frac{Pile\ Width}{2} - T * \frac{12"}{1ft} - F_x * 8.2"$$

$$R_{y4} * Pile\ Width + R_{y3} * Pile\ Width = 2 * T * \frac{12"}{1ft} + F_x * 16.4"$$

$$\left(R_{y3} + R_{y4}\right) * Pile\ Width = 2 * T * \frac{12"}{1ft} + F_x * 16.4"$$

$$\left(R_{y4} - F_y + R_{y4}\right) * Pile\ Width = 2 * T * \frac{12"}{1ft} + F_x * 16.4"$$

$$\left(R_{y4} - F_y + R_{y4}\right) = \frac{2 * T * \frac{12"}{1ft} + F_x * 16.4"}{Pile\ Width}$$

$$2 * R_{y4} = F_y + \frac{2 * T * \frac{12"}{1ft} + F_x * 16.4"}{Pile\ Width}$$

$$R_{y4} = \frac{F_y}{2} + \frac{T * \frac{12"}{1ft} + F_x * 8.2"}{Pile\ Width}$$

$$R_{y4} = \frac{F_y}{2} + \frac{T * \frac{12"}{1ft}}{Pile\ Width} + \frac{F_x * 8.2"}{Pile\ Width}$$

Reaction Force at Site Specific Loads

$$R_{y4} = \frac{F_y}{2} + \frac{T * \frac{12"}{1ft}}{Pile\ Width} + \frac{F_x * 8.2"}{Pile\ Width}$$

Where:

$F_y =$ ________ $lbf;\ T =$ ________ $ft\ lbs;\ Fx =$ ________ $lbf;\ Pile\ width =$ ________"

$R_{y4} =$ ________ $lbf < 9{,}017\ lbf \quad (Standard\ Load)$

$R_{y4} =$ ________ $lbf < 13{,}289\ lbf \quad (High\ Load)$

6. Appendix

[1] Assumption: Tu=0

It can be assumed that the hardware securing the u-bracket to the pile does not experience any significant tension due to external loading. External loads such as horizontal (drag) load and torque applied by the system could be resolved into side loads, but the bracket is not likely to apply extra tension to the hardware due to the u-shape of the bracket. For this reason, ksc can be resolved to zero in RCSC slip check calculations at the pile and u-bracket interface.

7. Relevant DVT Results

[2] DVT-17060-01

The capacity of the standard load bearing is established here. Note that this test report refers to the 30456-151 I-beam bracket, which is a 9.5mm [0.375"] thick bracket with grade 50 steel. This test, however, was performed with an 8.0mm [0.315"] thick bracket with grade 80 steel, which became the 30770-151 bracket.

"The connection withstood 3.48 kips loading, equivalent to 10.65 kips of slip force, with slip of only 0.07" and minimal deformation."

[3] DVT-17033-02

Maximum torque capability of the bearing stop was demonstrated in this test. Bearing stop failed at 4350 ft-lb torque load.

[4] DVT-17037-01

Maximum torque capability of the bearing stop was demonstrated in this test. Bearing stop survived 4425 ft-lb torque.

[5] DVT-20053-02

High Load test force of 5100 lbs was demonstrated in this test. "The high wind bracket withstood 5100 lbs of normal load and 4250 ft-lbs of torque while experiencing 0.08" of permanent slip along the I-beam. The bracket was fully functional at the end of the combined load test."

8. Supplemental Calculations

[6] Test Force & Resultant Design Limits

The design limits have been tested by using a single vertical test force with the assembly tilted 52 degrees, as shown in Figure 7. The vertical (uplift) force and horizontal (drag) force limits are calculated using this test force value. A torque load can be induced by applying this test force at a distance, as shown in Figure 8. The standard arm length used in DVT testing is 9.74" which is used to determine the torque limit. The ultimate torque limit of 4300 ft-lbs is determined from testing the limitation of the bearing stop[3][4]. The standard load and high load design limits are calculated here using the declared test forces below. Note that historical test data has used a variety of test forces depending on the application, but these test forces shall be controlled per the values stated below.

$$Test\ Force_{Standard} = 3480\ lbf\ \ [2]$$

$$Test\ Force_{High\ Load} = 5100\ lbf\ [5]$$

$$F_x = F * \sin(52)$$

$$F_y = F * \cos(52)$$

$$T = F * Arm\ Length * \frac{1ft}{12"}$$

Table 1: Test Force and Design Limits

	Test Force (lbf)	Fx (lbf)	Fy (lbf)	T (ft-lbs)
Standard	3480[2]	2742	2143	2825
High Load	5100[5]	4019	3140	4140

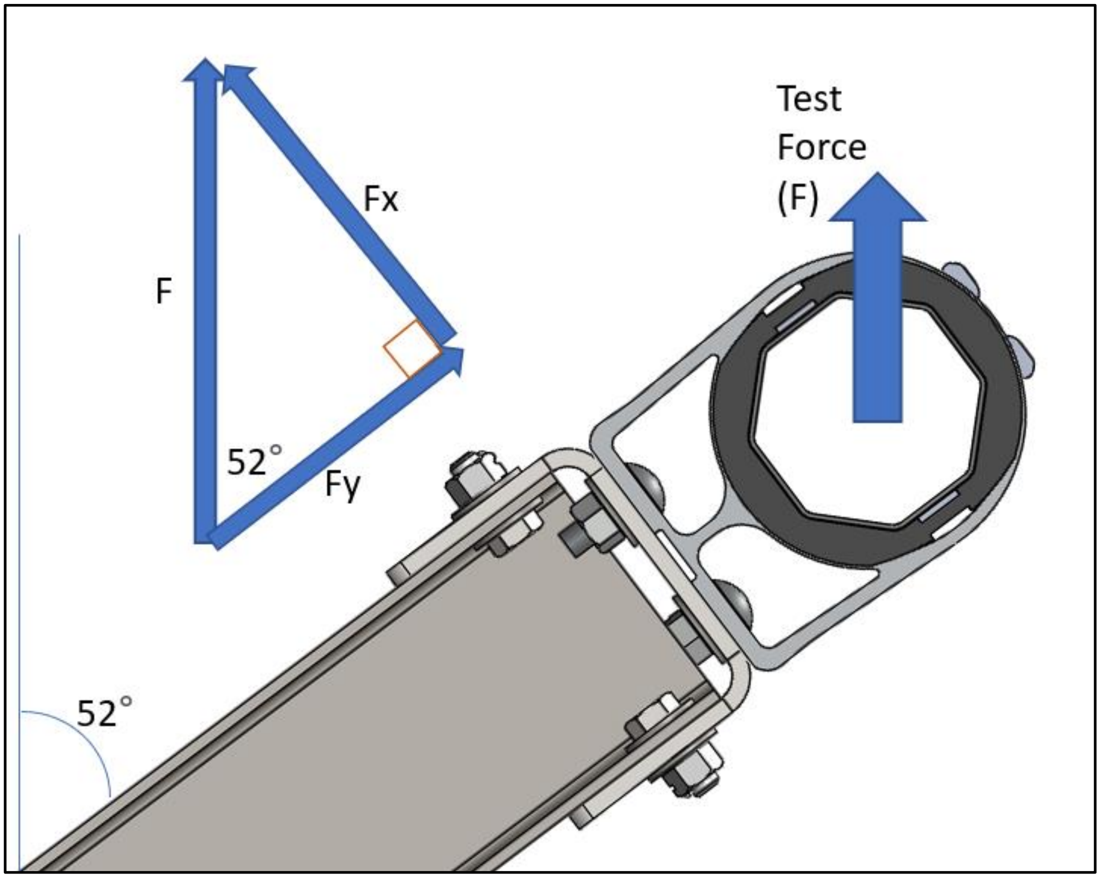


Figure 7: Resolved Test Force

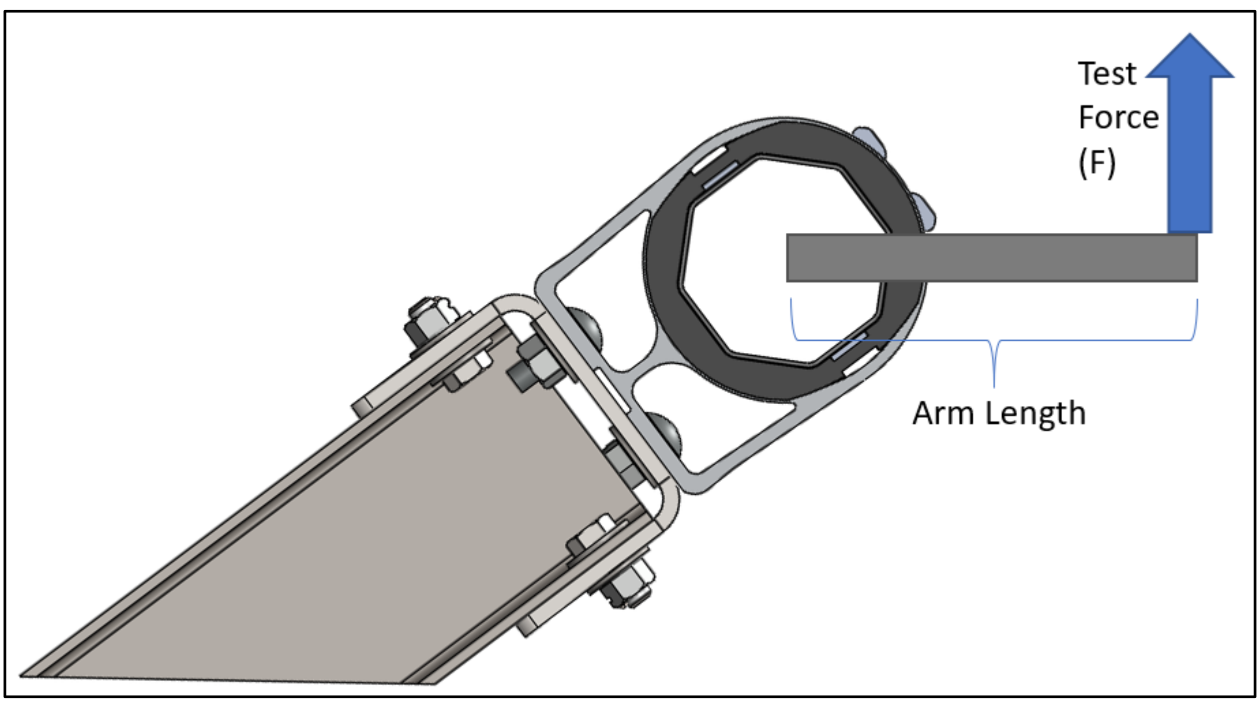
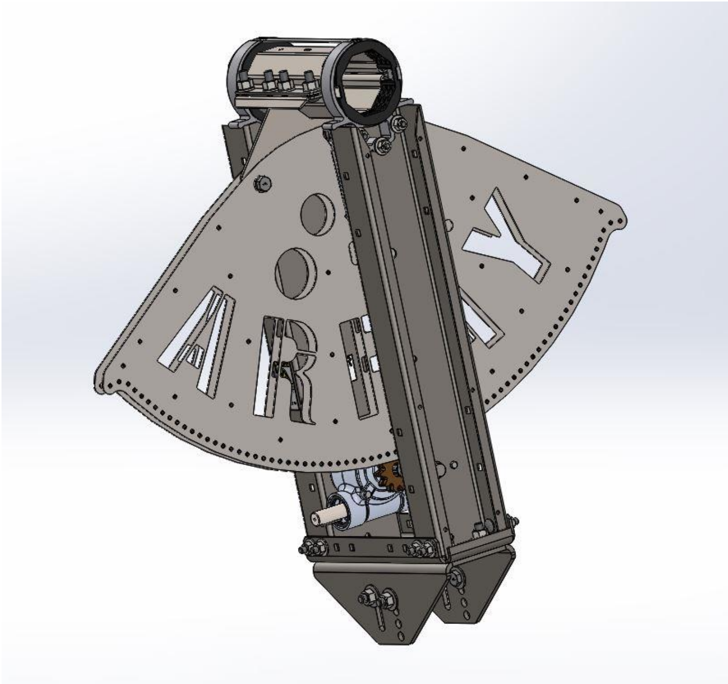


Figure 8: Test Force Distance

9. Revision History

RELEASE DATE	REVISION	DESCRIPTION	NAME
04/19/2021	0	Initial Release	M. Kuban



Center Structure Analysis of DuraTrack™ HZ Solar Tracker On Exterior Rows

Completed by:
Kiran Tuniki and Jason Tankersley
October 18, 2016
Array Technologies, Inc.

Center Structure Assembly ATI PN 20449-000

The center structure assembly is a bolted assembly composed of various parts. Those parts will be individually analyzed and rated in these calculations.

This structure is subject to a horizontal and vertical load due to wind as well as a moment due to torsion. The following formulas are used for computing the allowable horizontal (drag) force for each part:

F_d=Drag Force (Horizontal)
F_L=Lift Force (Vertical)
T=Torsional Moment
T_c=Resulting Couple Force From Torsion
G_{CM}=0.09 ⟹From Section 3 of RWDI study for 50 degrees
G_{CP}=0.90 ⟹From Section 3 of RWDI study for 50 degrees, uplift

$$T = \frac{0.09}{\sin(52) \times 0.90} \times 77.01" \times F_d = F_d \times 9.77"$$

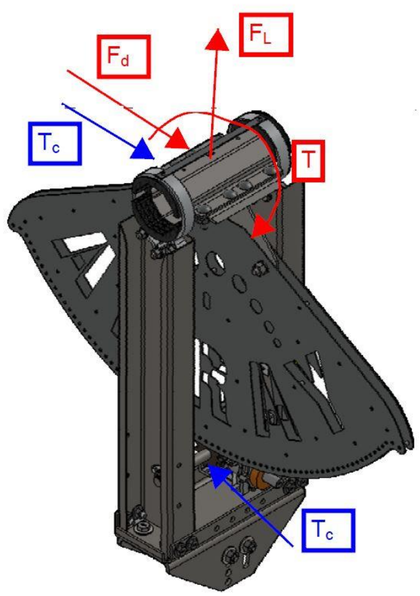
77.01" is the length of an average module

$$T_c = \frac{F_d \times 9.77"}{30.64"} = 0.319 F_d$$

30.64" is the distance from the shaft where the gear rack will lock onto and the axis of rotation.

$$F_L = \frac{F_d}{\tan(52)} = 0.78 F_d$$

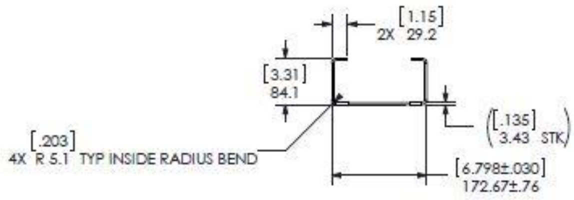
With the loads correlating into a ratio of the drag force the ultimate capacities can be obtained for the individual parts to establish an assembly load rating.

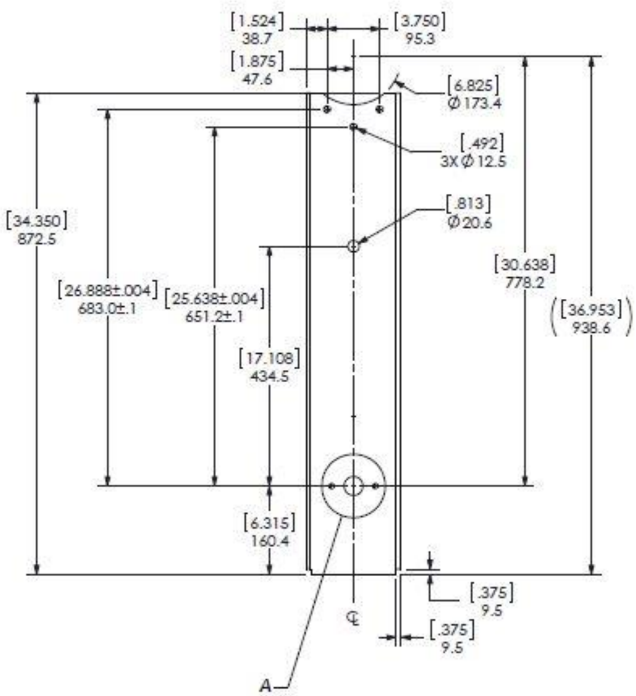


The free body diagram to the left depicts the loads applied to the assembly as a whole. Note, Tc is a resulting load from T not an additional load to the structure.

Upright, Electrical Box Side, Center Structure, Drive Column ATI PN 30500

Upright, Gearmotor Side, Center Structure, Drive Column ATI PN 30501





The channel uprights in the center structure assembly are subject to bending due to the resolving torsional moment as well as the drag force.

Material properties:

- 50KSI Min. grade of steel
- $Z_x = 4.95$ in^3
- $Z_y = 2.24$ in^3
- $I_x = 14.44$ in^4
- $I_y = 3.09$ in^4
- $A = 1.99$ in^2

Determine the maximum drag load both channels can be designed for in bending:

$M_n = 0.9(4.95\text{in}^3)(50\text{ksi}) = 222.8$ k-in

$F_d \leq M_n$

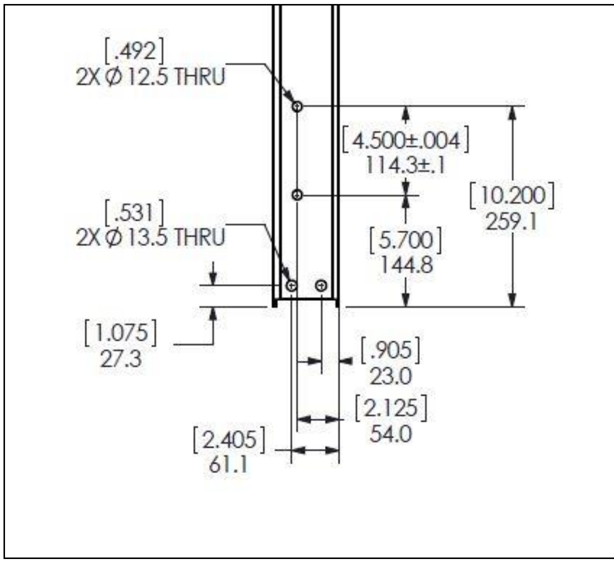
$\frac{1}{2}[F_d(36.96)+T_c(30.64)] \leq 222.8$ k-in

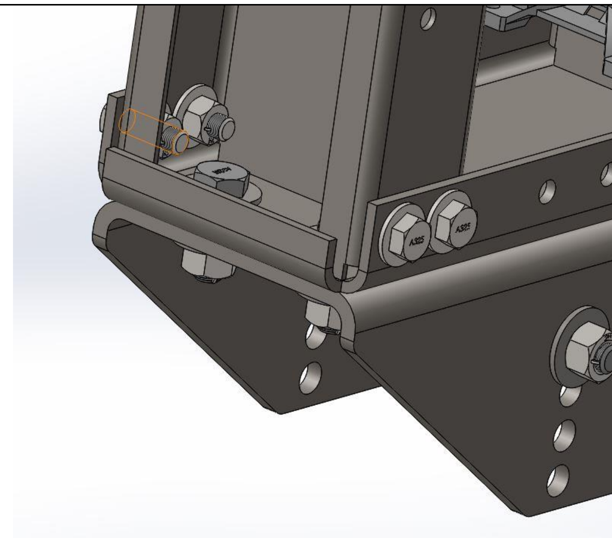
$\frac{1}{2}[F_d(36.96")+F_d(0.319)(30.64")] \leq 222.8$ k-in

$F_d(23.37") \leq 222.8$ k-in

$F_d \leq 9.53$ kips

Determine the maximum drag load the bolted connection to the bottom bracket can take.





The channel has a bolted flange to flange connection to another part of the assembly. The picture above shows the dimensional properties of the holes and the assembly connection. The following calculations will determine the maximum drag load for the bolts due to a shear failure.

5/8" Diameter Grade 5 Carriage Bolt Shear Capacity –

$\phi V_n = 0.75(0.307\text{in}^2)(48\text{ksi}) = 11$ kips

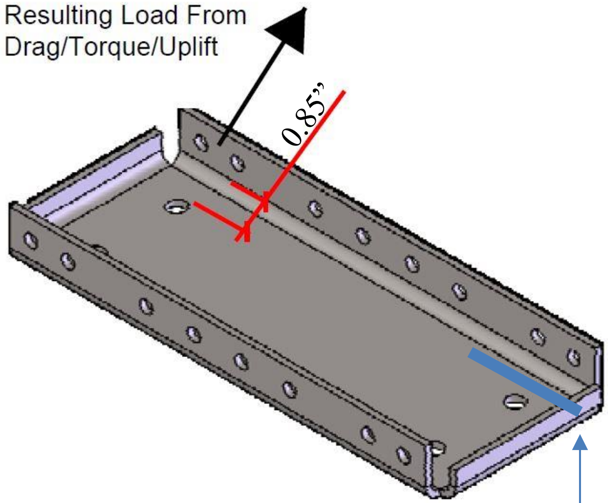
$$\frac{1}{8}F_L + \frac{1}{4}\left[\frac{F_d(36.96+30.64[0.319])}{6.8"}\right] \leq 11 \text{ kips}$$

$$\frac{1}{8}(0.78)(F_d) + (1.72)(F_d) \leq 11 \text{ kips}$$

$$F_d \leq 6.05 \text{ kips}$$

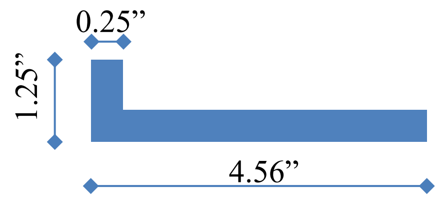
The end bearing capacity of the channel is not a limit state for this connection as the bottom bracket fits tightly around the upright, thus creating a fixed condition that doesn't allow for rotation of the channel upright, the assembly will rotate cohesively. The above check for shear is a conservative check for the same reasons, the channel cannot rotate inside the bracket independently.

<u>Base, Center Structure, Square Holes ATI PN 30452-000</u>



Section used for bending calculation

Properties of section in bending:



Material is 50 KSI and 0.25” thick.

Calculate the Neutral Axis:

$$\frac{4.56(0.25)(0.125) + 1.0(0.25)(0.75)}{4.56(0.25) + 1.0(0.25)}$$

$N.A. = 0.237in \approx 0.25in$

Calculate the plastic modulus:

$$4.56(0.25)(0.125) + 1.0(0.25)(0.5)$$

$Z = 0.269in^3$

This part supports the vertical channels in the prior calculation. The following analysis will determine the maximum drag load for the channel in a bending and an end bearing failure.

The bending capacity of the plate is:

$M_n = 0.9(50ksi)(0.269in^3) = 12.11$ k-in

Determine the maximum drag load the bracket can resist in bending:

$$\left[\frac{1}{2}\left(\frac{F_d[36.96+30.64(0.319)]}{6.8"} + \frac{F_L}{2}\right)\right] \times 0.85" \leq 12.11 \text{ k-in}$$

$$\left[\frac{1}{2}\left(6.87 \times F_d + \frac{0.78F_d}{2}\right)\right] \leq 14.25 \text{ k-in}$$

$$\left[\frac{1}{2}(7.26 \times F_d)\right] \leq 14.25 \text{ k-in}$$

$F_d \leq 3.93$ kips

Channel End Bearing Capacity -

R_n = 1.5(0.53in)(0.25in)(65ksi) ≤ 3.0(0.625in)(0.25in)(65ksi)

R_n = 12.92 kips ≤ 30.47 kips

ϕ R_n = (0.75)(12.92 kips) = 9.69 kips

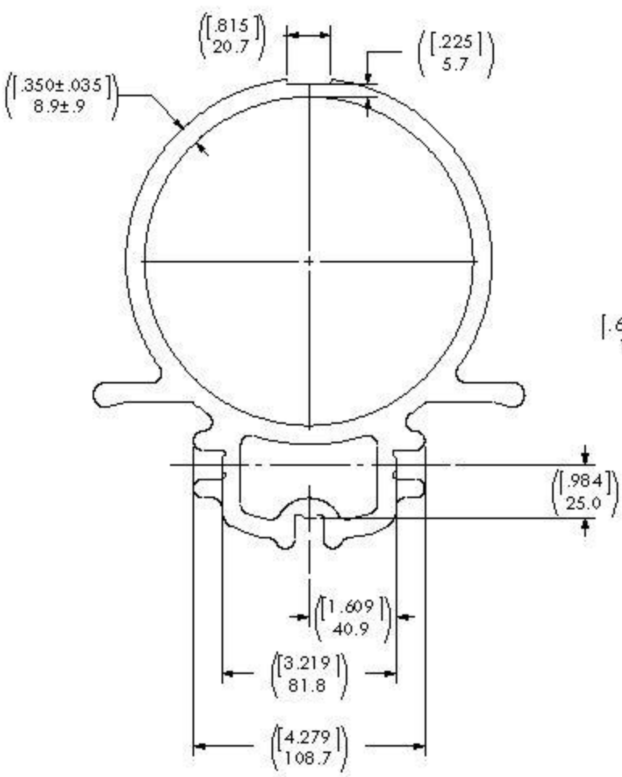
Maximum drag, use end bearing capacity:

$$\frac{1}{8}F_L + \frac{1}{4}\left[\frac{F_d(36.96+30.64[0.319])}{6.8"}\right] \leq 9.69\text{kips}$$

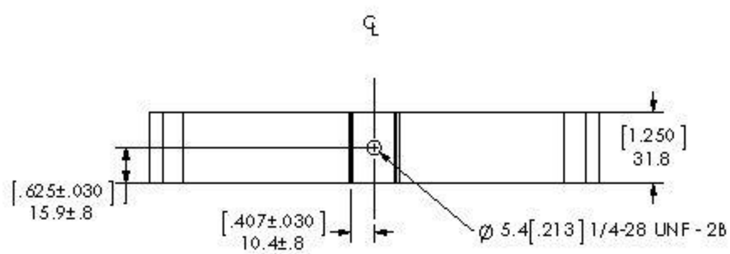
$$\frac{1}{8}(0.78)(F_d) + (1.72)(F_d) \leq 9.69 \text{ kips}$$

$$F_d \leq 5.33 \text{ kips}$$

Housing, Bushing, Center Structure, Outboard Supports, XXXmm, Strap Hole
ATI PN 30476-000



SIDE VIEW



TOP VIEW

Each center bearing housing will resist half of the applied drag load, vertical load, and resulting couple force from torsion. The following calculations will assess the capacity of the extrusion and bolts.

The extrusion is 1.25” wide and 0.225” thick at the narrowest cross section. It is composed of aluminum alloy 6005A/T61. The bolts are grade 5 carriage bolts, approximately 0.47” in diameter.

The capacity of the extrusion is:

$$P_n = 0.225''(1.25'')(35ksi)(0.9) = 8.86\ kips$$

The capacity of a single bolt in shear is:

$$V_n = \frac{(0.47'')^2}{4} \times \pi \times 0.75 \times 48ksi = 6.25\ kips$$

Maximum load for the extrusion:

$$\frac{1}{2}\left(\frac{F_d \times 4.38''}{3.75''} + F_L + T_c\right) \leq 8.86\ kips$$

$$\frac{1}{2}\left(\frac{F_d \times 4.38''}{3.75''} + 0.78F_D + 0.319F_D\right) \leq 8.86\ kips$$

$$F_d \leq 7.42\ kips$$

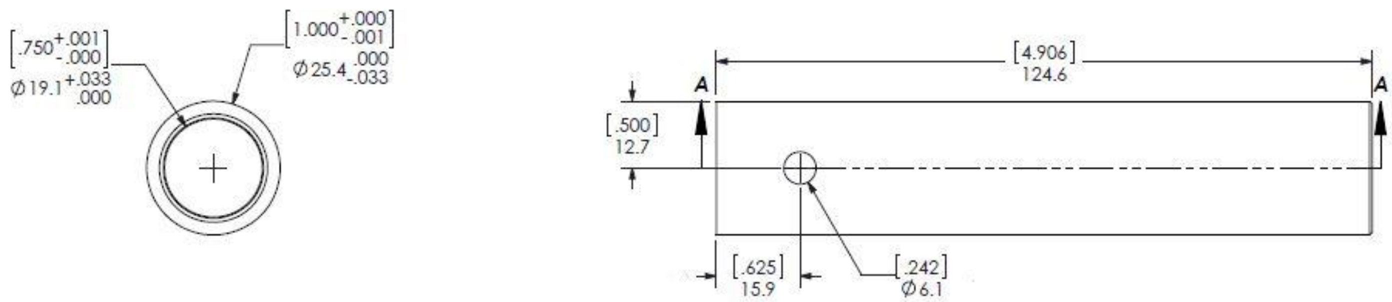
Maximum load for the bolts:

$$\frac{1}{2}\left(\frac{F_d \times 4.38''}{3.75''} + \frac{F_L}{6} + T_c\right) \leq 6.25\ kips$$

$$\frac{1}{2}\left(\frac{F_d \times 4.38''}{3.75''} + \frac{0.78}{3}F_D + 0.319F_D\right) \leq 6.25\ kips$$

$$F_d \leq 7.16\ kips$$

Gearbox, Output Stub Shaft, 25MM ATI PN 40102-000



The shaft is composed of mild steel 1018 with a minimum yield strength of 53 ksi. As seen in the free body diagram of the assembly the shaft will have to resist the resulting couple force from torsion in bending. The distance between the uprights which act as the support for the shaft is 10.75”. The maximum moment on the shaft will be at 3.25” from the bearing in the channel upright. The output shaft of the gearbox inserts into the bored shaft at a depth of 1 3/8” of an inch.

Shaft capacity:

$$M_n = 0.9 \times 53ksi \times \frac{1in^3}{6} = 7.95 \text{ k-in}$$

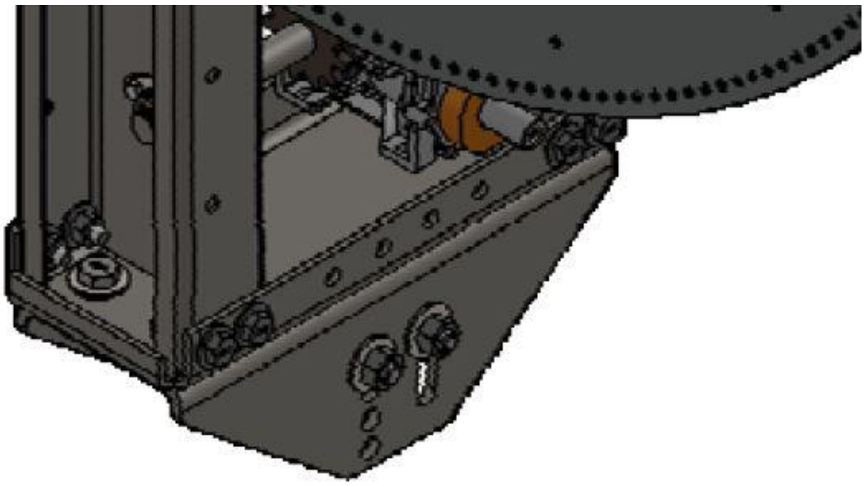
Maximum load on shaft:

$$\frac{T_c \times 3.25"}{2} \leq 7.95 \text{ k-in}$$

$$\frac{0.319F_d \times 3.25"}{2} \leq 7.95 \text{ k-in}$$

$$F_d \leq 15.34 \text{ kips}$$

Bracket, Mounting, Center, I-Beam, 0.375 in, W6 x(XX), XXX mm HDG ATI PN 30292-000



The bracket connects to a W6 I-beam, this connection is analyzed as a shear connection for the 5/8" diameter bolts. Through testing we have observed a small acceptable amount of slip from the oversize hole in the I-beam, but the bolt does not slip relative to the bracket. After the initial amount of movement the test was carried out to the reported loads at the end of this package without any failure occurring. The tested loads exceed ϕVn of the bolts, therefore limiting the capacity of this component to the shear strength of the bolts is a conservative approach.

The shear capacity of a 5/8" diameter A325 bolt is 11.00 kips.

$$\frac{F_L}{2} + \frac{F_d(36.96") + T_c(30.64")}{6.75"} \leq 11\ kips + 11\ kips$$

$$\frac{F_d(0.78)}{2} + \frac{F_d(36.96") + F_d(0.319)(30.64")}{6.75"} \leq 22\ kips$$

$$F_d(0.39) + F_d(6.92) \leq 22\ kips$$

$$F_d \leq 3.01\ kips$$

The following table is a summary of the weakest component of the critical parts of the gear rack center structure assembly.

		From Analysis
ATI PN 30500	F_d	6.05 kips
ATI PN 30452	F_d	3.93 kips
ATI PN 30476	F_d	7.16 kips
ATI PN 40102	F_d	15.34 kips
ATI PN 30292	F_d	3.01 kips

The weakest element of the structure is the connection to the I-beam, with only 3.01 kips of capacity. This correlates to the following applied loads:

F_d	3.01 kips
F_L	2.35 kips
T	2.45 k-ft

This results in a q_z of:

$$\frac{3010 lbs \times 12}{\sin(52)(0.90)(L")(77.01")} = \frac{659.36\ lbs}{L \text{ in-ft}}$$

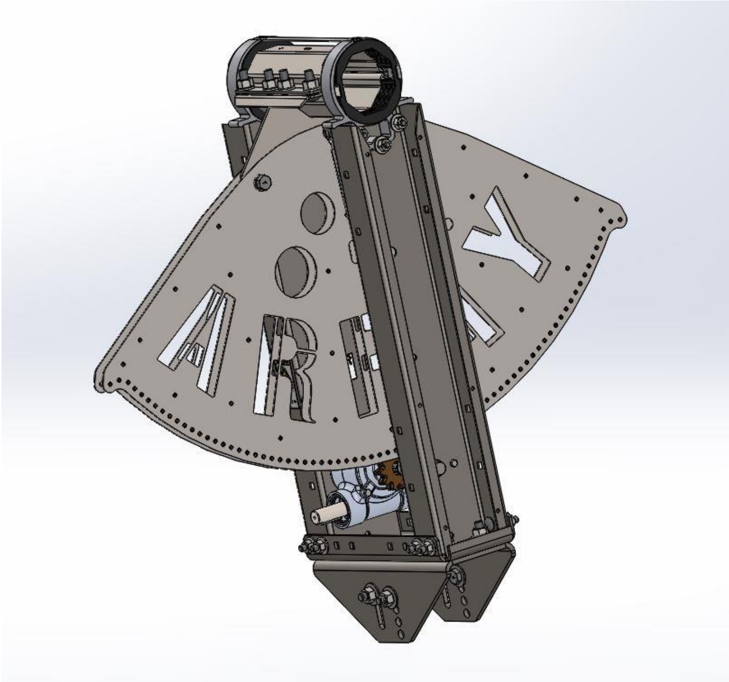
The maximum tributary area for a 130 MPH wind storm is:

$$\sqrt{\frac{659.36\ lbs}{L \text{ in-ft}(0.00256 \times 0.85 \times 0.85)}} = 130 \text{ MPH}$$

$$\frac{659.36\ lbs}{L \text{ in-ft}} = 31.26\ psf$$

$$L = 253.13\ in$$

Max Tributary Length at Various Wind Speeds for Exterior Rows	
130 MPH	253.13 in
120 MPH	297.07 in
110 MPH	353.54 in
100 MPH	427.70 in



Center Structure Analysis of DuraTrack™ HZ Solar Tracker On Interior Rows

Completed by:
Kiran Tuniki and Jason Tankersley
October 18, 2016
Array Technologies, Inc.

Center Structure Assembly ATI PN 20449-000

The center structure assembly is a bolted assembly composed of various parts. Those parts will be individually analyzed and rated in these calculations.

This structure is subject to a horizontal and vertical load due to wind as well as a moment due to torsion. The following formulas are used for computing the allowable horizontal (drag) force for each part:

F_d=Drag Force (Horizontal)
F_L=Lift Force (Vertical)
T=Torsional Moment
T_c=Resulting Couple Force From Torsion
G_{CM}=0.09 ⟹From Section 3 of RWDI study for 50 degrees
G_{CP}=0.90 ⟹From Section 3 of RWDI study for 50 degrees, uplift

$$T = \frac{0.09}{\sin(52) \times 0.65} \times 77.01" \times F_d = F_d \times 13.53"$$

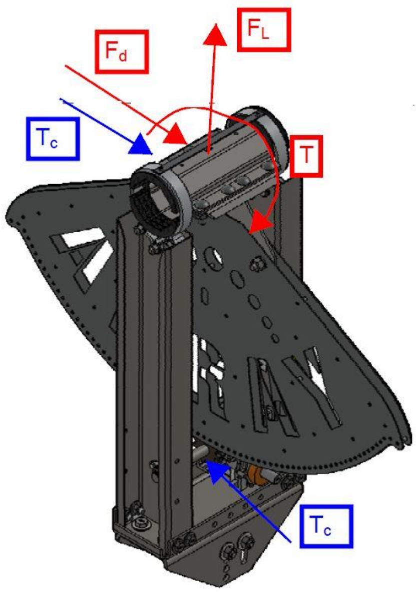
77.01" is the length of an average module

$$T_c = \frac{F_d \times 13.53"}{30.64"} = 0.44F_d$$

30.64" is the distance from the shaft where the gear rack will lock onto and the axis of rotation.

$$F_L = \frac{F_d}{\tan(52)} = 0.78F_d$$

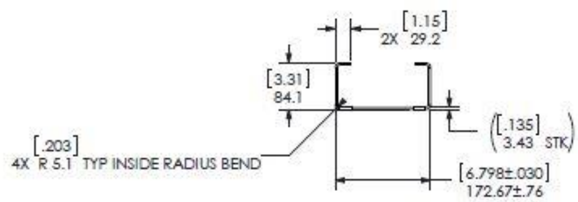
With the loads correlating into a ratio of the drag force the ultimate capacities can be obtained for the individual parts to establish an assembly load rating.

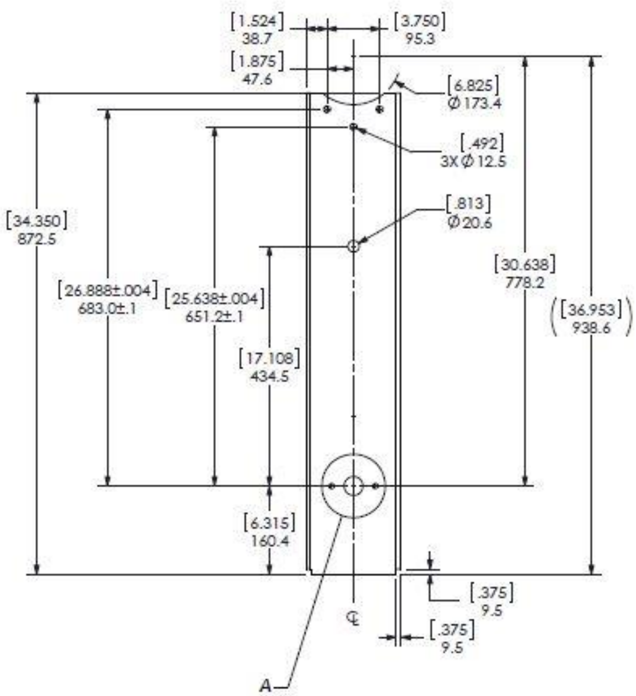


The free body diagram to the left depicts the loads applied to the assembly as a whole. Note, Tc is a resulting load from T not an additional load to the structure.

Upright, Electrical Box Side, Center Structure, Drive Column ATI PN 30500

Upright, Gearmotor Side, Center Structure, Drive Column ATI PN 30501





The channel uprights in the center structure assembly are subject to bending due to the resolving torsional moment as well as the drag force.

Material properties:

- 50KSI Min. grade of steel
- $Z_x = 4.95$ in^3
- $Z_y = 2.24$ in^3
- $I_x = 14.44$ in^4
- $I_y = 3.09$ in^4
- $A = 1.99$ in^2

Determine the maximum drag load both channels can be designed for in bending:

$M_n = 0.9(4.95\text{in}^3)(50\text{ksi}) = 222.8$ k-in

$F_d \leq M_n$

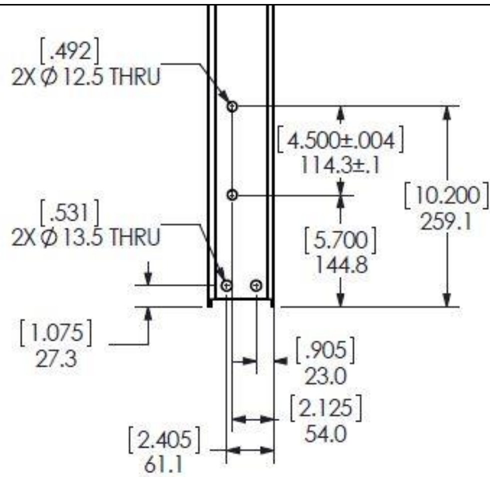
$$\frac{1}{2}[F_d(36.96) + T_c(30.64)] \leq 222.8 \text{ k-in}$$

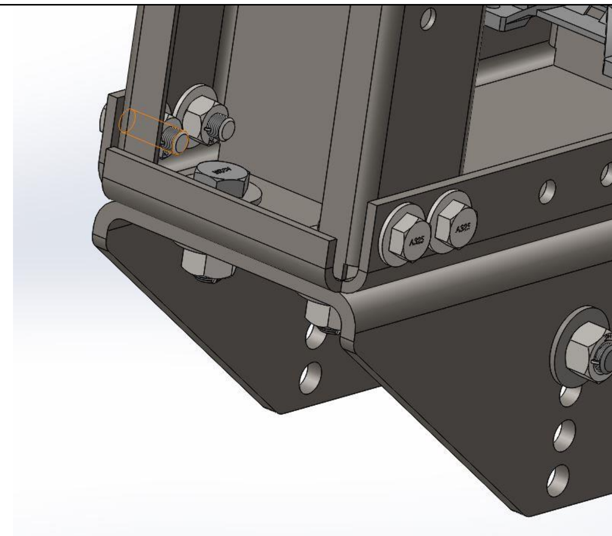
$$\frac{1}{2}[F_d(36.96") + F_d(0.44)(30.64")] \leq 222.8 \text{ k-in}$$

$F_d(25.22") \leq 222.8$ k-in

$F_d \leq 8.83$ kips

Determine the maximum drag load the bolted connection to the bottom bracket can take.





The channel has a bolted flange to flange connection to another part of the assembly. The picture above shows the dimensional properties of the holes and the assembly connection. The following calculations will determine the maximum drag load for the bolts due to a shear failure and the channel in an end bearing failure.

5/8" Diameter Grade 5 Carriage Bolt Shear Capacity –

$\phi V_n = 0.75(0.307\text{in}^2)(48\text{ksi}) = 11$ kips

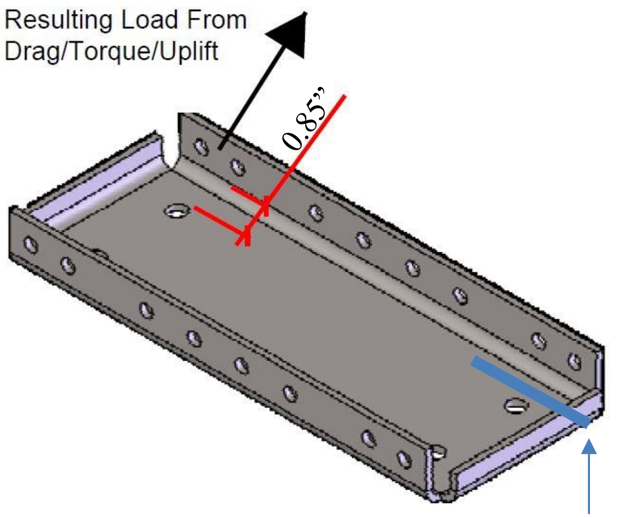
$$\frac{1}{8}F_L + \frac{1}{4}\left[\frac{F_d(36.96+30.64[0.44])}{6.8"}\right] \leq 11 \text{ kips}$$

$$\frac{1}{8}(0.78)(F_d) + (1.85)(F_d) \leq 11 \text{ kips}$$

$$F_d \leq 5.65 \text{ kips}$$

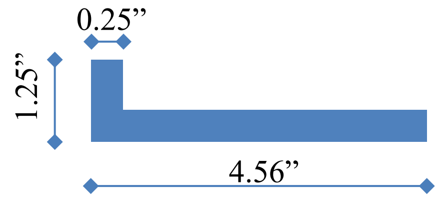
The end bearing capacity of the channel is not a limit state for this connection as the bottom bracket fits tightly around the upright, thus creating a fixed condition that doesn't allow for rotation of the channel upright, the assembly will rotate cohesively. The above check for shear is a conservative check for the same reasons, the channel cannot rotate inside the bracket independently.

Base, Center Structure, Square Holes ATI PN 30452-000



Section used for bending calculation

Properties of section in bending:



Material is 50 KSI and 0.25” thick.

Calculate the Neutral Axis:

$$\frac{4.56(0.25)(0.125) + 1.0(0.25)(0.75)}{4.56(0.25) + 1.0(0.25)}$$

$$N.A. = 0.237in \ \approx 0.25in$$

Calculate the plastic modulus:

$$4.56(0.25)(0.125) + 1.0(0.25)(0.5)$$

$$Z = 0.269in^3$$

This part supports the vertical channels in the prior calculation. The following analysis will determine the maximum drag load for the channel in a bending and an end bearing failure.

The bending capacity of the plate is:

$M_n = 0.9(50ksi)(0.269in^3) = 12.11$ k-in

Determine the maximum drag load the bracket can resist in bending:

$$\left[\frac{1}{2}\left(\frac{F_d[36.96+30.64(0.44)]}{6.8"} + \frac{F_L}{2}\right)\right] \times 0.85" \leq 12.11 \text{ k-in}$$

$$\left[\frac{1}{2}\left(7.42 \times F_d + \frac{0.78F_d}{2}\right)\right] \leq 14.25 \text{ k-in}$$

$$\left[\frac{1}{2}(7.81 \times F_d)\right] \leq 14.25 \text{ k-in}$$

$F_d \leq 3.65$ kips

Channel End Bearing Capacity -

R_n = 1.5(0.53in)(0.25in)(65ksi) ≤ 3.0(0.625in)(0.25in)(65ksi)

R_n = 12.92 kips ≤ 30.47 kips

ϕ R_n = (0.75)(12.92 kips) = 9.69 kips

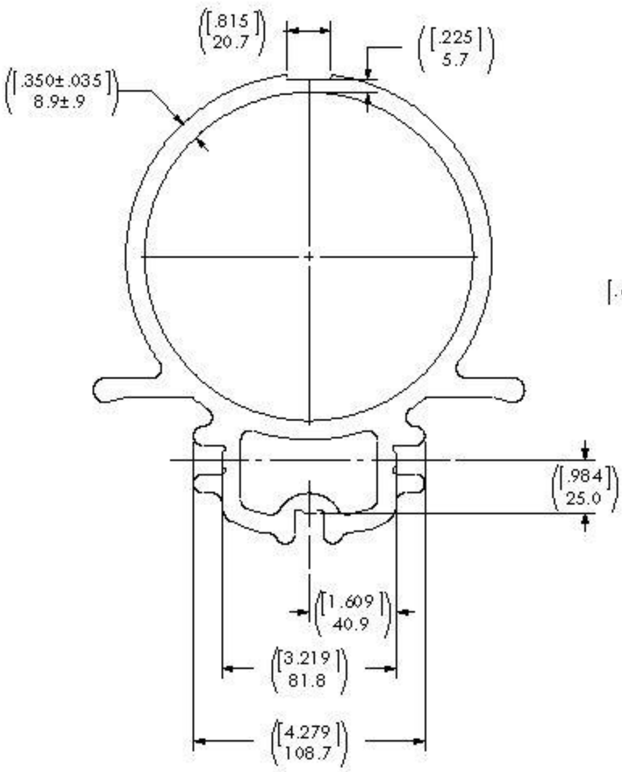
Maximum drag, use end bearing capacity:

$$\frac{1}{8}F_L + \frac{1}{4}\left[\frac{F_d(36.96+30.64[0.44])}{6.8''}\right] \leq 9.69 \text{ kips}$$

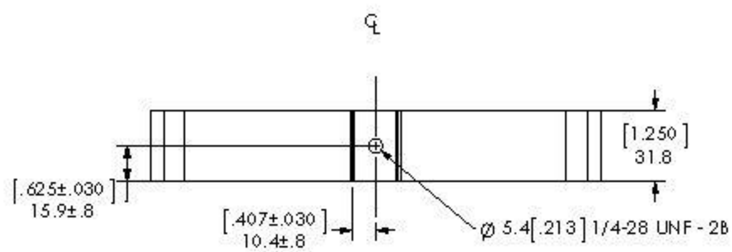
$$\frac{1}{8}(0.78)(F_d) + (1.85)(F_d) \leq 9.69 \text{ kips}$$

$$F_d \leq 4.98 \text{ kips}$$

<u>Housing, Bushing, Center Structure, Outboard Supports, XXXmm, Strap Hole</u>
<u>ATI PN 30476-000</u>



<u>SIDE VIEW</u>



<u>TOP VIEW</u>

Each center bearing housing will resist half of the applied drag load, vertical load, and resulting couple force from torsion. The following calculations will assess the capacity of the extrusion and bolts.

The extrusion is 1.25" wide and 0.225" thick at the narrowest cross section. It is composed of aluminum alloy 6005A/T61. The bolts are grade 5 carriage bolts, approximately 0.47" in diameter.

The capacity of the extrusion is:

$$P_n = 0.225"(1.25")(35ksi)(0.9) = 8.86\ kips$$

The capacity of a single bolt in shear is:

$$V_n = \frac{(0.47")^2}{4} \times \pi \times 0.75 \times 48ksi = 6.25\ kips$$

Maximum load for the extrusion:

$$\frac{1}{2}\left(\frac{F_d \times 4.38"}{3.75"} + F_L + T_c\right) \leq 8.86\ kips$$

$$\frac{1}{2}\left(\frac{F_d \times 4.38"}{3.75"} + 0.78F_D + 0.44F_D\right) \leq 8.86\ kips$$

$$F_d \leq 7.42\ kips$$

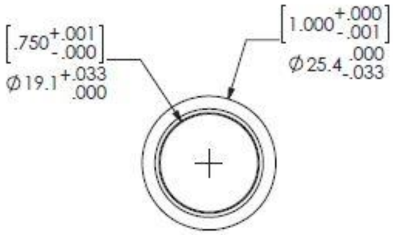
Maximum load for the bolts:

$$\frac{1}{2}\left(\frac{F_d \times 4.38"}{3.75"} + \frac{F_L}{6} + T_c\right) \leq 6.25\ kips$$

$$\frac{1}{2}\left(\frac{F_d \times 4.38"}{3.75"} + \frac{0.78}{3}F_D + 0.44F_D\right) \leq 6.25\ kips$$

$$F_d \leq 6.69\ kips$$

Gearbox, Output Stub Shaft, 25MM ATI PN 40102-000



The shaft is composed of mild steel 1018 with a minimum yield strength of 53 ksi. As seen in the free body diagram of the assembly the shaft will have to resist the resulting couple force from torsion in bending. The distance between the uprights which act as the support for the shaft is 10.75”. The maximum moment on the hollow shaft will be at 3.25” from the bearing in the channel upright. The output shaft of the gearbox inserts into the shaft at a depth of 1 3/8” of an inch.

Shaft capacity:

$$M_n = 0.9 \times 53ksi \times \frac{1.0in^3}{6} = 7.95 \text{ k-in}$$

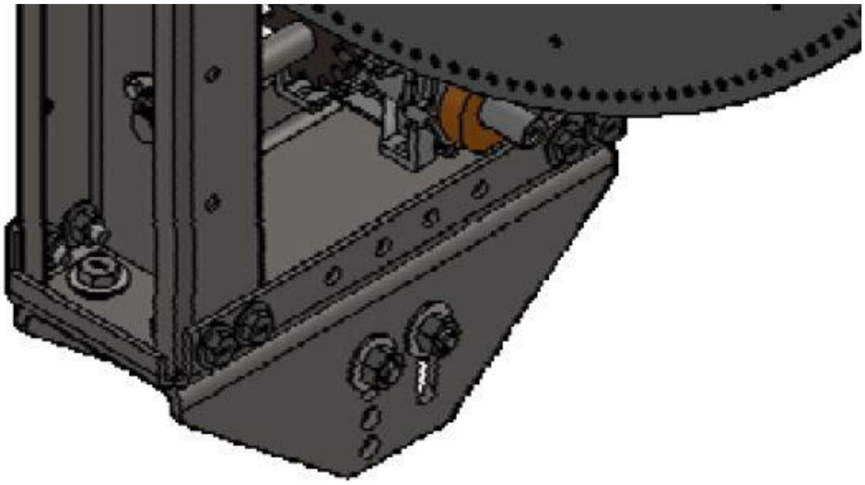
Maximum load on shaft:

$$\frac{T_c \times 3.25"}{2} \leq 7.95 \text{ k-in}$$

$$\frac{0.44F_d \times 3.25"}{2} \leq 7.95 \text{ k-in}$$

$$F_d \leq 11.12 \text{ kips}$$

Bracket, Mounting, Center, I-Beam, 0.375 in, W6 x(XX), XXX mm HDG ATI PN 30292-000



The bracket connects to a W6 I-beam, this connection is analyzed as a shear connection for the 5/8" diameter bolts. Through testing we have observed a small acceptable amount of slip from the oversize hole in the I-beam, but the bolt does not slip relative to the bracket. After the initial amount of movement the test was carried out to the reported loads at the end of this package without any failure occurring. The tested loads exceed ϕVn of the bolts, therefore limiting the capacity of this component to the shear strength of the bolts is a conservative approach.

The shear capacity of a 5/8" diameter A325 bolt is 11.00 kips.

$$\frac{F_L}{2} + \frac{F_d(36.96") + T_c(30.64")}{6"} \leq 11\ kips + 11 kips$$

$$\frac{F_d(0.78)}{2} + \frac{F_d(36.96") + F_d(0.44)(30.64")}{6.75"} \leq 22\ kips$$

$$F_d(0.39) + F_d(7.47) \leq 22\ kips$$

$$F_d \leq 2.80\ kips$$

The following table is a summary of the weakest component of the critical parts of the gear rack center structure assembly.

		From Analysis
ATI PN 30500	F_d	5.65 kips
ATI PN 30452	F_d	3.65 kips
ATI PN 30476	F_d	6.69 kips
ATI PN 40102	F_d	11.12 kips
ATI PN 30292	F_d	2.80 kips

The weakest element of the structure is the connection to the I-beam, with only 2.80 kips of capacity. This correlates to the following applied loads:

F_d	2.80 kips
F_L	2.18 kips
T	3.16 k-ft

This results in a q_z of:

$$\frac{2800\ lbs\ \times 12}{\sin(52)(0.65)(L")(77.01")} = \frac{851.8\ lbs}{L\ \text{in-ft}}$$

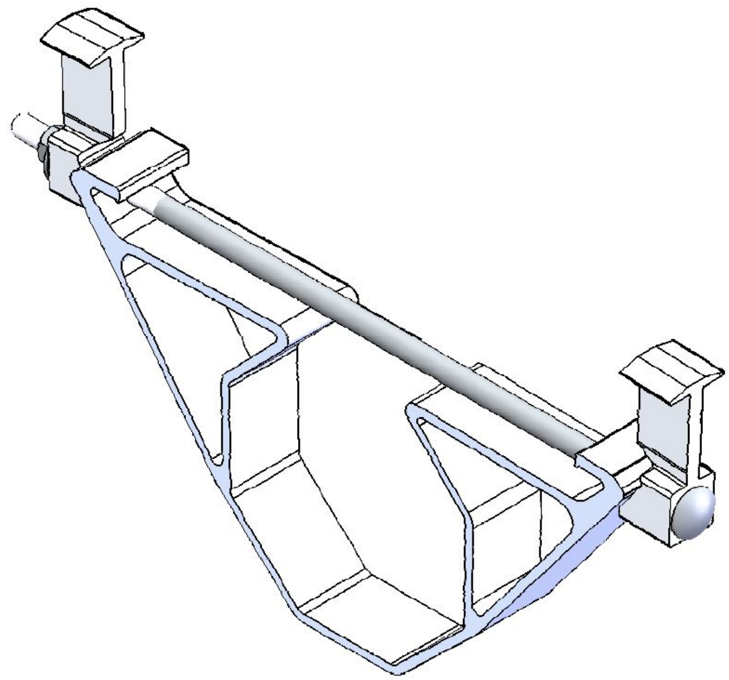
The maximum tributary area for a 130 MPH wind storm is:

$$\sqrt{\frac{851.8\ lbs}{L\ \text{in-ft}(0.00256 \times 0.85 \times 0.85)}} = 130\ \text{MPH}$$

$$\frac{851.8\ lbs}{L\ \text{in-ft}} = 31.26\ psf$$

$$L\ = 327.00\ in$$

Max Tributary Length at Various Wind Speeds for Interior Rows	
130 MPH	327.00 in
120 MPH	383.78 in
110 MPH	456.73 in
100 MPH	552.52 in

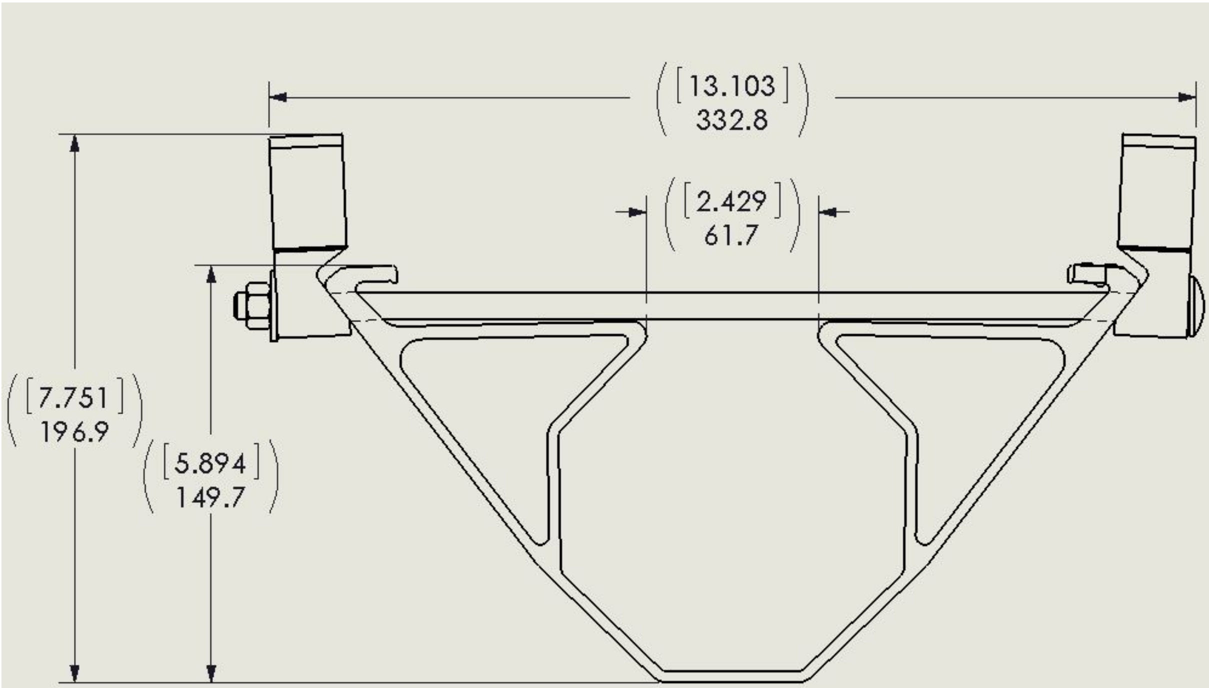


Module Mounting Clamp Analysis of DuraTrack® HZ Solar Tracker

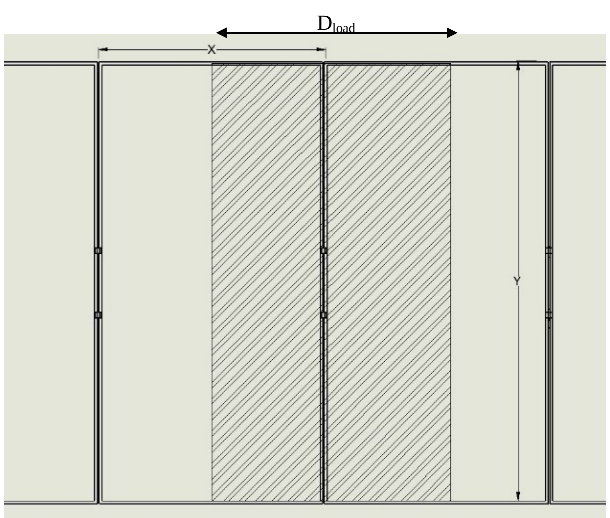
Completed by:
Kiran Tuniki P.E.
April 27, 2017
Array Technologies, Inc.

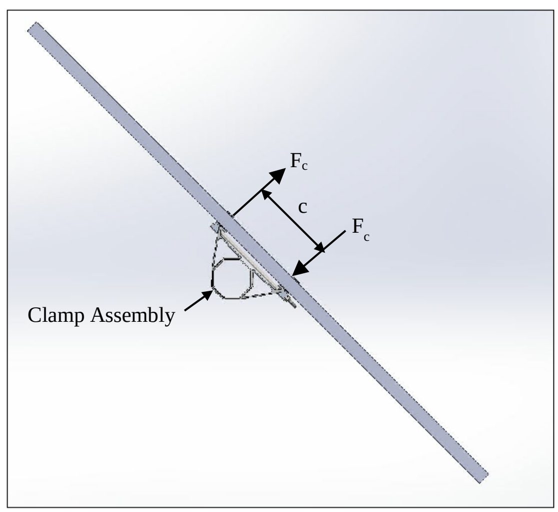
Module Mounting Clamp ATI PN 20415-000, 20563-000

The module mounting clamps are made of 6005A-T61 Aluminum per ASTM B221, 11.50" long, and have the following properties, with the cross-sections shown below:



The applicable surface area, A_S, for each clamp is shown shaded in the figure. To analyze the forces on the clamps, it is assumed that the average pressure on the panels will be resisted by a couple force, F_c, where clamp ears engages with module.





The hinge moment will be resisted by a force couple at the ends of the clamp, F_c. The octagonal tube and 3/8" bolt resist these forces with the tension in the bolts.

Assumption:

Module assembly width, x = 3.25 ft
Module assembly length, y = 6.42 ft

$d_{load} \cong x = 3.25 \text{ ft}, \quad c = 11.50 \text{ in}$

Considering the clamp as a truss element with axial forces. Axial compression and tension in the members would control the design. As there is pretension from clamping bolt that acts along with axial compression, top chord AB under compression will control the clamp assembly.

Using Aluminum Design Manual (ADM), chapter E to design compression members.

From E.4.2: Local buckling strength.

$P_n = F_c A_g$

F_c is determined section B.5.4.6.

$$\lambda_{eq} = \pi\sqrt{\frac{F}{F_e}} = \pi\sqrt{\frac{10{,}100}{35}} = 53.4$$

$$S_1 = \frac{B_p - F_{cy}}{D_p}$$

B_p and D_p are calculated from Table B.4.2

$$B_p = F_{cy}\left(1 + \left(\frac{F_{cy}}{1500k}\right)^{\frac{1}{3}}\right) = 35\left(1 + \left(\frac{35}{1500k}\right)^{\frac{1}{3}}\right) = 45$$

$$D_p = \frac{B_p}{10}\left(\frac{B_p}{E}\right)^{\frac{1}{2}} = \frac{45}{10}\left(\frac{45}{10{,}100}\right)^{\frac{1}{2}} = 0.30$$

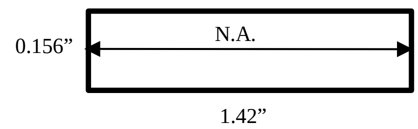
$$S_1 = \frac{45 - 35}{0.30} = 33.33$$

$$S_2 = \frac{k_1 B_p}{D_p}$$

From table B.4.3 $k_1 = 0.35$ and $k_2 = 2.27$

$$S_2 = \frac{0.35 \times 45}{0.30} = 52.5$$

$\lambda_{eq} \geq S_2$, post buckling applies:



$$F_c = \frac{k_2\sqrt{B_p \times E}}{\lambda_{eq}} = \frac{2.27\sqrt{45 \times 10{,}100}}{53.36} = 28.68 \text{ psi}$$

$$A_g = 1.42 \times 0.156 = 0.221 \text{ in}^2$$

$P_n = 28.68 \times 0.221 = 6.34$ kips from local buckling.

Check for member buckling: E3

$$P_n = F_c A_g$$

For $\frac{kL}{r} \geq S_2$, $F_c = \frac{0.85 \times \pi^2 E}{\left(\frac{kL}{r}\right)^2}$

From E.3.1 Flexural Buckling:

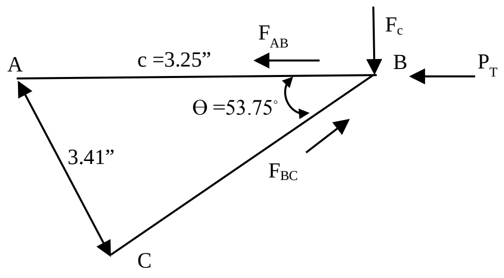
$$\frac{kL}{r} = \frac{1.0 \times 3.25}{\frac{0.156}{\sqrt{12}}} = 72.2, \ S_2 = 52.5$$

$$F_c = \frac{0.85 \times \pi^2 \times 10{,}100}{(72.2)^2} = 16.25 \text{ ksi}$$

$P_n = 16.25 \times 0.221 = 3.59$ kips, controls.

Member Analysis:

From the free body diagram of the clamp, considering pretension from bolt



Pretention in the clamping bolts, P_T, can be calculated as,

$$T = K \times D \times P_T$$

K – 0.25 for HDG,
D – nominal diameter, 0.375”
T – 20 Ft-Lbs

$$20 = 0.25 \times \frac{0.375}{12} \times P_T$$

P_T = 2,560 lbs, assuming that the pretension is equally resisted by both the half sections of the clamp. P_T = 1,280 lbs

$$F_c = P_{local} \times X \times Y \times \frac{Y}{11.5"} = P_{local} \times 3.25 \times 6.42 \times \frac{6.42}{11.5" \div 12} = 139.8 * P_{local} \text{ lbs}$$

Summing all horizontal and vertical forces at B:
$\Sigma H = 0$: F_{AB}+F_{BC} cos (53.75) = 0
$\Sigma V = 0$: - F_C + F_{BC} sin (53.75) = 0 →F_{BC} = 172.60 * P_{local} lbs

F_{AB} = 101.83*P_{local} lbs
F_{BC} = 172.59* P_{local} lbs

From maximum allowable axial compression of $P_n = 3.59$ kips -P_T = 2.31 kips

F_{AB} = 101.83*P_{local} lbs ≤ 2.31 kips

P_{local} ≤ 22.68 psf

The maximum GCm strip coefficient for 52 degrees is 0.24.

$P_{local} = q_z$ x GC_m ⟶ qz = 94.5 psf

Check for Clamping Bolt:

Strength of grade 2, 3/8” diameter carriage bolt loaded in shear and axial tension:

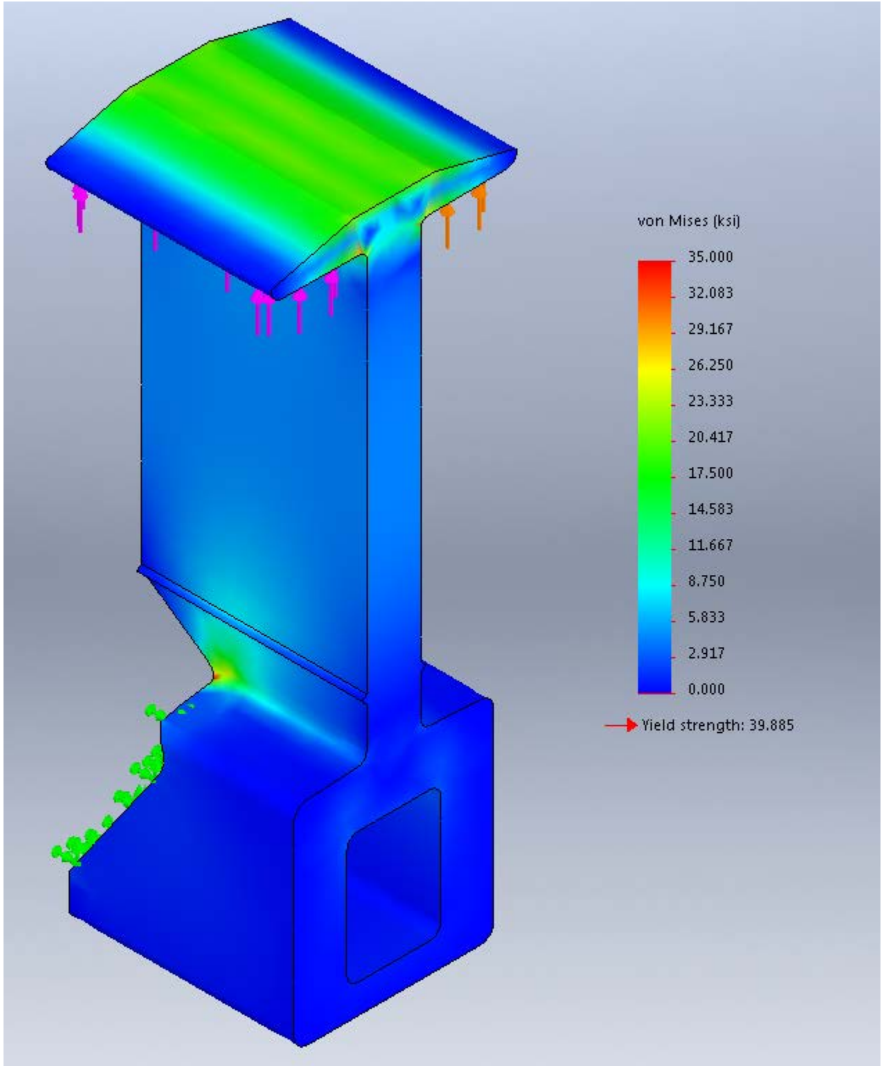
Shear Strength: shear strength of the SAE grade 2 bolt is similar to ASTM A307. Per AISC J3.6

$R_n = F_n \times A_b$
$A_b = \pi d^2 = \pi \times 0.375^2 = 0.442 \text{ in}^2$
$\emptyset R_n = 0.75 \times 24 \times 0.442 = 7.96$ kips > F_{AB} Clamp controls

F_n – for shear 24 ksi

Check for Module Ears:

Finite element analysis has been performed on module ear for a maximum pressure that a modules are generally rated to i.e. 110 psf and the average stress in module ear is 24 ksi leaving an additional safety factor of 1.50.

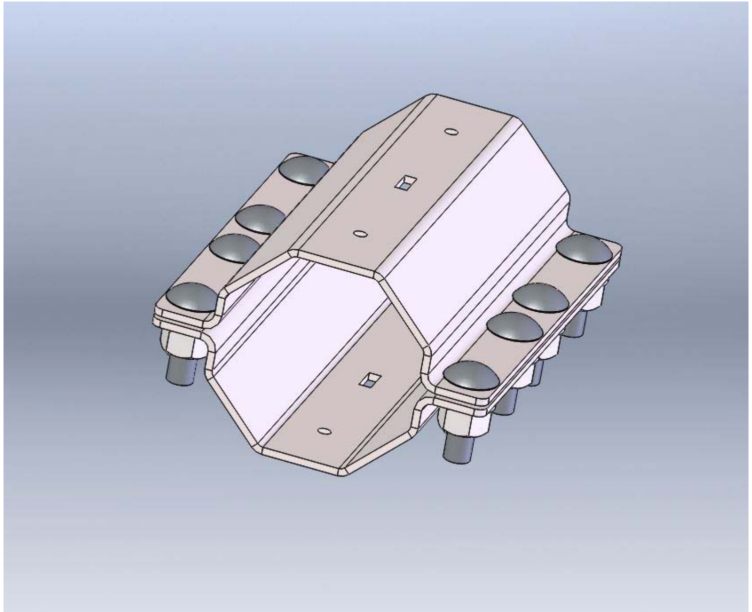


Results are as follows.

		From Analysis	From Test Results
For 12” clamp, Torque Pressure	P_{torque}	94.5 psf	28.46 psf*
For 12” clamp, Normal Pressure	P_{normal}	NA	110 psf

Limiting pressure 94.5 psf is adequate as the pressure on clamps for torque is well under this limit. Normal pressure for which clamps are tested and rated is 110 psf.

*In testing there is no failure noticed either in clamp or module but the testing was terminated once the rated pressure is achieved.

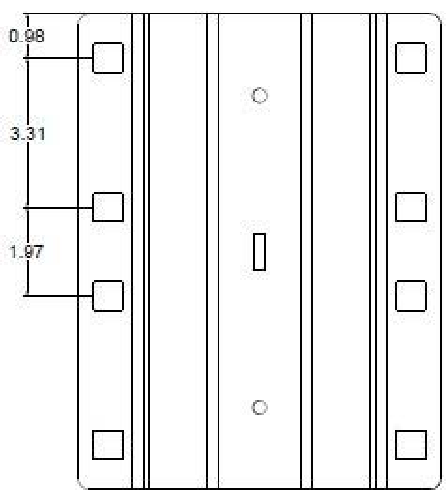


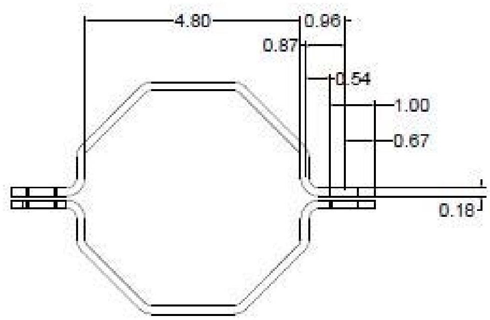
Coupler Analysis of DuraTrack™ HZ Solar Tracker

Completed by:
Kiran Tuniki and Jason Tankersley
March 12, 2015
Array Technologies, Inc.

Kit, Coupler, Octagon Tube Adaptor ATI PN 25031-000

The coupler is used to join the torque tubes throughout the row. The part is two roll formed pieces, made from A572 50 KSI material, that are bolted together with (8) 5/8" diameter Grade 5 carriage bolts torqued at 80 ft-lbs. The coupler is subject to torsion and bending similar to the torque tube. The governing factor of this analysis is bending of the lip where the two pieces of the coupler are bolted together. Both bending and torsion will result in tension in the bolt that creates the prying action phenomena that governs the thickness of the material. The roll formed pieces are of the same material as the torque tube and have a larger wall thickness. Therefore bending of the section will not govern the design, as the section in bending is stronger than the tubes the coupler joins. The below diagram shows the dimensions used in this calculation set in inches.





The pre-tension in the bolts will counter the applied tension through bending or torsion. The resulting clamping force of a single carriage bolt is:

$$T = KDP$$

$$80\ lb - in = 0.25(0.625)\frac{1}{12}(P)$$

$$P = 6{,}144\ lbs$$

The capacity of a 5/8" diameter bolt in tension is 20.7 kips. As long as the capacity of the plate results in a load less than 11 kips the bolts are adequate. Capacity per AISC 13th Edition, Table 7-2.

The following prying action analysis is in accordance with AISC 13th Edition, Chapter 9.

$$t_{min} = \sqrt{\frac{4.44Tb'}{pF_u(1+\delta\alpha')}}$$

$$\delta = 1 - \frac{d'}{p} = 1 - \frac{0.655}{2.63} = 0.751$$

β will be assumed at this point to be greater than 1, and verified at the end of the analysis. If β is greater than 1, α' will equal 1. Therefore:

$$0.18" = \sqrt{\frac{4.44(T - 6.144kips)(0.54")}{2.63"(65)(1 + 0.751)}}$$

$$0.032" = 0.00801(T - 6.144kips)$$

$T = 10.14$ kips

Verify β is greater than 1.

$$\beta = \frac{1}{\rho}\left(\frac{B}{T} - 1\right)$$

$$\rho = \frac{b'}{a'} = \frac{0.54"}{1.00"} = 0.54$$

$$\beta = \frac{1}{0.54}\left(\frac{20.7}{(10.16 - 6.144)} - 1\right) = 8.45 \geq 1.0 \implies Assumptions\ are\ OK$$

The allowable torsional moment is:

$Tor = 10.14kips(2\ bolts)(4.80") = 97.34$ k-in → 8.11 k-ft

*Note: 4.8" is the width of the torque tube.

The allowable bending moment is:

$Tor = 10.16kips(2\ bolts)(4.30") = 87.38$ k-in → 7.28 k-ft

*Note: 5.275" is the distance from the center of the bolt on the end to the center of the coupler.

		From Analysis	From Test Results
ATI PN 25031	Torsional Moment	8.11 k-ft	8.21 k-ft
ATI PN 25031	Bending Moment	7.28 k-ft	9.15 k-ft

Octagonal Torque Tube Structural Strength Calculation

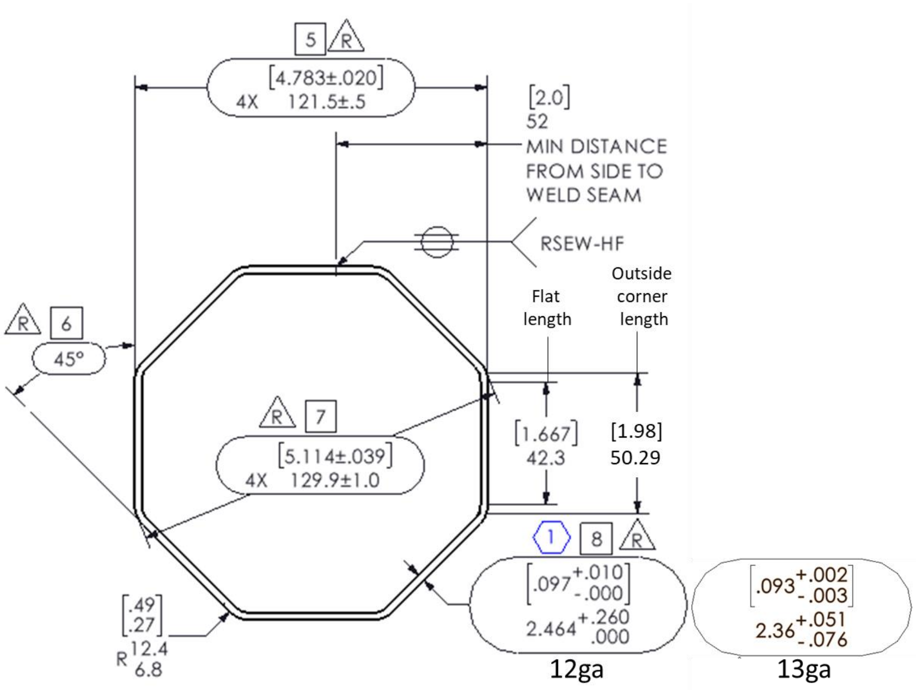
Revision: 1

Date: June 12, 2023

1. Purpose

This document establishes the ultimate flexural strength, shear strength, and torsional strength of the 12ga and 13ga octagonal torque tubes used in Array Technologies single axis trackers.

2. Cross Sectional Geometry



3. Material Properties

STEEL, TUBING, ASTM A500C. USE TUBING SPECIFICATION A500 FOR ALL DIMENSIONAL TOLERANCES EXCEPT AS NOTED ON DRAWING. POST FORMING PROPERTIES SHALL MEET THE FOLLOWING:

A. TENSILE STRENGTH, MIN: 76 ksi (525 MPA)
B. YIELD STRENGTH, MIN: 65 ksi (450 MPA)
C. ELONGATION, 2 in, MIN: 14%

Additionally, the Elastic Modulus is taken as 2.9e7 psi.

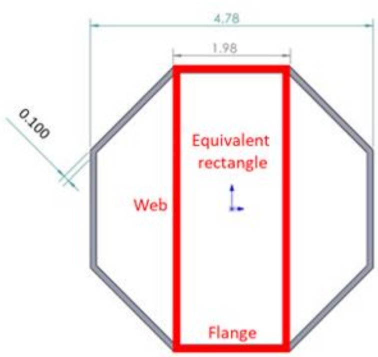
4. Methodology

Methods used here are according to 14th Edition of AISC Specification for Construction of Steel Buildings Load and Resistance Factor Design (LRFD). Flexural strength is per Chapter F. Shear strength is per Chapter G. Torsional strength is per Chapter H.

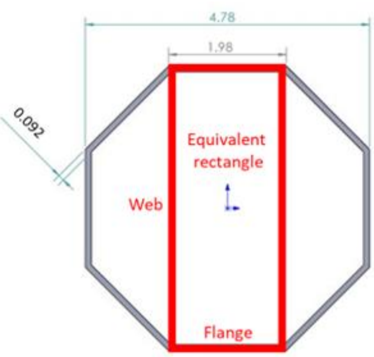
4.1. Flexural Strength

The nominal flexural strength, M_n, is taken as the lowest value obtained according to the limit states of yielding, flange local buckling, and web local buckling.

To determine the applicability of web and flange local buckling, an equivalent hollow rectangular cross section is considered per this schematic:



12ga



13ga

The analysis performed to justify the use of an equivalent rectangle to establish web and flange local buckling can be found in the appendix. The analysis used to establish t=0.100" as the calculation thickness for 12ga t=0.092" as the calculation thickness for 13ga can also be found in the appendix.

4.2. Shear Strength

For the assessment of shear strength, the cross section shall be viewed as an equivalent round HSS with a diameter, D, of 4.78". Note that assuming the octagon is a round HSS results in a lower strength than if the equivalent rectangle approach is assumed. This can be easily shown and therefore the proof of this is not included here. Since shear stress in the torque tube is not a significant contributor to the total stress state of the tube, the conservative approach of assuming an equivalent round shape is used here.

ROUND HSS

The *nominal shear strength*, V_n, of round *HSS*, according to the *limit states* of *shear yielding* and *shear buckling*, is

$$V_n = F_{cr} A_g / 2 \quad \text{(G6-1)}$$

where

F_{cr} shall be the larger of

$$F_{cr} = \frac{1.60E}{\sqrt{\frac{L_v}{D}}\left(\frac{D}{t}\right)^{\frac{5}{4}}} \quad \text{(G6-2a)}$$

and

$$F_{cr} = \frac{0.78E}{\left(\frac{D}{t}\right)^{\frac{3}{2}}} \quad \text{(G6-2b)}$$

but shall not exceed $0.6F_y$

4.3. Torsional Strength

The assessment of torsional strength is done by considering an equivalent round HSS with an outside diameter of 4.78".

Round and Rectangular HSS Subject to Torsion

The *design torsional strength*, $\phi_T T_n$, and the *allowable torsional strength*, T_n/Ω_T, for round and rectangular *HSS* according to the *limit states* of *torsional yielding* and *torsional buckling* shall be determined as follows:

$$\phi_T = 0.90 \text{ (LRFD)} \qquad \Omega_T = 1.67 \text{ (ASD)}$$

$$T_n = F_{cr} C \quad \text{(H3-1)}$$

where

C is the HSS torsional constant

The critical *stress*, F_{cr}, shall be determined as follows:

(a) For round HSS, F_{cr} shall be the larger of

(i)
$$F_{cr} = \frac{1.23E}{\sqrt{\frac{L}{D}}\left(\frac{D}{t}\right)^{\frac{5}{4}}} \quad \text{(H3-2a)}$$

and

(ii)
$$F_{cr} = \frac{0.60E}{\left(\frac{D}{t}\right)^{\frac{3}{2}}} \quad \text{(H3-2b)}$$

but shall not exceed $0.6F_y$,

User Note: The torsional constant, C, may be conservatively taken as:

For round HSS: $C = \frac{\pi(D-t)^2 t}{2}$

5. Calculations for 12ga Tube

5.1. Flexural Strength

<u>Per Table B4.1 of AISC:</u>

$$Thickness\ Ratio\ Limit\ for\ Compact\ Flange = 1.12 * \sqrt{2.9e7 / 65{,}000} = 23.65$$

$$\frac{1.98}{0.100} = 19.8 < 23.65 \quad therefore\ flange\ is\ compact$$

Flange Local Buckling

(a) For *compact sections*, the *limit state* of flange *local buckling* does not apply.

$$Thickness\ Ratio\ Limit\ for\ Compact\ Web = 2.41 * \sqrt{2.9e7 / 65{,}000} = 51.1$$

$$\frac{4.78}{0.100} = 47.8 < 51.1 \quad therefore\ web\ is\ compact$$

Web Local Buckling

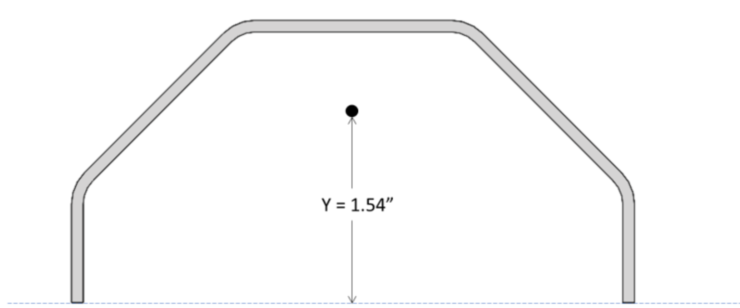
(a) For *compact sections*, the *limit state* of web *local buckling* does not apply.

Yielding

$$M_n = M_p = F_y Z \qquad \text{(F7-1)}$$

where

Z = plastic section modulus about the axis of bending, in.^{3} (mm^3)



Z = (Cross Sectional Area)*Y = (1.54 in^2)*(1.54 in) = 2.37 in^3

M_n = (65,000 psi)*(2.37 in^3) = 154,050 in-lbf = 12,838 ft-lbf = 154.05 in-kip

Design Flexural Strength = 0.9*154.05 = **138.65 in-kip**

5.2. Shear Strength

From equation G6-2b:

$$F_{cr} = \frac{0.78 * 2.9e7}{\left(\frac{4.78}{0.100}\right)^{3/2}} = 68{,}446 > 0.6F_y \ \ therefore\ F_{cr} = 0.6F_y = 0.6 * 65{,}000 = 39{,}000\ psi$$

From equation G6-1:

$$V_n = 39{,}000 * \frac{1.54}{2} = 30{,}030\ lbf\ = 30.03\ kips$$

Design Shear Strength = 0.9*30.03 = **27.03 kips**

5.3. Torsional Strength

From equation H3-2b:

$$F_{cr} = \frac{0.60 * 2.9e7}{\left(\frac{4.78}{0.100}\right)^{3/2}} = 52{,}651 > 0.6F_y \ \ therefore\ F_{cr} = 0.6F_y = 0.6 * 65{,}000 = 39{,}000\ psi$$

$$C = \frac{\pi * (4.78 - 0.100)^2 0.100}{2} = 3.44$$

From equation H3-1:

$$T_n = 39{,}000 * 3.44 = 134{,}176\ in - lbf\ =\ 11{,}181\ ft - lbf\ = 11.18\ ft - kip$$

Design Torsional Strength = 0.9*11.18 = **10.063 ft- kip**

6. Calculations for 13ga Tube

6.1. Flexural Strength

Per Table B4.1 of AISC:

$$Thickness\ Ratio\ Limit\ for\ Compact\ Flange = 1.12 * \sqrt{2.9e7/65{,}000} = 23.65$$

$$\frac{1.98}{0.092} = 21.5 < 23.65 \quad therefore\ flange\ is\ compact$$

Flange Local Buckling

(a) For *compact sections*, the *limit state* of flange *local buckling* does not apply.

$$Thickness\ Ratio\ Limit\ for\ Compact\ Web = 2.41 * \sqrt{2.9e7/65{,}000} = 51.1$$

$$\frac{4.78}{0.092} = 51.9 \approx 51.1 \quad therefore\ web\ is\ compact$$

O.K. since calculation uses length across outside corners. Using flat length gives much lower thickness ratio.

Web Local Buckling

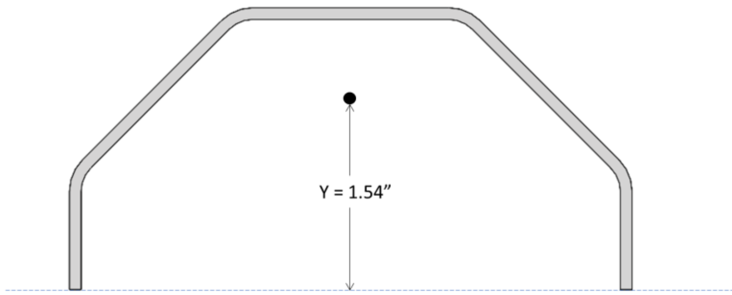
(a) For *compact sections*, the *limit state* of web *local buckling* does not apply.

Yielding

$$M_n = M_p = F_y Z \qquad \text{(F7-1)}$$

where

Z = plastic section modulus about the axis of bending, in.^{3} (mm^3)



Z = (Cross Sectional Area)*Y = (1.42 in^2)*(1.54 in) = 2.19 in^3

M_n = (65,000 psi)*(2.19 in^3) = 142,350 in-lbf = 11,862 ft-lbf = 142.35 in-kip

Design Flexural Strength = 0.9*142.35 = **128 in-kip**

6.2. Shear Strength

From equation G6-2b:

$$F_{cr} = \frac{0.78 * 2.9e7}{\left(\frac{4.78}{0.092}\right)^{3/2}} = 60{,}399 > 0.6F_y \ \ therefore\ F_{cr} = 0.6F_y = 0.6 * 65{,}000 = 39{,}000\ psi$$

From equation G6-1:

$$V_n = 39{,}000 * \frac{1.42}{2} = 27{,}690\ lbf = 27.69\ kips$$

Design Shear Strength = 0.9*27.69 = **24.92 kips**

6.3. Torsional Strength

From equation H3-2b:

$$F_{cr} = \frac{0.60 * 2.9e7}{\left(\frac{4.78}{0.092}\right)^{3/2}} = 46{,}461 > 0.6F_y \ \ therefore\ F_{cr} = 0.6F_y = 0.6 * 65{,}000 = 39{,}000\ psi$$

$$C = \frac{\pi * (4.78 - 0.092)^2 0.092}{2} = 3.18$$

From equation H3-1:

$$T_n = 39{,}000 * 3.18 = 124{,}020\ in - lbf = \ 10{,}335\ ft - lbf = 10.34\ ft - kip$$

Design Torsion Strength = 0.9*10.34 = **9.30 ft- kip**

7. Summary

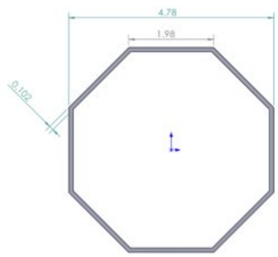
	12ga Tube	**13ga Tube**
Flexure, ϕM_n	138.65 in-kip	128 in-kip
Shear, ϕV_n	27.03 kip	24.92 kip
Torsional, ϕT_n	10.063 ft-kip	9.30 ft-kip

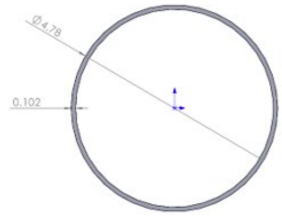
8. Appendix

8.1. Local Buckling Analysis

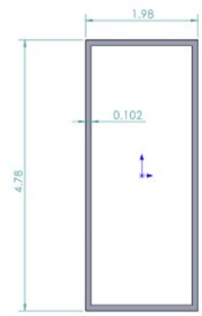
TABLE B4.1 (cont.)
Limiting Width-Thickness Ratios for Compression Elements

Case	Description of Element	Width Thickness Ratio	Limiting Width-Thickness Ratios λ_p (compact)	λ_r (noncompact)	Example
12	Uniform compression in flanges of rectangular box and hollow structural sections of uniform thickness subject to bending or compression; flange cover plates and diaphragm plates between lines of fasteners or welds	b/t	$1.12\sqrt{E/F_y}$	$1.40\sqrt{E/F_y}$	
13	Flexure in webs of rectangular HSS	h/t	$2.42\sqrt{E/F_y}$	$5.70\sqrt{E/F_y}$	
15	Circular hollow sections				
	In uniform compression	D/t	NA	$0.11E/F_y$	
	In flexure	D/t	$0.07E/F_y$	$0.31E/F_y$	

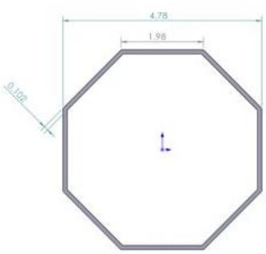


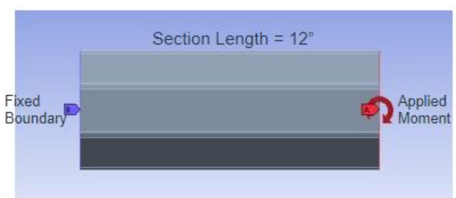


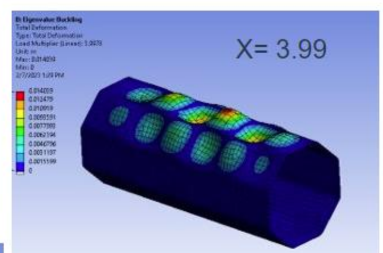
- E = 2.9e7 psi
- Fy = 65,000 psi



- Octagon is not explicitly covered in in Table B4.1 for local buckling
- Equivalent round and equivalent rectangle are options for local buckling assessment
- FEA to be used to determine which approach is more closely aligned with local buckling behavior of the octagon

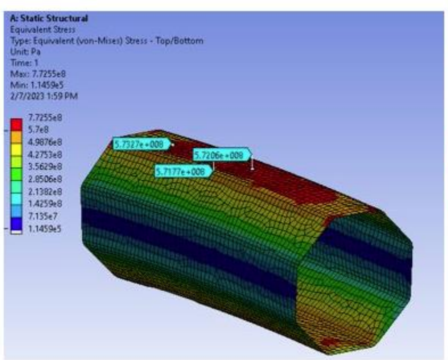


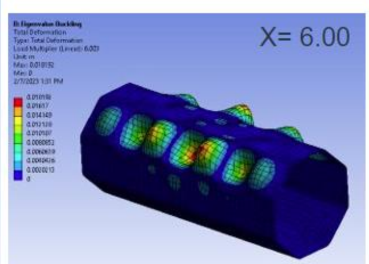




Lowest Buckling Mode: *Top face buckling*

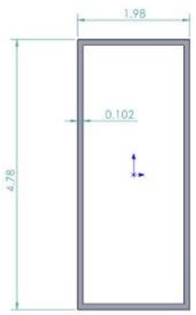
- Shell element mesh
- 8mm mesh size
- Arbitrary applied moment
- Linear bucking analysis

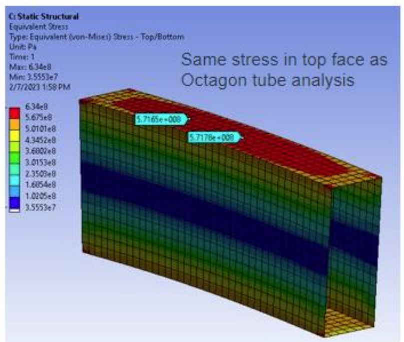


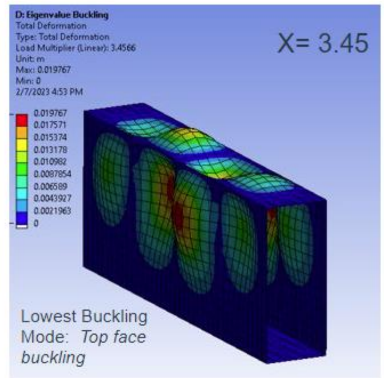


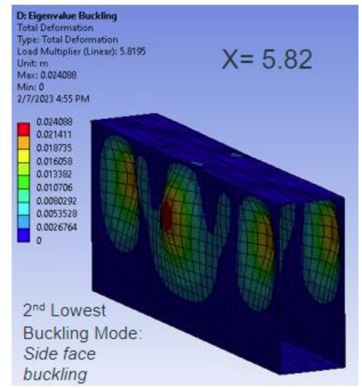
2nd Lowest Buckling Mode: *45deg face buckling*

Side face buckling is higher than mode 100 with factor > 22.0



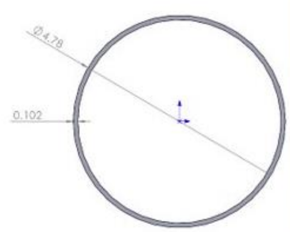


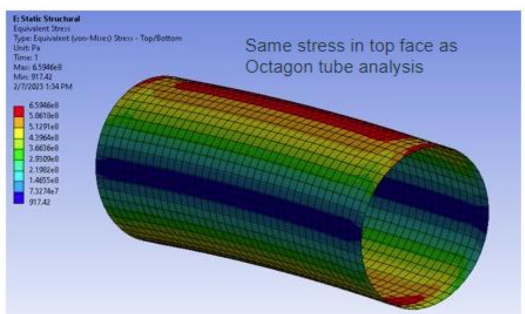


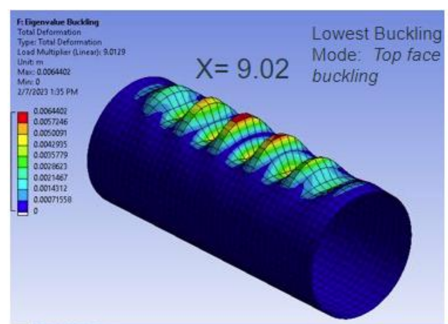


- Shell element mesh
- 8mm mesh size
- Arbitrary applied moment
- Linear bucking analysis

Rectangle shape approximation gives very similar local buckling results as the Octagon, with Octagon giving ~15% more capacity than the rectangle.

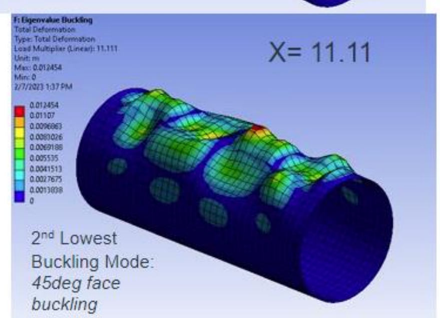


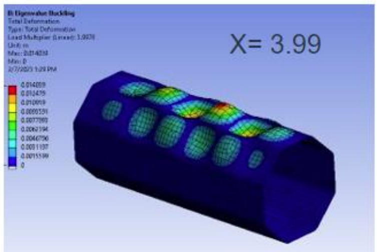


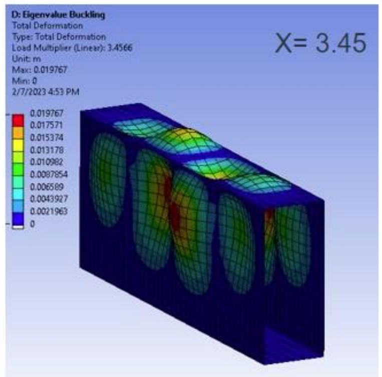


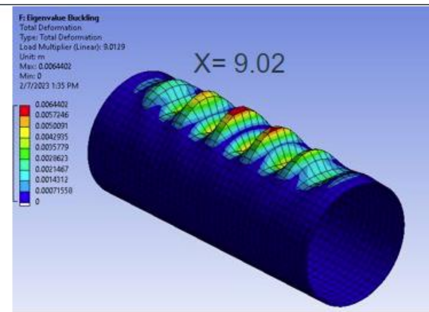
- Shell element mesh
- 8mm mesh size
- Arbitrary applied moment
- Linear bucking analysis

Round shape approximation does not match octagon local buckling with round giving ~ 225% higher capacity









Using the equivalent rectangle to establish criteria in AISC for "compact" or "non-compact" section is much more appropriate than using the equivalent round.

8.2. Calculation Thickness Analysis

Torque Tube Thickness Tolerance Comparison and Design Thickness Determination_12ga

G6. ROUND HSS

t = *design wall thickness*, equal to 0.93 times the nominal wall thickness for ERW *HSS* and equal to the nominal thickness for SAW HSS, in. (mm)

Hollow Structural Sections

Acceptable dimensional tolerances for HSS are given in ASTM A500 Section 10, A501 Section 11, A618 Section 8, or A847 Section 10, as applicable, and summarized in Tables 1–27 and 1–28, for rectangular and round HSS, respectively. Supplementary information can also be found in literature from HSS producers and the Steel Tube Institute, such as *Recommended Methods to Check Dimensional Tolerances on Hollow Structural Sections (HSS) Made to ASTM A500.*

THICK (in)	Array 12ga Tube	Square HSS	Round HSS (A53)	Round HSS (A500)
Nominal	0.102	0.102	0.102	0.102
Minimum	0.097	0.092	.0893	0.092
Maximum	0.107	0.112	none	0.112
0.93*Nom	0.095	N/A	0.095	0.095
	Below min thick		1.064*min thick	1.033*min thick

Table 1–27
Tolerances for Rectangular and Square HSS

ASTM A500, ASTM A501, ASTM A618, and ASTM A847				
Outside Dimensions	The outside dimensions, measured across the flats at positions at least 2 in. from either end, shall not vary from the specified dimensions by more than the applicable amount given in the following table:			
	Largest Outside Dimension Across Flats, in.		Permissible Variation Over and Under Specified Dimensions[a,b], in.	
	2½ and under		0.020	
	Over 2½ to 3½, incl.		0.025	
	Over 3½ to 5½, incl.		0.030	
	Over 5½		1 percent[c]	
Length	HSS are commonly produced in random lengths, in multiple lengths, and in definite cut lengths. When cut lengths are specified for HSS, the length tolerances shall be in accordance with the following table:			
	Length tolerance for specified cut lengths, in.			
	22 ft and under		Over 22 to 44 ft, incl.	
	Over	Under	Over	Under
	½	¼	¾	¼
Wall Thickness	ASTM A500 and ASTM A847 only: The tolerance for wall thickness exclusive of the weld area shall be plus and minus 10 percent of the nominal wall thickness specified. The wall thickness is to be measured at the center of the flat.			

Table 1–28
Tolerances for Round HSS and Pipe

ASTM A53	
Weight	The weight as specified in ASTM A53 Table X2.2 and Table X2.3 or as calculated from the relevant equation in ANSI/ASME B36.10M shall not vary by more than ± 10 percent. Note that the weight tolerance is determined from the weights of the customary lifts of pipe as produced for shipment by the mill, divided by the number of ft of pipe in the lift. On pipe sizes over 4 in. where individual lengths may be weighed, the weight tolerance is applicable to the individual length.
Diameter	For pipe 2 in. and over in nominal diameter, the outside diameter shall not vary more than ± 1 percent from the standard specified.
Thickness	The minimum wall thickness at any point shall not be more than 12.5 percent under the nominal wall thickness specified.
ASTM A500 and ASTM A847	
Diameter[a]	For HSS 1.900 in. and under in nominal diameter, the outside diameter shall not vary more than ± 0.5 percent, rounded to the nearest 0.005 in., from the nominal diameter specified. For HSS 2.000 in. and over in nominal diameter, the outside diameter shall not vary more than ± 0.75 percent, rounded to the nearest 0.005 in., from the nominal diameter specified.
Thickness	The wall thickness at any point, excluding the weld seam of welded tubing, shall not be more than 10 percent under or over the nominal wall thickness specified.

- AISC requirement for 0.93*nominal wall thickness is not completely clear
- Drawing tolerances for Array TT are tighter controlled than normal HSS
- AISC seems to be accounted for the wide tolerance of round HSS with 0.93*nominal requirement
- Better approach to use multiplier of minimum thickness rather than multiplier of nominal thickness

Possible thickness options for Array 12ga tube in design calculations:

Option 1: 0.93*nom = 0.93*0.102 = 0.095" this is lower than minimum thickness; not valid

Option 2: 1.064*min = 1.064*.097 = 0.103" this is higher than nominal thickness and may not be a good approach

Option 3: 1.033*min = 1.033*0.097 = 0.100" just below nominal thickness; good approach

Use **t=0.100"** for Array 12ga tube strength calculations

Torque Tube Thickness Tolerance Comparison and Design Thickness Determination_13ga

G6. ROUND HSS

t = *design wall thickness*, equal to 0.93 times the nominal wall thickness for ERW *HSS* and equal to the nominal thickness for SAW HSS, in. (mm)

Hollow Structural Sections

Acceptable dimensional tolerances for HSS are given in ASTM A500 Section 10, A501 Section 11, A618 Section 8, or A847 Section 10, as applicable, and summarized in Tables 1–27 and 1–28, for rectangular and round HSS, respectively. Supplementary information can also be found in literature from HSS producers and the Steel Tube Institute, such as *Recommended Methods to Check Dimensional Tolerances on Hollow Structural Sections (HSS) Made to ASTM A500.*

THICK (in)	Array 12ga Tube	Square HSS	Round HSS (A53)	Round HSS (A500)
Nominal	0.093	0.093	0.093	0.093
Minimum	0.090	0.084	0.081	0.084
Maximum	0.095	0.102	none	0.102
0.93*Nom	0.086	N/A	0.086	0.086
	Below min thick		1.062*min thick	1.024*min thick

Table 1–27
Tolerances for Rectangular and Square HSS

ASTM A500, ASTM A501, ASTM A618, and ASTM A847				
Outside Dimensions	The outside dimensions, measured across the flats at positions at least 2 in. from either end, shall not vary from the specified dimensions by more than the applicable amount given in the following table:			
	Largest Outside Dimension Across Flats, in.		Permissible Variation Over and Under Specified Dimensions[a,b], in.	
	2½ and under		0.020	
	Over 2½ to 3½, incl.		0.025	
	Over 3½ to 5½, incl.		0.030	
	Over 5½		1 percent[c]	
Length	HSS are commonly produced in random lengths, in multiple lengths, and in definite cut lengths. When cut lengths are specified for HSS, the length tolerances shall be in accordance with the following table:			
	Length tolerance for specified cut lengths, in.			
	22 ft and under		Over 22 to 44 ft, incl.	
	Over	Under	Over	Under
	½	¼	¾	¼
Wall Thickness	ASTM A500 and ASTM A847 only: The tolerance for wall thickness exclusive of the weld area shall be plus and minus 10 percent of the nominal wall thickness specified. The wall thickness is to be measured at the center of the flat.			

Table 1–28
Tolerances for Round HSS and Pipe

ASTM A53	
Weight	The weight as specified in ASTM A53 Table X2.2 and Table X2.3 or as calculated from the relevant equation in ANSI/ASME B36.10M shall not vary by more than ± 10 percent. Note that the weight tolerance is determined from the weights of the customary lifts of pipe as produced for shipment by the mill, divided by the number of ft of pipe in the lift. On pipe sizes over 4 in. where individual lengths may be weighed, the weight tolerance is applicable to the individual length.
Diameter	For pipe 2 in. and over in nominal diameter, the outside diameter shall not vary more than ± 1 percent from the standard specified.
Thickness	The minimum wall thickness at any point shall not be more than 12.5 percent under the nominal wall thickness specified.
ASTM A500 and ASTM A847	
Diameter[a]	For HSS 1.900 in. and under in nominal diameter, the outside diameter shall not vary more than ± 0.5 percent, rounded to the nearest 0.005 in., from the nominal diameter specified. For HSS 2.000 in. and over in nominal diameter, the outside diameter shall not vary more than ± 0.75 percent, rounded to the nearest 0.005 in., from the nominal diameter specified.
Thickness	The wall thickness at any point, excluding the weld seam of welded tubing, shall not be more than 10 percent under or over the nominal wall thickness specified.

- AISC requirement for 0.93*nominal wall thickness is not completely clear
- Drawing tolerances for Array TT are tighter controlled than normal HSS
- AISC seems to be accounted for the wide tolerance of round HSS with 0.93*nominal requirement
- Better approach to use multiplier of minimum thickness rather than multiplier of nominal thickness

<u>Possible thickness options for Array 12ga tube in design calculations:</u>

Option 1: 0.93*nom = 0.93*0.093 = 0.086" this is lower than minimum thickness; not valid
Option 2: 1.062*min = 1.062*0.090 = 0.096" this is higher than nominal thickness and may not be a good approach
Option 3: 1.024*min = 1.024*0.090 = 0.092" just below nominal thickness; good approach

Propose to use **t=0.092"** for Array 12ga tube strength calculations

Driveline Tube Analysis
Of
DuraTrack™ HZ Solar Tracker

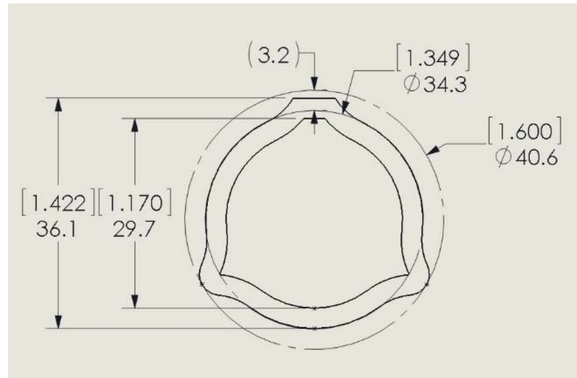
Completed by:
Kiran Tuniki and Jason Tankersley
August 19, 2015
Array Technologies, Inc.

Driveline Tubes

The driveline tube is cold formed from AISI 1020 steel with following properties.

F_y=42 ksi, A=0.522 in^2

There are no transverse loads applied to driveline tubes. Flexural capacity is not checked in this analysis. The section is primary checked for applied torsion.



Tube Section

(1) Torsional Strength: Using Table 20, case 14, from Roark's Formulas for Stress and Strain,

$$\tau = \frac{T}{2tA}$$

τ –allowable shear stress.
t- thickness of tube
A- mean area enclosed by outer and inner boundaries or area with in median boundary
T – torsional moment

$$0.6 \times 42 = \frac{T}{2 \times 0.126 \times 1.243}$$

$T = 7.89$ k-"
$\emptyset T_n = 0.9 \times 7.89 = 6.71$ k-" i.e. 593 lb-'

Summary:

	Limiting Strength
Torsion, $\emptyset T_n$	593 lb-ft

Applied torsion to the driveline in the worst case scenario is 525 lb-ft

References:

1. McGraw –Hill, Inc., 1989, *Roark's Formulas for Stress and Strain*, Warren C. Young

1 Executive Summary

The 400mm Thru-Bolt Mount (21011) is rated for loads corresponding to at least the following conditions:

- Max Normal Force, Uplift: -1,249 lbf (-5,558 N)
- Max Normal Force, Down: 1,314 lbf (5,843 N)
- Max Moment: 1,044 ft-lbs (1,416 Nm)

Under these conditions, the clamp assembly will pass testing when loaded as described in Section 4. The governing failure modes of this product are flexural yielding of the Module Rail, and flexural yielding of the strap or fasteners, resulting in loosening of bolted connections.

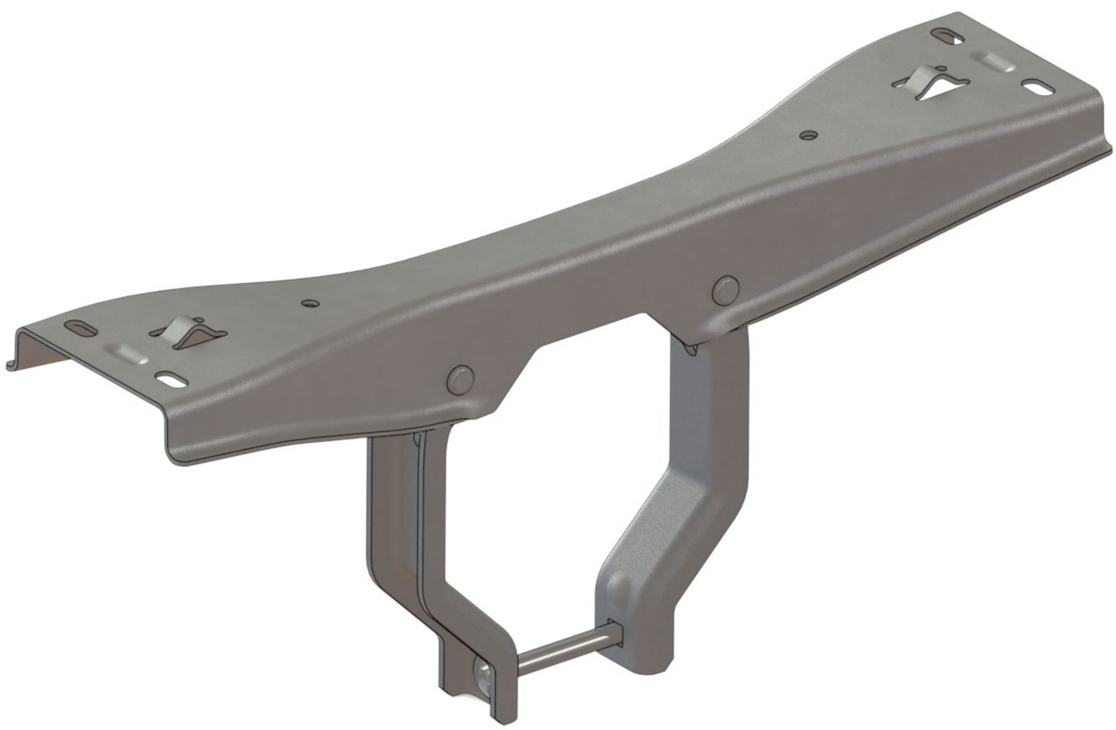


Table of Contents

2 Assembly Description

Array's 400mm Thru-Bolt Mount, 21011-901, attaches the photovoltaic (PV) modules to an octagonal steel torque tube. This arrangement is presented in Figure 1. This document provides a summary of the governing design limits of the product and their methods of calculation.

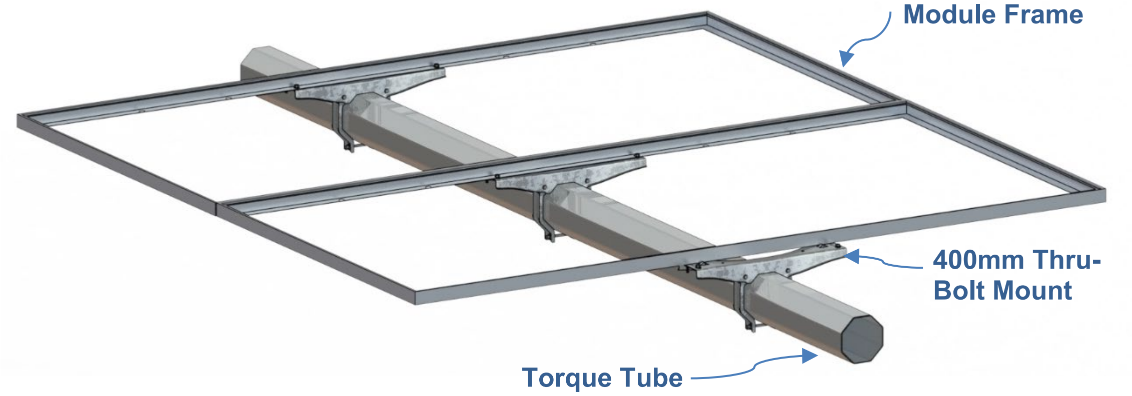


Figure 1: Through-Bolt Module Mount with Torque Tube and Module Frame

Figure 2 presents the components of the thru-bolt mount. The primary steel components include a module rail and two straps. Fasteners includes module attachement nuts and bolts, strap rivets, and torque tube/strap fasteners.

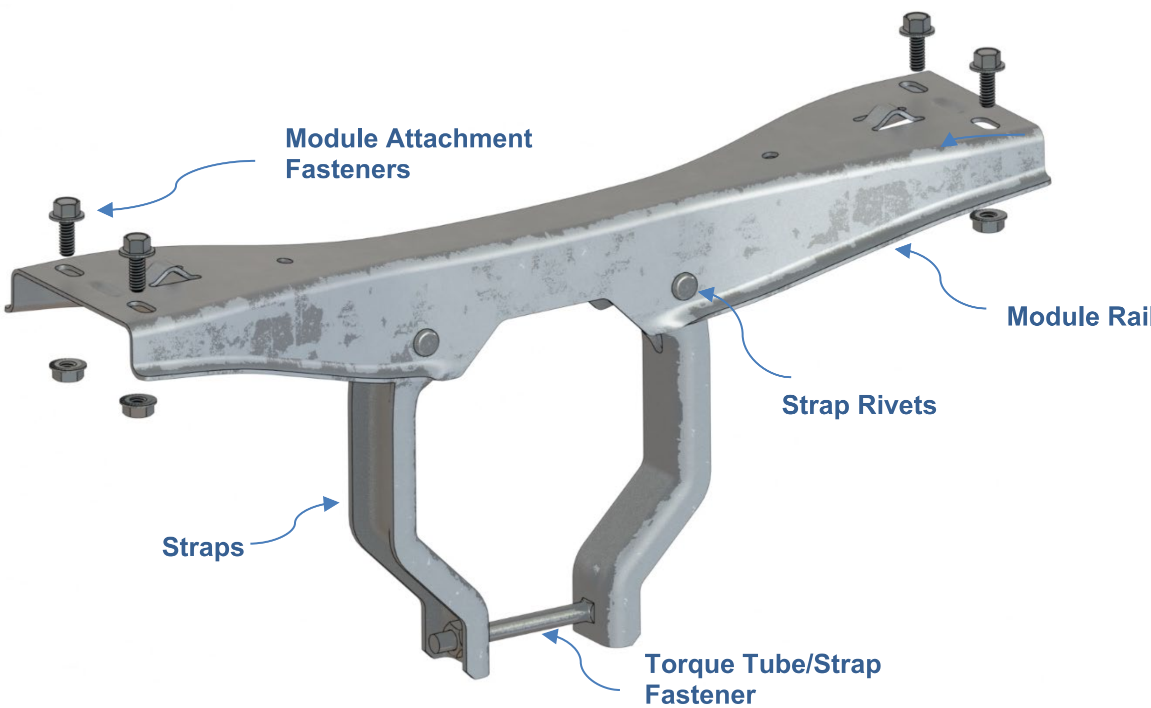


Figure 2: 400mm Through-Bolt Module Mount

Applying pretension to the torque tube/strap fasteners secures the module rail to the torque tube. The module is secured to the assembly by tightening the module attachment fasteners which applies clamping force to the module frame.

3 Detailed Description of Components

Each of the components in Figure 2 are described in this section, including material properties, bolt torques, manufacturing methods, and relevant dimensions.

3.1 Module Rail

The Module Rail (Figure 3) is stamped from 2.0mm (14 gauge) steel with a yield strength of 413 MPa (60ksi). The overall dimensions of the Module Rail are 432mm x 105mm x 62mm (17.0in x 4.1in x 2.4 in). The purpose of the module rail is to secure the module to the torque tube. It provides connection points to the module frame and to the torque tube straps interfacing with the torque tube. There are four slots on the top of the body for securing the module. The Module Rail also has four 8 mm (0.32in) holes for torque tube strap mounting.

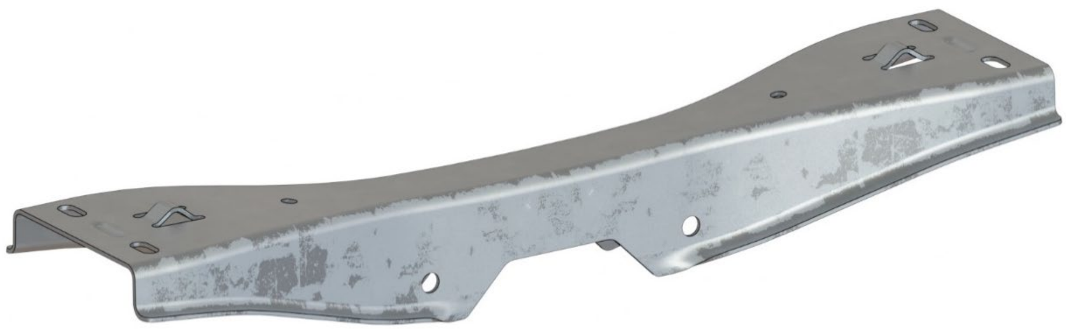


Figure 3: Module Rail

3.2 Torque Tube Straps

The torque tube straps are a stamped steel component made from pre-galvanized sheet with a minimum yield strength of 413 MPa (60ksi). The sheet is made from 11 gauge steel, with a nominal thickness of 3.13mm (0.123in). Figure 4 presents the overall dimensions of the cross section. The rivet hole that connects to the module rail has a diameter of 9.8mm (0.386in) and a minimum edge distance of 6.38mm (0.251in). The square carriage bolt hole has a minimum edge distance of 7.65mm (0.301in) and a square opening with 8.71mm (0.343in) across the flats.

Figure 4: Torque Tube Strap Overview

3.3 Strap Rivets

The strap rivets (Figure) secure the torque tube straps to the module rail, while allowing the straps to rotate freely for installation to the torque tube. The clevis pin is made from 7.94mm (0.3125”) diameter, 1018-1021 hot rolled steel or 302 stainless steel with a minimum yield strength of 345 MPa (50 ksi).

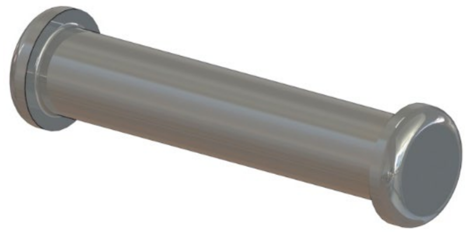


Figure 5: Strap Rivet

3.4 Torque Tube / Strap Fasteners

The torque tube/strap fasteners (Figure) include a 76mm (3.0in) long 5/16”-18 grade 8 carriage bolt and a serrated flange nut. The fastener assembly secures the clamp assembly to the torque tube by applying pretension to the bolt.

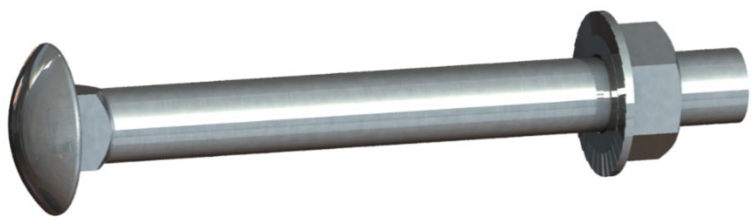


Figure 6: Torque Tube / Strap Fasteners

3.5 Module Attachment Fasteners

The module attachment fasteners (Figure 7) include a hex flange serrated bolt and hex flange serrated washer. The bolt is 15.8mm (0.625”) long, 1/4”-20, grade 5.

Figure 7: Module Attachment Fasteners

4 Load Inputs, Safety Factors, and Design Codes

The 400mm Thru-bolt Mount is designed to meet the following code criteria:

A. Wind loading is calculated in accordance with ASCE 7-10, Method 3.

B. Steel is designed to comply with AISC 360-10 standard.

The wind loads acting on the PV module are calculated in accordance with the ASCE 7 procedure using aerodynamic coefficients from a wind tunnel study performed by Cermak Peterka Petersen, Inc. (CPP). The coefficients selected represent the worst case loading condition from all wind directions within each region. The loading conditions evaluated include max pressure, max uniform load, and max torque in both uplift and downforce.

$$P = q_z \times GC_p$$

Where

P is the design wind pressure acting on the module

q_z is the velocity pressure evaluated at height z for the selected exposure as per ASCE 7 procedure.

GC_p is a loading coefficient provided via the wind tunnel testing discussed above

There are six different load cases considered for the mount. Max Pressure is presented in Figure 5 and Figure 6, Max Uniform is presented in Figure 7 and Figure 8, and Max Torque is presented in Figure 9 and Figure 10.

4.1 Max Pressure

Max Pressure is derived from the peak normal force coeffienents resulting in the maximum force being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition. Wind tunnel data provides unique GC_p values for each of the four quadrants presented below.

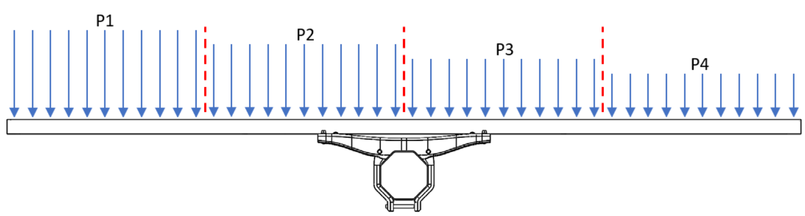


Figure 5: Max Pressure, Downforce

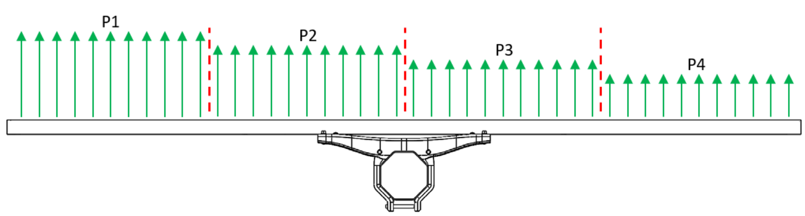


Figure 6: Max Pressure, Uplift

4.2 Max Uniform Pressure

Max Uniform is the area average of the max pressure load condition used to determine the design pressure in accordance with IEC 61215 MQT 16 static mechanical load test.

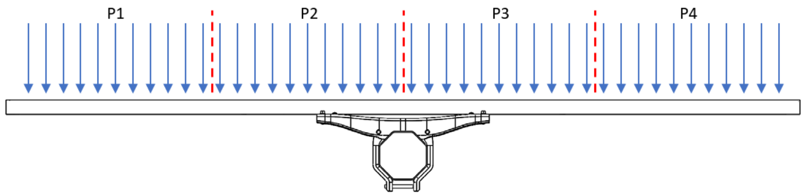


Figure 7: Max Uniform, Downforce

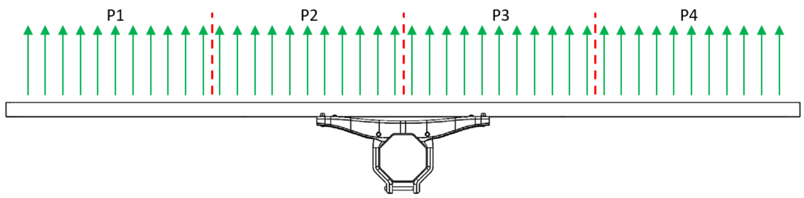


Figure 8: Max Uniform, Uplift

4.3 Max Torque

Max Torque is derived from the peak normal force coefficients resulting in maximum torque being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition.

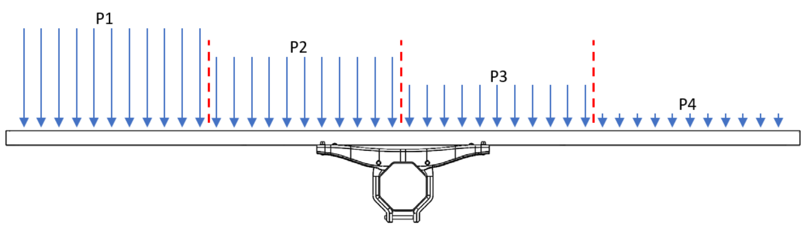


Figure 9: Max Torque, Downforce

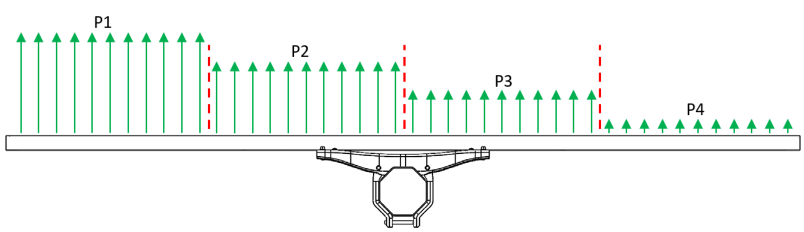


Figure 10: Max Torque, Uplift

The normal force and torque acting on the clamp are evaluated as:

$$F_N = (P_1A_1) + (P_2A_2) + (P_3A_3) + (P_4A_4)$$

$$M_{Torque} = \left[\left(\frac{3}{8}P_1A_1\right) + \left(\frac{1}{8}P_2A_2\right) - \left(\frac{1}{8}P_3A_3\right) - \left(\frac{3}{8}P_4A_4\right)\right]L$$

where;

A is the area of a strip equal to ¼ the module length times its width.

L is the cord length of the module.

The thru-bolt mount was designed using the ASD load combinations from Section 2.4.1 of ASCE 7-10 presented in Table 1.

Table 1: ASD Load Combinations

Combo	D	L	W	S	E
1	1	0	0	0	0
2	1	1	0	0	0
3	1	0	0	1	0
4	1	0.75	0	0.75	0
5	1	0	0.6	0	0
6a	1	0.75	0.45	0.75	0
6b	1	0.75	0	0.75	0.525
7	0.6	0	0.6	0	0
8	0.6	0	0	0	0.7

In addition to the strength calculations detailed in this report, the structural performance of the through-bolt mount has been established through testing[1], from which the allowable strength, R_a, has been calculated as follows:

$$R_a = R_n/\Omega$$

where;

R_n = Average failure value of all test results

Ω = safety factor;

[1.5] for max uniform load,

[1.21] for max pressure and max torsion

Results of a sample calculation (Table 3) with inputs (

Table 2) are shown below. These loads were tested in the above referenced DVT report. Alternate combinations of module size and wind speed may result in similar loads, so neither the wind speed nor module size can be considered a maximum when evaluated in isolation. The clamp is qualified for the applied load, which varies with each project site.

Table 2: Calculation Inputs

Wind Speed, ASCE 7	106.6	mph
kz	0.85	-
kzt	1	-
kd	0.85	-
I	1	-
H/L Ratio	0.6	-
Clamp Width	400	mm
Module Length	2384	mm
Module Width	1303	mm
Module Area	3.11	m²
Basic Wind Pressure	21.0	PSF
Uniform Loads Safety Factor	1.5	-
Non-Uniform Safety Factor	1.21	-
Service Factor	0.6	-
H/L Pressure Increase Factor	1.00	-
Module Length/Width Ratio	0.55	-

Table 3: Calculation Results

	A&B						C, D, &E					
	Downforce			Uplift			Downforce			Uplift		
Test Pressure	Pressure	Torque	Uniform	Pressure	Torque	Uniform	Pressure	Torque	Uniform	Pressure	Torque	Uniform
EE	1572	1260	1879	-1779	-2070	-1788	-1049	1066	1132	-1011	-811	-1177
E	1542	988	1879	-1703	-769	-1788	-1023	870	1132	-978	-534	-1177
W	1424	582	1879	-1608	-304	-1788	-884	597	1132	-839	-195	-1177
WW	1131	355	1879	-1455	-187	-1788	-697	271	1132	-765	-96	-1177
Test Loads Applied At Clamp Width (Metric)												
Total Force (N)	4402	2473	5837	-5083	-2586	-5553	-2836	2177	3516	-2791	-1270	-3657
Total Torque (N·m)	333	722	0	-247	-1415	0	-277	615	0	-203	-575	0
West Mount Load (N)	3034	3041	2918	-3159	-4832	-2776	-2110	2626	1758	-1902	-2072	-1828
East Mount Load (N)	1368	-568	2918	-1924	2246	-2776	-726	-449	1758	-889	802	-1828
Test Loads Applied At Clamp Width (Imperial)												
Total Force (lbf)	990	556	1312	-1143	-581	-1248	-638	489	790	-627	-286	-822
Total Torque (ft-lbs)	246	532	0	-182	-1044	0	-204	454	0	-149	-424	0
West Mount Load (lbf)	682	684	656	-710	-1086	-624	-474	590	395	-428	-466	-411
East Mount Load (lbf)	308	-128	656	-433	505	-624	-163	-101	395	-200	180	-411

The load case leading to maximum bending moment is “Region A&B- Max Uniform- Uplift”. However, when “Max Torque Uplift” loads are resolved to interior dimensions, the single-side torsional load governs the design.

5 Primary Component Limits

The following sub-sections provide summary calculations for the primary structural components in this assembly; the module rail and torque tube straps.

5.1 Module Rail

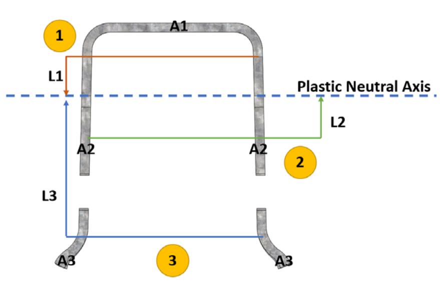
5.1.1 Module Rail Flexural Yield

The Module Rail is designed for “Max Uniform Up”, “Max Uniform Down”, “Max Pressure Up”, “Max Pressure Down”, “Max Torque Up” and “Max Uniform Down” load cases.

“Max Uniform” load cases lead to maximum stresses in the Module Rail and design calculation for the same is shown below.

The part is determined to be in flexure and checked for failure in terms of material strength.

I	=	area moment of inertia of the section	= $6.217*10^{-8}m^4$ ($0.149in^4$)
Y	=	distance from the centroid to the most extreme fiber	= 0.0317m (1.248in)
F_y	=	specified minimum yield stress of the steel	= 413.7 MPa (60ksi)
L_e	=	distance to load application	= 0.139m (5.45in)



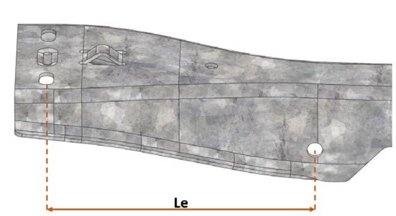


Figure 11: Module Rail Sectional Properties

S_y = elastic section modulus = 1.956*10^{-6} m^3 (0.119 in^3)

Z_y = plastic section modulus = 3.264*10^{-6} m^3 (0.199 in^3)

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 1.6 \times F_y S_y$$

$M_{n,\ yield}$ = 1350Nm (11.9 kip-in) plastic, or
1290Nm (11.4 kip-in) elastic

The Module Rail is also analyzed for buckling as a mode of failure. A nonlinear buckling analysis was performed using finite element method to evaluate the buckling failure modes and load multiplier. The design is proven to be safe for buckling through analysis and testing.

5.1.2 Module Rail Bearing Capacity

The torque tube straps are attached to the Module Rail using two 8.0mm (5/16") diameter rivets.

The minimum clear distance between the hole and edge of the strap is 9.3mm (0.36in) and the two pins are separated by a distance of 122.5mm (4.823in). Each side contains two bearing faces to distribute the respective load, and section J3.10 of AISI 360 provides the following guidance.

The bearing strength at the rivet holes, when deformation at the bolt hole at service load is a design consideration

$$R_n = 1.2 l_c t F_u \leq 2.4 d t F_u$$

For local compressive yielding, the nominal bearing strength is;

R_n = 15.8 kN (3.56 kips) per hole or 31.6 kN (7.12 kips) per connection.

For shear rupture, the nominal bearing strength is;

R_n = 11.6 kN (2.61 kips) per hole or 23.2 kN (5.22 kips) per connection.

The worst-case loading on the rivet holes connection is in the max-torque uplift scenario.

5.2 Torque Tube Straps

The torque tube straps are evaluated both for flexural yield and for bearing strength at the fastener mounting holes. While flexural yield is calculated here, plastic flexural yield is actually required for a proper clamping connection to the torque tube.

5.2.1 Strap Flexural Yield

The torque tube straps are subject to flexure of the web where the straps are bolted together.

This analysis uses ANSI/AISC 360-16, Chapter F6: I Shaped Members and Channels Bent About Their Minor Axis. The nominal flexural strength (M_n) of the component is the lower value of either yielding or flange local buckling. The calculations below reference the dimensions noted in Figure 4.

First evaluating the yielding failure mode:

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 1.6 \times F_y S_y$$

where

I = area moment of inertia of the section = 2.776 x 10^{-9} m^4 (0.00667in^4)

Y = distance from the centroid to the most extreme fiber = 0.00965m (0.380in)

F_y = specified minimum yield stress of the material = 413.7 MPa (60ksi)

L_e = distance to load application = 0.016m (0.639in)

S_Y = elastic section modulus taken about the y-axis = 2.868 x 10^{-7} m^3 (0.0175in^3)

Z_Y = plastic section modulus = 5.433 x 10^{-7} (0.0332in^3)

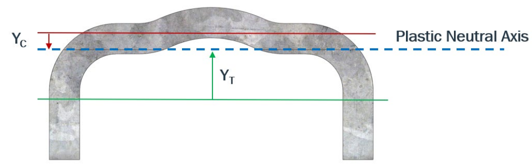


Figure 12: Strap Sectional Properties

Thus,

$M_{n,\,yield}$ = 225.1 Nm (1.99 kip-in) plastic, or
189.8 Nm (1.68 kip-in) elastic

Plastic yielding is considered the governing failure mode for this design, as elastic yielding is required to attain clamping around the torque tube.

For flange local buckling,

$$M_{n,buckling} = M_p - \left(M_p - 0.7 \times F_y S_y\right)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)$$

$$\lambda = \frac{b}{t_f}$$

where,

b = the full nominal dimension of the flange = 0.014m (0.551in)

t_f = thickness of the flange = .00313m (0.1233in)

λ_{pf} = λ_p, the limiting slenderness for a compact flange, defined below = 9.15

λ_{rf} = λ_r, the limiting slenderness for a noncompact flange, defined below = 24.08

E = modulus of elasticity = 200 GPa (29000 ksi)

$$\lambda_p = 0.38 \times \sqrt{\frac{E}{F_y}}$$

$$\lambda_r = 1.0 \times \sqrt{\frac{E}{F_y}}$$

thus:

$M_{n,buckling}$ = 257.91 Nm (2.283 kip-in)

If the flange were to be considered slender, then:

$$M_n = F_{cr} S_y$$

$$F_{cr} = \frac{0.69E}{\left(\frac{b}{t_f}\right)^2}$$

Thus,

$M_{n,slenderbuckling}$ = 1978.3 Nm (17.51 kip-in)

The governing failure mode for the lower strap is yielding, with a moment of 225.1 Nm (1.99 kip-in).

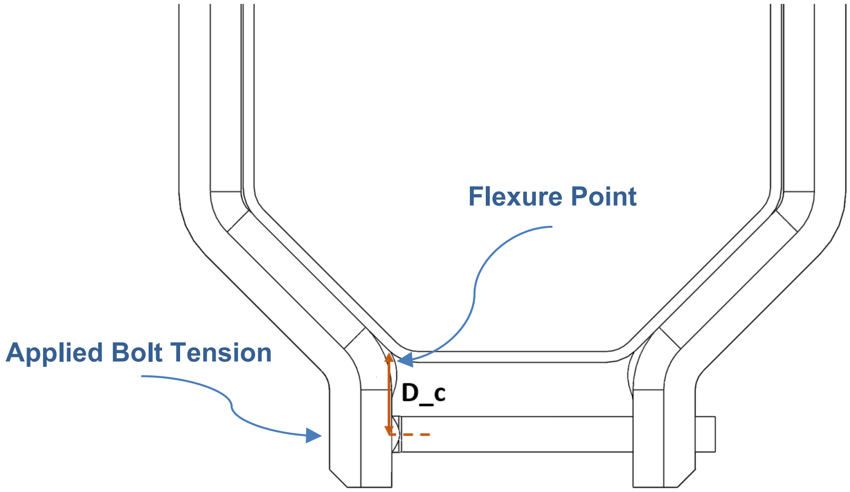


Figure 13: Flexural Point of the Torque Tube Straps

The 5/16-18 grade 8 bolt has a maximum pretension of 13.5 kN (3.04 kips), resulting in a utilization ratio of the torque tube strap of 97%. But while the base material of the torque tube strap has a yield strength of 413.7 MPa (60ksi), work hardening during the forming process increases the yield strength of the material around the bends, which is also the region of the flexure point. Thus, the work hardened material has a higher utilization ratio than noted above. Additionally, plastic deformation of the torque tube strap does not constitute a failure. Rather, it applies the necessary clamping load to the torque tube and relaxes the bolt pretension. Furthermore, the flexure region of the torque tube strap does not generally experience additional loading due to wind effects. The frictional faying forces of the straps on the torque tube provide resistance to wind loading, and flexure point on the straps themselves remain only exposed to the bolt tension.

5.2.2 Strap Bearing Capacity

The torque tube strap is attached to the Module Rail with a 8 mm (5/16 in) diameter pin.

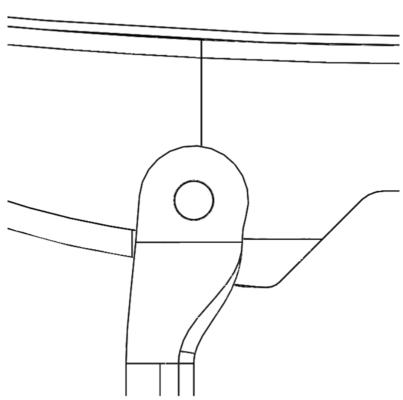


Figure 14: Torque Tube Strap Bearing Connection

The minimum material thickness between the hole and edge of the strap is 6.38mm (0.251in) and the two pins are separated by a distance of 122.5mm (4.823in). Each strap contains two bearing faces to distribute the respective load, and section J3.10 of AISI 360 provides the following guidance.

When deformation at the bolt hole at service load is a design consideration

$R_n = 2.4dtF_u$

R_n = 24.6 kN (5.54 kips) per hole or 49.2 kN (11.07 kips) per connection.

6 Hardware Limits

ANSI/AISC 360-16 was used to calculate tensile and shear capacity for each of the fastener sets. Per the code, the allowable tensile or shear strength, R_n, is provided by

$$R_n = F_n A_b$$

where:

A_b = nominal unthreaded body area of bolt or threaded part, in^2

F_n = nominal tensile stress, F_{nt}, or shear stress, F_{nv}, ksi

6.1 Strap Rivets

The straps are connected to the Module Rail using two 8mm (5/16”) diameter rivets with a minimum tensile strength of 440 MPa (63.8 ksi). Per ANSI/AISC 360-16, the rivets have a nominal shear strength of 247.7 MPa (35.9 ksi).

The body/strap fasteners are loaded in double shear. Thus, their design shear strength is; 2 x F_n x A_b = 24.5 kN (5.51 kips).

The hole-to-hole spacing of these fasteners is 122mm (4.82 in). The worst-case loading on these bolts is in the max-torque uplift scenario.

6.2 Torque Tube Fastener

The straps are connected to the torque tube using a 5/16”-18 grade 8 carriage bolt. Per ANSI/AISC 360-16, grade 8 bolts have a nominal tensile stress of 775.7 MPa (113 ksi).

Thus, the design tensile strength is; F_n x A_b = 38.3 kN (8.63 kips).

The carriage bolt is preloaded to 25.8 N.m. (19 ft.lbs.)

The torque tube/strap fastener is loaded in tension. From the free body diagram in Figure 15, considering the applied load on strap, P, the tension on the bolt, T_b, can be calculated as,

$P = R_{tY} = R_{tX}$

$F_F = 0.3R_t$ for galvanized steel

$$\sum M_0 = (0.589\, P) + (3.891\, P) - (0.589 \times 0.3\, P) - (3.891 \times 0.3\, P) - (5.361\, T_b) = 0$$

Therefore,

$T_b = 0.58\, P$

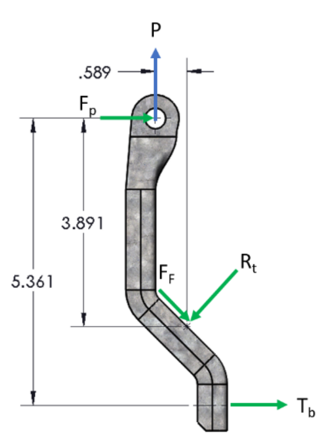


Figure 15: Free Body Diagram of Torque Tube Strap

6.3 Module Attachment Fasteners

The module connection is made using four 1/4”-20 grade 5 bolts. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 620.5 MPa (90 ksi).

The module attachment fasteners are loaded in tension. Thus, the design tensile strength is;

F_n x A_b = 19.66 kN (4.42 kips).

The bolts are preloaded to 12.2 N.m. (9 ft.lbs.).

The hole-to-hole spacing of these fasteners is 400mm (15.75 in). The worst-case loading on these bolts is in the max-torque uplift scenario.

7 Summary of Results

Below is a summary of the calculations and results discussed herein. For comparative purposes, an example site condition is provided below. In this example, a 47.7 m/s (106.6 mph) wind speed is assumed. The module dimensions are in accordance with the example calculations in Section 4. The governing load cases are max uniform up and max torque up. The results in Table 4 summarize the allowable load and the loads experienced at each of the components at the example site for both Max Uniform and Max Torque cases.

Table 4: Results Summary

Component	Limiting Load	Calculation Location	Test Case Uniform Load	Test Case Torque Load	Test Case Utilization Factor
Module Rail, Flexural	1290 Nm (11.4 kip-in)	5.1.1	404 N m (3.58 kip-in)	670 N m (5.93 kip-in)	52%
Module Rail, Buckling	27.4 kN (6.17 kips)	5.1.1	5.84 kN (1.312 kips)	5.84 kN (1.312 kips)	21%
Module Rail, Bearing	23.2 kN (5.22 kips)	5.1.2	9.45 kN (2.12 kips)	19.44 kN (4.37 kips)	84%
Torque Tube Strap, Flexural	225.1 Nm (1.99 kip-in)	5.2.1	219.1 Nm (1.94 kip-in)	219.1 Nm (1.94 kip-in)	97%[1]
Torque Tube Strap, Bearing	49.2 kN (11.07 kips)	5.2.2	9.45 kN (2.12 kips)	19.44 kN (4.37 kips)	40%
Rivets, Shear	24.5 kN (5.51 kips)	6.1	9.45 kN (2.12 kips)	19.44 kN (4.37 kips)	79%
Carriage Bolt, Tension	38.3 kN (8.63 kips)	6.2	14.86 kN (3.34 kips)	21.24 kN (4.78 kips)	55%
Module Attachment Fasteners, Tension	19.66 kN (4.42 kips)	6.3	11.19 kN (2.5 kips)	11.57 kN (2.6 kips)	59%

[1] The torque tube strap relies on some flexural yield to clamp the module mounting system to the torque tube. This flexural yield does not constitute a failure of the clamp.

Revision History:

Release Date	Revision	Description	Name
10/5/2022	A	Original Release	BF, SC

1 Executive Summary

The Through Bolt Clamp, 20895-901, is rated for loads corresponding to at least the following conditions:

- Wind Speed: 62.6 m/s (140 mph) 3-second gust
- Module Dimensions 2293 x 1131 mm (90.28 x 44.53 in)
- Module Uniform Design Pressure: 2224 Pa (46.45 psf)
- Module Uniform Test Pressure: 3336Pa (69.67 psf)

Under these conditions, 20895-901 will pass testing when the module is mounted at both the 1300 mm (51.2 in) and 400 mm (15.75 in) bolt locations. Other bolt location combinations may also pass in accordance with the governing limits discussed herein. The governing failure modes of this product are flexural yielding of the rail (dependent on bolt location), shear capacity of the rail/bracket fasteners, and flexural yielding of the strap.

Table of Contents

2 Assembly Description

Array's through-bolt module mount, 20895-901, attaches photovoltaic (PV) modules to an octagonal steel torque tube. This arrangement is presented in Figure 1. This document provides a summary of the governing design limits of the product and their methods of calculation.

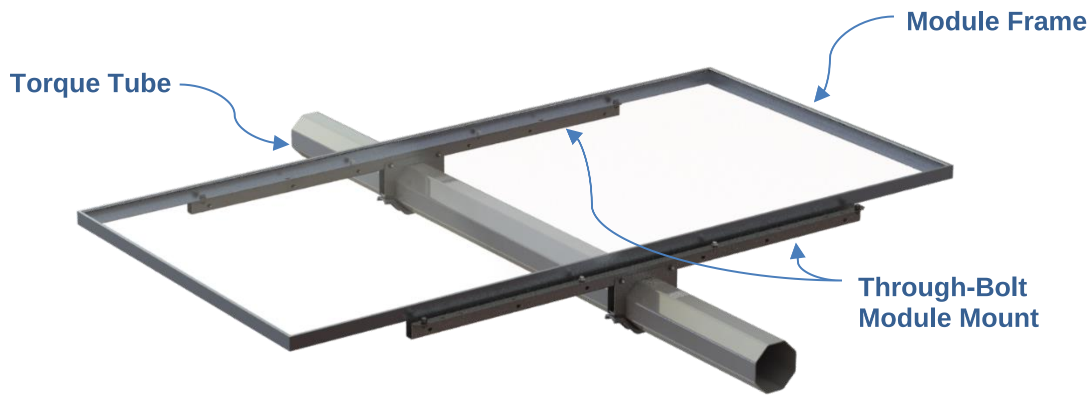


Figure 1: Through-Bolt Module Mount with Torque Tube and Module Frame

Figure 2 presents the components of the through-bolt module mount. The primary steel components include a rail, two brackets, and a strap. Hardware includes module attachment fasteners, bracket/purlin fasteners, and bracket/strap fasteners.

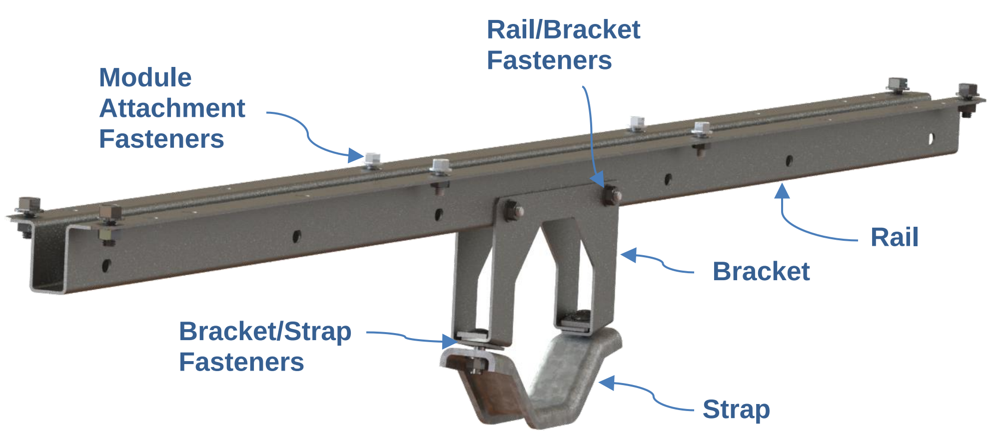


Figure 2: Through-Bolt Module Mount

Applying tension to the bracket/strap fasteners clamps the bracket and strap to the torque tube, and the PV module is attached to the assembly via the module attachment fasteners. Module attachment fasteners are placed in pre-defined locations that are dictated by the module selected for a given project. Depending on the module specifications, site wind speed, and module location within the field, each module will be attached with either four or eight fasteners. Eight fasteners are used for higher load conditions.

3 Detailed Description of Components

Each of the components in Figure 2 are described in this section, including material properties, bolt torques, manufacturing methods, and relevant dimensions.

3.1 Rail

The rail (Figure 1) is a roll-formed section of 14 gauge steel with a yield strength of 550 MPa (80 ksi). There are also two-length configurations, 1300 and 1400 mm (51.2 and 55.1 in). The overall dimensions of rails are 1350.0 x 73.9 x 42.4 mm (53.13 x 2.91 x 1.67 in) and 1447.0 x 73.9 x 42.4 mm (56.97 x 2.91 x 1.67 in) respectively for 1300 and 1400 mm (51.2 and 55.1 in) rails. The purpose of the rail is to clamp the module through the module mounting bolts and provide connection points for the bracket which interfaces with the torque tube. There are a series of 9 mm (0.354 in) diameter holes and four slots on top of the rails for module interface. There are twelve slots on the side surface of the rail for wire management.

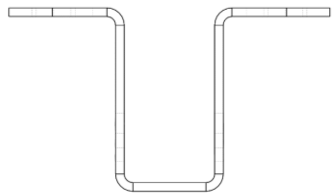


Figure 3: Rail

3.2 Bracket

The bracket (Figure 4) is a two-piece stamped 14 gauge steel component with a yield strength of 550 MPa (80ksi). The two pieces interface to capture the upper portion of the torque tube and provide connection points for the rail and strap. The overall dimensions of the bracket are 188 x 102 x 24mm (7.4 x 4 x 0.96 in). There are two 7.4mm (0.29 in) holes on the side surface of the bracket for the rail interface. Additionally, there are two 9 mm (0.354 in) square holes on the legs of the bracket for the strap interface.

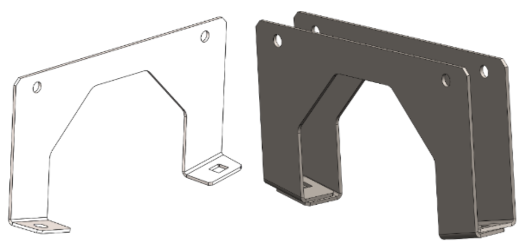


Figure 4: Bracket

3.3 Strap

The strap (Figure 5) is stamped from 7 gauge sheet steel with a minimum yield strength of 550 MPa (80ksi).

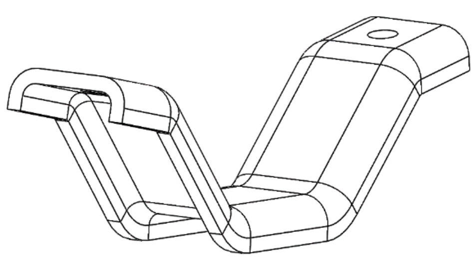


Figure 5: Strap

3.4 Bracket/Strap Fasteners

The bracket/strap fasteners (Figure 6) include a Grade 5 5/16-18 carriage bolt and serrated flange nut, and a washer plate that is 3.1mm (0.123 in) thick with outer dimensions of 20.5 x 28.0 mm (0.807 x 1.102 in). The washer plate is made from steel with a minimum yield strength of 500 MPa (72 ksi).

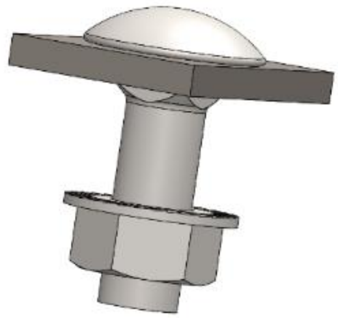


Figure 6: Bracket/Strap Fasteners

3.5 Rail/Bracket Fasteners

The rail/bracket fasteners (Figure 7) include a Grade 5 1/4-20 serrated flange bolt and serrated flange nut, and a steel spacer with a yield strength of 250 MPa (36ksi). The spacer fits between the vertical walls of the rail and acts as a compression limiter to keep the side walls of the rail from deforming under the bolt tension.

Figure 7: Rail/Bracket Fasteners

3.6 Module Attachment Fasteners

The module attachment fasteners (Figure 8) are Grade 5 serrated flange bolts and serrated flange nuts. In most scenarios, a 5/16-18 hardware set is used. Certain modules require bolting at the 400 mm (15.75 in) hole locations, which may require a 1/4-20 hardware set. This scenario is only used if mounting holes are not provided at the 800 mm (31.5 in) location.

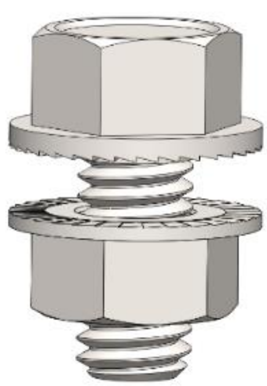


Figure 8: Module Attachment Fasteners

4 Load Inputs, Safety Factors, and Design Codes

The through-bolt module mount (20895-901) is designed to meet the following code criteria:

A. Wind loading is calculated in accordance with ASCE 7-10, Method 3.

B. Steel is designed to comply with AISC 360-10, and AISI S100-16 standards.

The wind loads acting on the PV module are calculated in accordance with the ASCE 7 procedure using aerodynamic coefficients from a wind tunnel study performed by CPP, Inc. The coefficients selected represent the worst case loading condition from all wind directions within each region. The loading conditions evaluated include max pressure, max uniform load, and max torque in both uplift and downforce.

$$P = q_z \times GC_p$$

Where:

P is the design wind pressure acting on the module

q_z is the velocity pressure evaluated at height z for the selected exposure as per ASCE 7 procedure.

There are six load cases considered for the clamp and presented below: Max Pressure (Figure 9 and Figure 10), Max Uniform (Figure 11 and Figure 12), and Max Torque (Figure 13 and Figure 14).

4.1 Max Pressure

Max Pressure is derived from the peak normal force coeffienents resulting in the maximum force being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition.

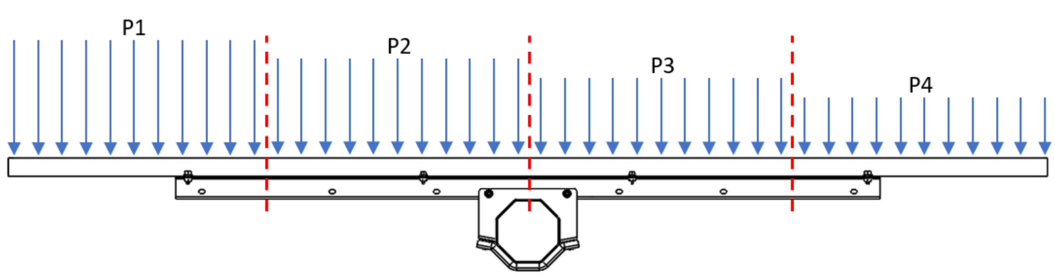


Figure 9: Max pressure, downforce

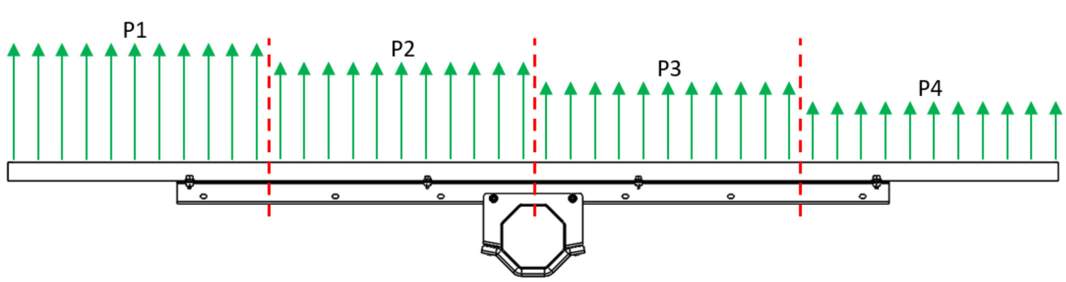


Figure 10: Max pressure, uplift

4.2 Max Uniform

Max Uniform is the area average of the max pressure load condition used to determine the design pressure in accordance with IEC 61215 MQT 16 static mechanical load test.

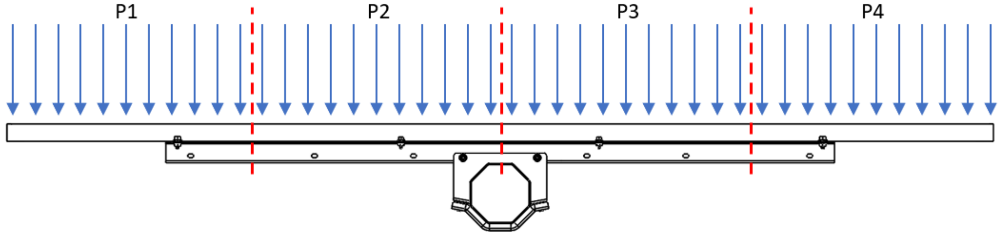


Figure 11: Max uniform, downforce

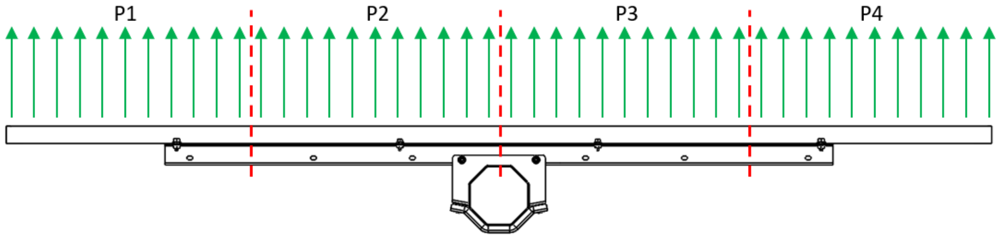


Figure 12: Max uniform, uplift

4.3 Max Torque

Max Torque is derived from the peak normal force coefficients resulting in maximum torque being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition.

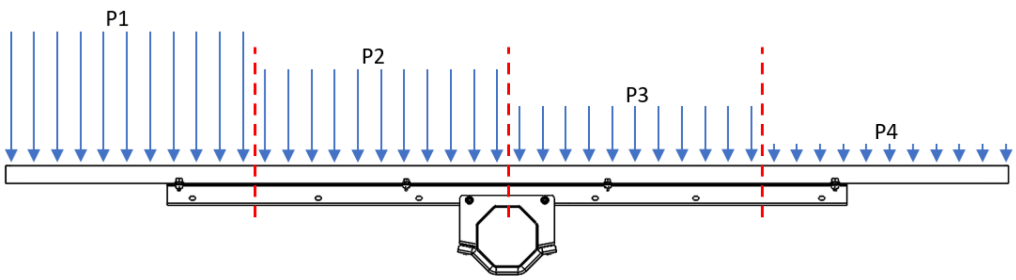


Figure 13: Max torque, downforce

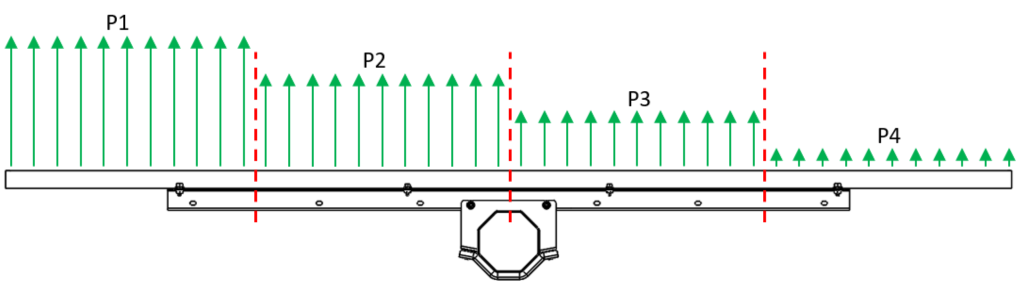


Figure 14: Max torque, uplift

The normal force and torque acting on the clamp are evaluated as:

$$F_N = (P_1A_1) + (P_2A_2) + (P_3A_3) + (P_4A_4)$$

$$M_{Torque} = \left[\left(\frac{3}{8}P_1A_1\right) + \left(\frac{1}{8}P_2A_2\right) - \left(\frac{1}{8}P_3A_3\right) - \left(\frac{3}{8}P_4A_4\right)\right]L$$

where;

A is the area of a strip equal to ¼ the module length times its width.

L is the cord length of the module.

The through-bolt mount was designed using ASD load combinations from Section 2.4.1 of ASCE 7-10.

Table 1: ASD Load Combinations

Combo	D	L	W	S	E
1	1	0	0	0	0
2	1	1	0	0	0
3	1	0	0	1	0
4	1	0.75	0	0.75	0
5	1	0	0.6	0	0
6a	1	0.75	0.45	0.75	0
6b	1	0.75	0	0.75	0.525
7	0.6	0	0.6	0	0
8	0.6	0	0	0	0.7

In addition to the strength calculations detailed in this report, the structural performance of the through-bolt mount has been established through testing[1], from which the allowable strength, R_a, has been calculated as follows:

$$R_a = R_n/\Omega$$

where

R_n = Average failure value of all test results

Ω = safety factor;

[1.5] for max uniform load,

[1.21] for max pressure and max torsion

[1] The test report DVT-20021-05 is available upon request.

Results of a sample calculation (Table 3) with inputs (Table 2) are shown below. These loads were tested in the above referenced DVT report. Alternate combinations of module size and wind speed may result in similar loads, so neither the wind speed nor module size can be considered a maximum when evaluated in isolation. The clamp is qualified for the applied load, which varies with each project site.

Table 2: Calculation Inputs

Pressure and Clamp Load Calcs

Wind Speed, ASCE 7*	mph	140
Uniform Loads Safety Factor		1.5
Non-uniform Safety Factor		1.21
H/L Pressure Increase Factor**		1
Uniform Pressure A&B Override	Pa	
Uniform Pressure CD&E Override	Pa	
Applied Load Width AB	mm	1300
Applied Load Width CDE	mm	1300
Panel Length	cm	228.5
Panel Width	cm	109.8
Panel Area	m²	2.51

Table 3: Calculation Results

Wind Pressure Prior to Safety Factor	A&B					
	Downforce			Uplift		
	#1 Max Pressure	#3 Max Torque	#5 Max Uniform	#2 Max Pressure	#4 Max Torque	#6 Max Uniform
EE	2241	1796	2020	-2536	-2952	-2333
E	2198	1409	2020	-2428	-1097	-2333
W	2031	830	2020	-2293	-433	-2333
WW	1612	506	2020	-2074	-266	-2333
Design Loads Applied At Clamp Span Including Safety Factor (Imperial)						
Total Force (lbf)	1379	775	1709	-1592	-810	-1974
Total Torque (ft-lbs)	328	711	0	-243	-1394	0
West Mount Load (lbf)	766	554	855	-853	-732	-987
East Mount Load (lbf)	612	221	855	-739	-78	-987

The load case leading to maximum bending moment is “Region A&B- Max Uniform- Uplift”. However, when “Max Torque Uplift” loads are resolved to interior dimensions, the single-side torsional load governs the design.

5 Primary Steel Component Limits

5.1 Rail

Rail is designed for “Max Uniform Up”, “Max Uniform Down”, “Max Pressure Up”, “Max Pressure Down”, “Max Torque Up” and “Max Uniform Down” load cases.

“Max uniform up” load case leads to maximum stresses in the rail and design calculation for the same is shown below. Different mounting holes on the top of the rail can be used to mount solar modules. This analysis shows use of 1300mm mounting holes on the rail. The analysis also assumed no influence of module frame on the bending capacity of the rail.

<u>Bending Moment Capacity of the Rail</u>

I= area moment of inertia of the section = 6.87 cm^4 (0.165 in^4)

Y= distance from the plastic neutral axis to the most extreme fiber = 31.5 mm (1.24 in)

F_y= specified minimum yield stress of the type of steel being used = 550 MPa (80 ksi)

Calculations for plastic neutral axis:

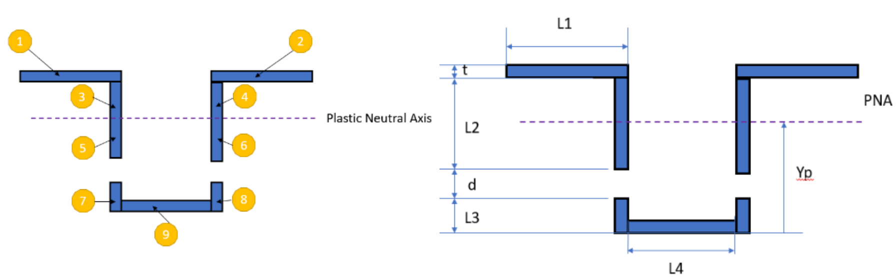


Figure 15: Rail Plastic Neutral Axis

$$\Sigma F = 0$$

$$F_1 = F_2 = F_y L_1 t$$

$$F_3 = F_4 = F_y(L_5 - Y_p)t \; ; \; L_5 = L_2 + D + L_3$$

$F_5 = F_6 = F_y(Y_p - d - L_3)t$

$F_7 = F_8 = F_y L_3 t$

$F_9 = F_y L_4 t$

$F_1 + F_2 + F_3 + F_4 + F_5 + F_6 + F_7 + F_8 + F_9 = 0$

$2(F_y L_1 t) + 2[F_y(L_5 - Y_p)t] - 2[F_y(Y_p - d - L_3)t] - 2(F_y L_3 t) - F_y L_4 t = 0$

$2L_1 + 2L_5 - 2Y_p - 2Y_p + 2d + 2L_3 - 2L_3 - L_4 = 0$

$4Y_p = 2L_1 + 2L_5 + 2d - L_4$

$4Y_p = 2L_1 + 2L_3 + 2d + 2L_2 + 2d - L_4$

$4Y_p = 2L_1 + 2L_2 + 2L_3 - L_4 + 4d$

$$Y_p = \frac{2L_1 + 2L_2 + 2L_3 - L_4 + 4d}{4}$$

$L_1 = 26.65\ mm\ ;\ d = 6.50\ mm\ ;\ L_2 = 26.95\ mm\ ;\ L_3 = 6.91\ mm\ ;\ L_4 = 20.85\ mm;\ t = 1.98\ mm$

$(L_1 = 1.049\ in\ ;\ d = 0.256\ in\ ;\ L_2 = 1.061\ in\ ;\ L_3 = 0.272 in\ ;\ L_4 = 0.821\ in;\ t = 0.078\ in)$

$Y_p = 31.54\ mm\ (1.24\ in)$

Calculations for Max Bending Moment

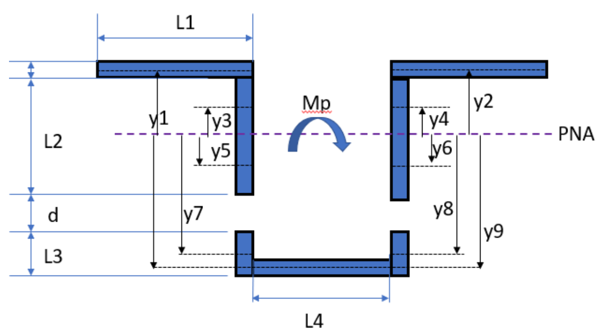


Figure 16: Rail Dimensions

$$y_1 = y_2 = L_5 - Y_p + \frac{t}{2}$$

$$y_3 = y_4 = \frac{L_5 - Y_p}{2}$$

$$y_5 = y_6 = \frac{Y_p - d - L_3}{2}$$

$$y_7 = y_8 = Y_p - \frac{L_3}{2}$$

$$y_9 = Y_p - \frac{t}{2}$$

$$\sum Mpna = 0$$

$Mpna = M_1 + M_2 + M_3 + M_4 - M_5 - M_6 - M_7 - M_8 - M_9$

$Mpna = F_y A_1 y_1 + F_y A_2 y_2 + F_y A_3 y_3 + F_y A_4 y_4 - F_y A_5 y_5 - F_y A_6 y_6 - F_y A_7 y_7 - F_y A_8 y_8 - F_y A_9 y_9$

$Mpna = 2134\ Nm\ (18.9\ kip - in)$

The higher load capacity of the clamp can be achieved by of use of multiple bolts to mount the module on the clamp. The frame of the module also provides added stiffness which increases the load-carrying capacity of the clamp. Special case calculation can be provided on request.

The rail is also analyzed for buckling as a mode of failure. Nonlinear buckling analysis was performed on ANSYS to make sure of any buckling failures. The design is proven to be safe for buckling through prototype testing (DVT-20021-05).

5.2 Bracket

The bracket is designed for "Max Uniform Up", "Max Uniform Down", "Max Pressure Up", "Max Pressure Down", "Max Torque Up" and "Max Uniform Down" load cases.

The "Max Torque up" load case leads to maximum stresses in the bracket and design calculation for the same is shown below. Different mounting holes on the top of the rail can be used to mount solar modules. This analysis shows use of 1300 mm (51.2 in) mounting holes on the rail.

Tensile Yield on vertical section

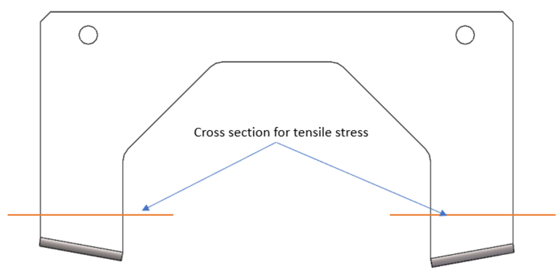


Figure 17: Bracket Cross Section

Applying section D2, Tensile Strength from the AISC/ANSI 360-16 code, the allowable tensile strength for tensile yielding in the gross section and for tensile rupture in the net section, the sectional properties are calculated for the combined area of two brackets.

For tensile yielding in the gross section:

$$P_n = F_y A_g$$

For tensile rupture in the net section:

$$P_n = F_u A_e$$

where,

Ae	= effective net area,	= 131mm^2 (0.204 in^2)
Ag	= gross area of member,	= 131mm^2 (0.204 in^2)
Fy	= specified minimum yield stress,	= 550 MPa (80 ksi)
Fu	= specified minimum tensile strength,	= 620 MPa (90 ksi)

thus:

$$P_{n,yield} = 72.6\ kN\ (16.32\ kips)$$

$$P_{n,rupture} = 81.6\ kN\ (18.35\ kips)$$

This load is below the tensile load of the bolt, which is 21.0 kN (4.72 kips).

5.3 Strap

The strap is subject to bending of the web where the strap is bolted to the bracket. Both uniform load and torsion will result in tension in the bolts, creating a prying action that governs the thickness of the strap material.

This analysis uses ANSI/AISC 360-16, Chapter F6: I Shaped Members and Channels Bent About Their Minor Axis. The nominal flexural strength (M_n) of the component is the lower value of either yielding or flange local buckling. The calculations below reference the dimensions noted in Figure 18.

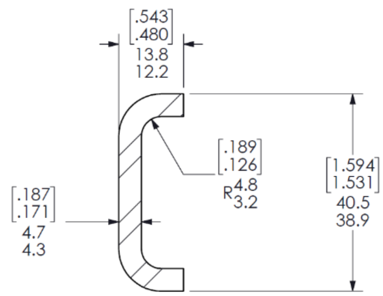


Figure 18: Cross Section of Strap

First evaluating the yielding failure mode:

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 0.6 \times F_y S_y$$

where

I	= area moment of inertia of the section	= 3.87 cm^4 (0.093 in^4)
Y	= distance from the neutral axis to the most extreme fiber	= 8.46 mm (0.333 in)
F_y	= specified minimum yield stress of the type of steel being used	= 550 MPa (80 ksi)
S_y	= elastic section modulus taken about the y-axis	= 0.344 cm^3 (0.021 in^3)
Z_y	= plastic section modulus taken about the y-axis	= 0.667 cm^3 (0.041 in^3)

thus

$M_{n,\ yield}$ = 368 Nm (3.26 kip-in) plastic or 114 Nm (1.013 kip-in) elastic

Plastic yielding is considered the governing failure mode for this design, as elastic yielding is required to attain clamping around the torque tube.

For flange local buckling,

$$M_{n,buckling} = M_p - \left(M_p - 0.7 \times F_y S_y\right)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)$$

$$\lambda = \frac{b}{t_f}$$

where,

b	= the full nominal dimension of the flange	= 13.0 mm (0.512 in)
t_f	= thickness of the flange	= 4.5 mm (0.179 in)
λ_{pf}	= λ_p, the limiting slenderness for a compact flange, defined below	= 7.235
λ_{rf}	= λ_r, the limiting slenderness for a noncompact flange, defined below	= 19.039
E	= modulus of elasticity	= 200 GPa (29,000 ksi)

$$\lambda_p = 0.38 \times \sqrt{\frac{E}{F_y}}$$

$$\lambda_r = 1.0 \times \sqrt{\frac{E}{F_y}}$$

thus:

$M_{n,buckling}$ = 455 Nm (4.025 kip-in)

If the flange were to be considered slender, then:

$$M_n = F_{cr} S_y$$

$$F_{cr} = \frac{0.69E}{\left(\frac{b}{t_f}\right)^2}$$

Thus,

$M_{n,slenderbuckling}$ = 5.84 kN-m (51.7 kip-in)

The governing failure mode for the lower strap is yielding, with a moment of 368 Nm (3.256 kip-in).

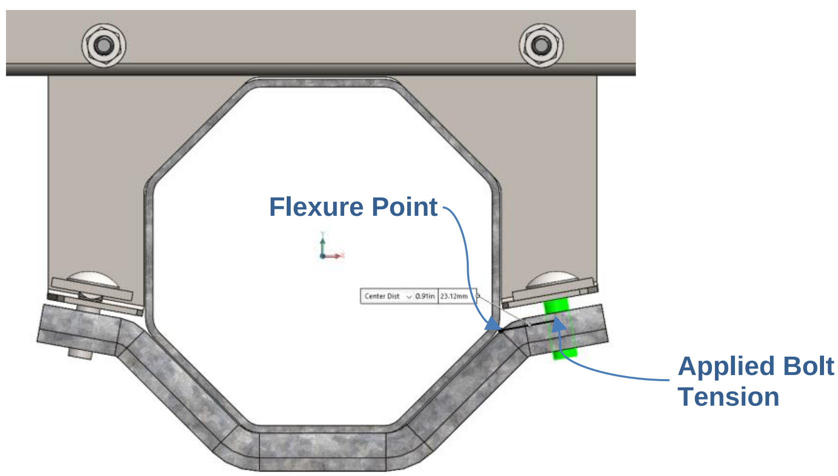


Figure 19: Flexure Point on Strap

With a distance to the load application of 23.1 mm (0.91 in), the governing load at the bolt location is 368 Nm / 23.1 mm = 15.9 kN (3.256 kip-in / 0.91 in = 3.58 kips).

6 Hardware Limits

ANSI/AISC 360-16 was used to calculate tensile and shear capacity for each of the fastener sets. Per the code, the allowable tensile or shear strength, R_n, is provided by

$$R_n = F_n A_b$$

where:

A_b = nominal unthreaded body area of bolt or threaded part

F_n = nominal tensile stress, F_{nt}, or shear stress, F_{nv}

6.1 Bracket/Strap Fasteners

The Bracket/Strap connection is made via grade 8, 5/16-18 fasteners. Per ANSI/AISC 360-16, grade 8 bolts have a nominal tensile stress of 1034 MPa (150 ksi) and a nominal shear stress of 620 MPa (90 ksi) when threads are not excluded from the shear plane. Thus, Rn = 51.1 kN (11.5 kips) in tension and 17.3 kN (6.90 kips) in shear. The bracket/strap fasteners are loaded in tension.

6.2 Rail/Bracket Fasteners

The Rail/Bracket connection is made via grade 5 ¼-20 fasteners. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 780 MPa (113 ksi) and a nominal shear stress of 469 MPa (68 ksi) when threads are not excluded from the shear plane. Thus, Rn = 24.6 kN (5.54 kips) in tension and 14.9 kN (3.34 kips) in shear. The rail/bracket fasteners are loaded in shear.

The hole-to-hole spacing of these fasteners is 150 mm (5.91 in). The worst-case loading on these bolts is in the max-torque uplift scenario. Following the same methodology as outlined in Section 4, one may calculate the maximum allowable load on these fasteners.

6.3 Module Attachment Fasteners

The module attachment connection is made via grade 5, 5/16-18 fasteners. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 780 MPa (113 ksi) and a nominal shear stress of 469 MPa (68 ksi) when threads are not excluded from the shear plane. Thus, Rn = 38.6 kN (8.67 kips) in tension and 23.2 kN (5.21) kips in shear. The module attachment fasteners are loaded in tension.

Alternately, Grade 5, ¼"-20 fasteners may be used at the 400 mm (15.75 in) hole locations. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 780 MPa (113 ksi) and a nominal shear stress of 469 MPa (68 ksi) when threads are not excluded from the shear plane. Thus, Rn = 24.6 kN (5.54 kips) in tension and 14.9 kN (3.34 kips) in shear. The module attachment fasteners are loaded in tension.

7 Summary of Results

Table 4 presents a summary of the calculations and results discussed herein. For comparative purposes, an example site condition is provided below. This example passed testing and is recorded in Array document DVT-20021-05. In this example, a 62.6 m/s (140 mph) wind is assumed with bolting at 1300 mm (51.2 in) with 5/16-18 fasteners and at 400mm (15.75 in) with ¼-20 fasteners. The module has dimensions of 2285 x 1134 mm (90 x 44.65 inches). The governing load cases are max uniform up and max torque up, with a uniform design load pressure of 2256 Pa (47.1 psf) and a test pressure of 3384Pa (70.7 psf).

Table 4: Summary of Results

Failure Mode	Limiting Load	Calculation Location	Test Case Uniform Load	Test Case Torque Load	Test Case Utilization Factor
Bending Moment of Rail – 1300mm Only	2.14 kN-m (18.9 kip-in)	5.1	2.53 kN-m (22.4 kip-in)	1.94 kN-m (17.2 kip-in)	119%
Bending Moment of Rail – 1300mm and 400mm	2.14 kN-m (18.9 kip-in)	5.1	1.54 kN-m (13.6 kip-in)	1.18 kN-m (10.4 kip-in)	72%
Tensile load on the brackets (per side)	72.51 kN (16.3 kips)	5.2	25.35 kN (5.7 kips)	36.03 kN (8.1 kips)	50%
Flexural Yield of the Strap	16.01 kN (3.6 kips)	5.3	4.45 kN (1 kips)	14.68 kN (3.3 kips)	92%
Bracket/Strap Fasteners Tension	51.15 kN (11.5 kips)	6.1	25.35 kN (5.7 kips)	36.03 kN (8.1 kips)	70%
Rail/Bracket Fasteners, Shear	14.68 kN (3.3 kips)	6.2	4.45 kN (1 kips)	14.86 kN (3.34 kips)	100%
Module Attachment Fasteners, Tension (5/16")	38.7 kN (8.7 kips)	6.3	2.22 kN (0.5 kips)	0.89 kN (0.2 kips)	6%
Module Attachment Fasteners, Tension (1/4")	24.47 kN (5.5 kips)	6.3	2.22 kN (0.5 kips)	0.89 kN (0.2 kips)	9%

Note, in the test case applied to this summary site design engineer should choose to use module bolts at two sets of holes, both 1300 mm (51.2 in) and 400 mm (15.75 in). The utilization factor of the rail exceeds 100% if only the 1300 mm (51.2 in) holes are used. Additional options may be evaluated on a site-by-site basis with additional hole location options. In the DVT report noted, the rail did yield during the test with bolts at 1300 mm (51.2 in) and passed with bolts in both locations. Also note that while a safety factor is built into the test loads, the rail/bracket fasters are at their limit with the loads applied.

Revision History:

Release Date	Revision	Description	Name
12/11/2020	A	Original Release	NS, NK, BF
1/15/2021	B	Dual dimensions added	NS

1 Executive Summary

The 850mm Steel Three-Bolt Clamp (20904) is rated for loads corresponding to at least the following conditions:

- Wind Speed: 58 m/s (130mph) maximum 3-second gust
- Module Dimensions: 2100 x 1084mm (82.7 x 42.7 inches)
- Module Uniform Design Pressure: 2011 Pa (42.0 psf)
- Module Uniform Test Pressure: 3017 Pa (63.0 psf)

Under these conditions, the clamp assembly will pass testing when loaded as described in Section 4. Detailed results of the testing can be found in Array document DVT-20026-03. The governing failure modes of this product are flexural yielding or buckling of the clamp body, and flexural yielding of the strap, which would result in loosening of bolted connections.

Table of Contents

2 Assembly Description

Array's Steel three-bolt clamp, 20904-901, attaches the photovoltaic (PV) modules to an octagonal steel torque tube. This arrangement is presented in Figure 1. This document provides a summary of the governing design limits of the product and their methods of calculation.

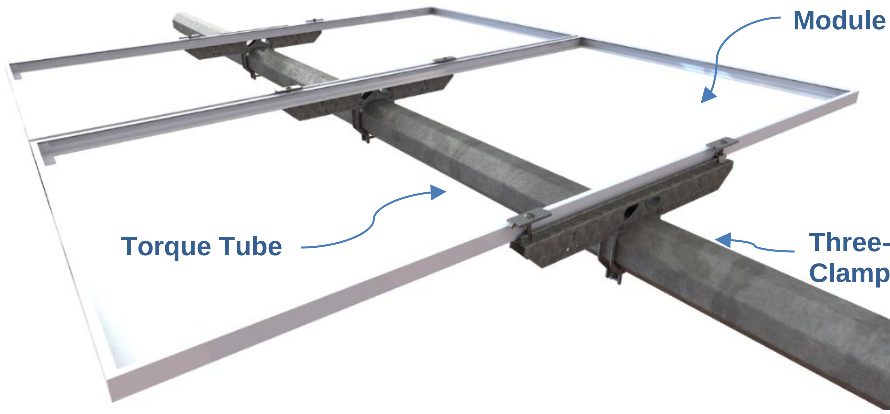


Figure 1: Through-Bolt Module Mount with Torque Tube and Module Frame

Figure 2 presents the components of the steel three-bolt clamp. The primary steel components include a clamp body and two straps. The module clips are made of aluminum. Hardware includes module clip fasteners, clamp body/strap fasteners, and torque tube/strap fasteners.

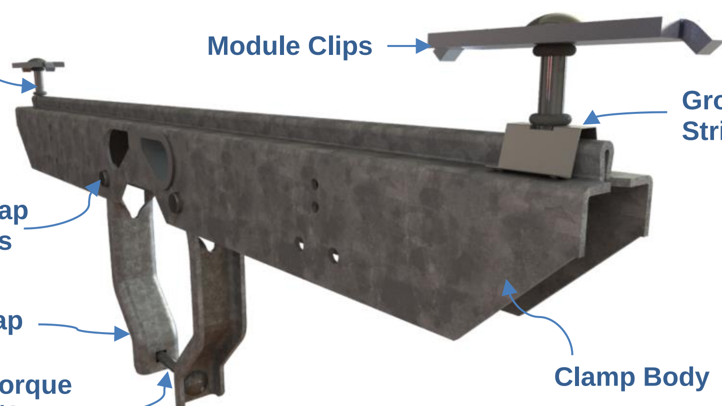


Figure 2: Steel Three-Bolt Clamp

Applying pretension to the torque tube/strap fasteners fastens the clamp assembly to the torque tube. The module is secured to the clamp assembly by tightening the module clip fasteners which applies clamping force to the module frame.

3 Detailed Description of Components

Each of the components in Figure 2 are described in this section, including material properties, bolt torques, manufacturing methods, and relevant dimensions.

3.1 Clamp Body

The clamp body (Figure 3) is roll-formed from 2.75mm (12 gauge) steel with a yield strength of 413 MPa (60ksi). The overall dimensions of the clamp body are 850mm x 60.7mm x 39.6mm (33.465in x 2.39in x 1.56in). The purpose of the clamp body is to clamp the module through the module clip. It also provides connection points for the torque tube strap which interfaces with the torque tube. There are two cut-outs on the top of the body for hardware associated with the module clips. There are four teardrop-shaped holes on the side of the body for the electrical pass-through sleeves. The clamp body also has four 10mm (0.40in) holes for torque tube strap mounting. Additionally, 12 smaller holes are provided as a provision for module alignment jig.

Figure 3: Clamp Body

3.2 Torque Tube Straps

The torque tube straps are a stamped steel component made from pre-galvanized sheet with a minimum yield strength of 344 MPa (50ksi). The sheet is made from 11 gauge steel, with a nominal thickness of 3.13mm (0.123in). Figure 4 presents the overall dimensions of the cross section. The dowel hole that connects to the clamp body has a diameter of 9.8mm (0.386in) and a minimum edge distance of 6.38mm (0.251in). The square carriage bolt hole has a minimum edge distance of 7.65mm (0.301in) and a square opening with 8.71mm (0.343in) across the flats.

Figure 4: Torque Tube Strap Overview

3.3 Module Clip

The module clips (Figure 5) are stamped from 5mm (0.197in) thick aluminum alloy 5052-H32 with a minimum yield strength of 193 Mpa (28 ksi). There are two module clips per clamp assembly which retain the module by means of a 5/16”-18 carriage bolt. The module clips measure 81.3mm (3.2in) long by 30.5mm (1.2in) wide. Each clip includes two tabs measuring 8mm (0.315in) wide. The tabs establish the desired spacing between modules and prevent rotation of the clip during tightening.

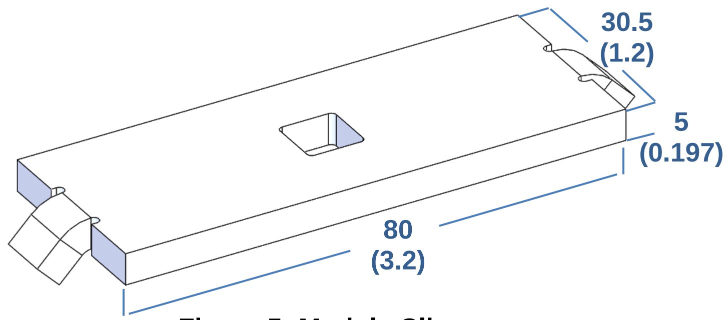


Figure 5: Module Clip

3.4 Clamp Body / Strap Fasteners

The clamp body/strap fasteners (Figure 6) include a 9.5mm (0.375”) diameter clevis pin and cotter pin. The fasteners secure the straps to the clamp assembly, while allowing the straps to rotate freely for installation to the torque tube. The clevis pin is made from 1008-1010 hot rolled steel with a minimum yield strength of 345 MPa (50 ksi).

Figure 6: Clamp Body / Strap Fastener

3.5 Torque Tube / Strap Fasteners

The torque tube/strap fasteners (Figure 7) include a 76mm (3.0in) long 5/16”-18 grade 5 carriage bolt and a serrated flange nut. The fastener assembly secures the clamp assembly to the torque tube by applying pretension to the bolt.

Figure 7: Torque Tube / Strap Fasteners

3.6 Module Attachment Fasteners

The module attachment fasteners (Figure 8) include a carriage bolt, flat washer, split lock washer, and a hex nut. The carriage bolt is 63.5mm (2.5in) long, 5/16”-18, grade 5. Above the clamp body, the o-rings retain the module clips and carriage bolt in an elevated position to assist with module installation. The grounding strip is installed on one of the module attachment bolts and serves as an electrical grounding device for the module. Below the clamp body, a 5/16”-18, grade 5 hex nut is positioned below a split-lock washer and a flat washer. The flat washer has an outer diameter of 22.2mm (0.875in) and a thickness of 1.4mm (0.055in).

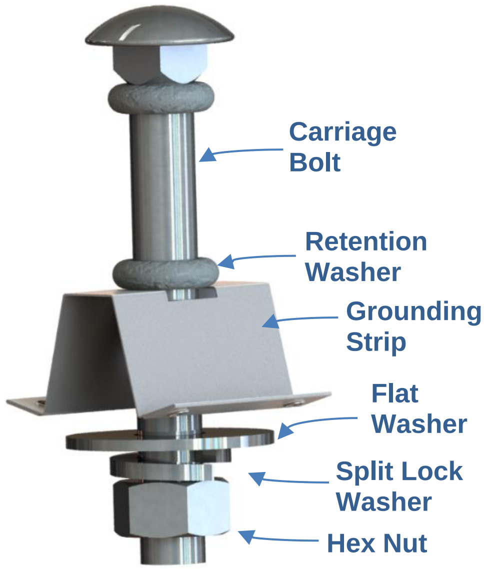


Figure 8: Module Attachment Fasteners

3.7 Electrical Passthrough Sleeve

The electrical passthrough sleeve (Figure 9) is an injection-molded plastic part with a yield strength of 2.76ksi. The sleeve serves as a routing hole for module cables and connectors. The outer surface of the sleeve interfaces with the clamp body and the snap-lock keeps it in place in the assembly. The inner surface interface with electrical cables. Smooth inner surface ensures no wear of electrical cables during product life. The overall dimensions of the sleeve are 52.8mm x 50.8mm x 35.3mm (2.08in x 2.00in x 1.39in). The sleeve does not affect the structural capacity of the assembly. Structural calculations for the part are not added in the design report.

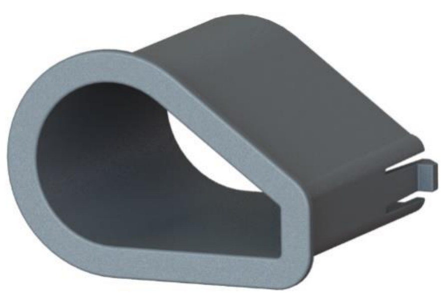


Figure 9: Electrical Passthrough Sleeve

4 Load Inputs, Safety Factors, and Design Codes

The Steel Three-bolt Clamp assembly is designed to meet the following code criteria:

A. Wind loading is calculated in accordance with ASCE 7-10, Method 3.

B. Steel is designed to comply with AISC 360-10, and AISI S100-16 standards.

C. Aluminum is designed to comply with Aluminum Association Aluminum Design Manual.

The wind loads acting on the PV module are calculated in accordance with the ASCE 7 procedure using aerodynamic coefficients from a wind tunnel study performed by Cermak Peterka Petersen, Inc. (CPP). The coefficients selected represent the worst case loading condition from all wind directions within each region. The loading conditions evaluated include max pressure, max uniform load, and max torque in both uplift and downforce.

$$P = q_z \times GC_p$$

Where

P is the design wind pressure acting on the module

q_z is the velocity pressure evaluated at height z for the selected exposure as per ASCE 7 procedure.

GC_p is a loading coefficient provided via the wind tunnel testing discussed above

There are six different load cases considered for the clamp. Max Pressure is presented in Figure 10 and Figure 11, Max Uniform is presented in Figure 12 and Figure 13, and Max Torque is presented in Figure 14 and Figure 15.

4.1 Max Pressure

Max Pressure is derived from the peak normal force coeffienents resulting in the maximum force being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition. Wind tunnel data provides unique GC_p values for each of the four quadrants presented below.

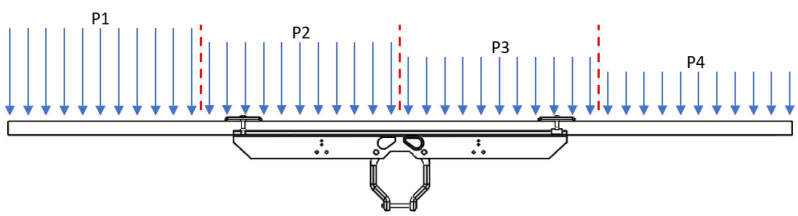


Figure 10: Max Pressure, Downforce

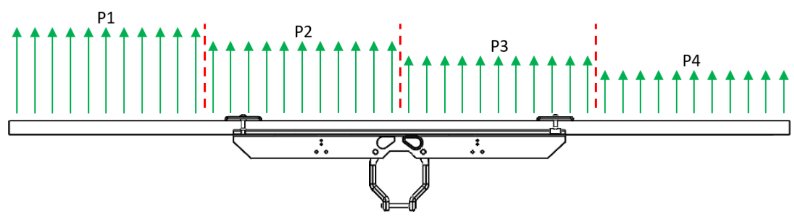


Figure 11: Max Pressure, Uplift

4.2 Max Uniform

Max Uniform is the area average of the max pressure load condition used to determine the design pressure in accordance with IEC 61215 MQT 16 static mechanical load test.

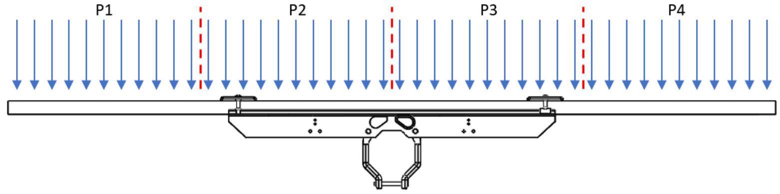


Figure 12: Max Uniform, Downforce

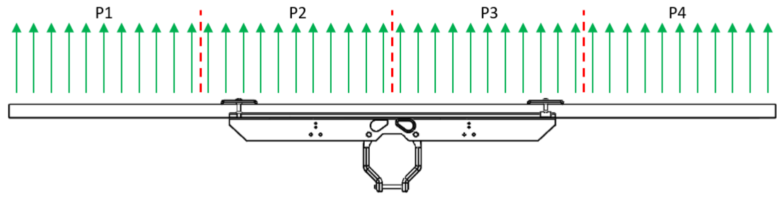


Figure 13: Max Uniform, Uplift

4.3 Max Torque

Max Torque is derived from the peak normal force coefficients resulting in maximum torque being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition.

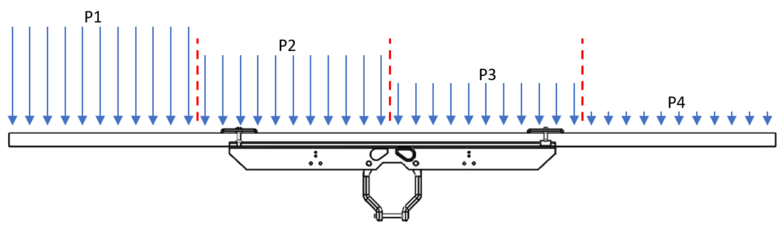


Figure 14: Max Torque, Downforce

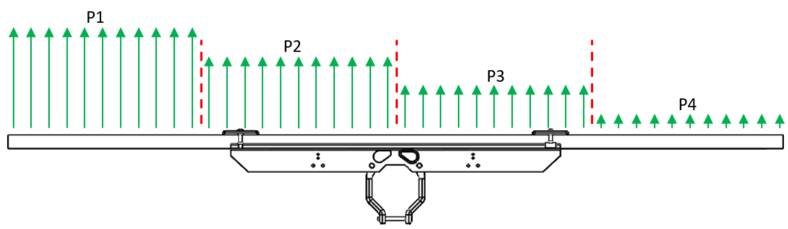


Figure 15: Max Torque, Uplift

The normal force and torque acting on the clamp are evaluated as:

$$F_N = (P_1 A_1) + (P_2 A_2) + (P_3 A_3) + (P_4 A_4)$$

$$M_{Torque} = \left[\left(\frac{3}{8} P_1 A_1\right) + \left(\frac{1}{8} P_2 A_2\right) - \left(\frac{1}{8} P_3 A_3\right) - \left(\frac{3}{8} P_4 A_4\right)\right] L$$

where;

A is the area of a strip equal to ¼ the module length times its width.

L is the cord length of the module.

The three-bolt mount was designed using the ASD load combinations from Section 2.4.1 of ASCE 7-10 presented in Table 1.

Table 1: ASD Load Combinations

Combo	D	L	W	S	E
1	1	0	0	0	0
2	1	1	0	0	0
3	1	0	0	1	0
4	1	0.75	0	0.75	0
5	1	0	0.6	0	0
6a	1	0.75	0.45	0.75	0
6b	1	0.75	0	0.75	0.525
7	0.6	0	0.6	0	0
8	0.6	0	0	0	0.7

In addition to the strength calculations detailed in this report, the structural performance of the through-bolt mount has been established through testing[1], from which the allowable strength, R_a, has been calculated as follows:

$$R_a = R_n/\Omega$$

where;

R_n = Average failure value of all test results

Ω = safety factor;

[1.5] for max uniform load,

[1.21] for max pressure and max torsion

[1] The test report DVT-20026-03 is available upon request.

Results of a sample calculation (Table 3) with inputs (Table 2) are shown below. These loads were tested in the above referenced DVT report. Alternate combinations of module size and wind speed may result in similar loads, so neither the wind speed nor module size can be considered a maximum when evaluated in isolation. The clamp is qualified for the applied load, which varies with each project site.

Table 2: Calculation Inputs

Wind Speed, ASCE 7	130	mph
kz	0.85	-
kzt	1	-
kd	0.85	-
I	1	-
H/L Pressure Increase Factor	1	-
Uniform Pressure A&B Override		Pa
Uniform Pressure CD&E Override		Pa
Clamp Width AB	850	mm
Clamp Width CDE	850	mm
Module Length	2100	mm
Module Width	1084	mm
Module Area	2.28	m^2
Basic Wind Pressure	31.3	PSF
Uniform Loads Safety Factor	1.5	-
Non-Uniform Safety Factor	1.21	-
Service Factor	0.6	-

Table 3: Calculation Results

	A&B						C, D, &E					
	Downforce			Uplift			Downforce			Uplift		
Test Pressure	Pressure	Torque	Uniform	Pressure	Torque	Uniform	Pressure	Torque	Uniform	Pressure	Torque	Uniform
EE	2338	1874	2613	-2646	-3079	-3017	1561	1586	1684	-1504	-1206	-1657
E	2293	1470	2613	-2534	-1145	-3017	1521	1293	1684	-1455	-795	-1657
W	2118	866	2613	-2393	-452	-3017	1315	889	1684	-1248	-290	-1657
WW	1682	528	2613	-2164	-277	-3017	1036	403	1684	-1139	-142	-1657
Test Loads Applied At Clamp Width (Metric)												
Total Force (N)	4799	2696	5949	-5541	-2819	-6868	3092	2373	3833	-3042	-1385	-3772
Total Torque (N·m)	320	693	0	-237	-1359	0	266	591	0	-194	-552	0
West Mount Load (N)	2776	2164	2974	-3049	-3009	-3434	1859	1881	1916	-1750	-1342	-1886
East Mount Load (N)	2023	532	2974	-2491	189	-3434	1233	492	1916	-1292	-43	-1886
Test Loads Applied At Clamp Width (Imperial)												
Total Force (lbf)	1079	606	1337	-1246	-634	-1544	695	534	862	-684	-311	-848
Total Torque (ft-lbs)	236	511	0	-175	-1002	0	196	436	0	-143	-407	0
West Mount Load (lbf)	624	486	669	-685	-676	-772	418	423	431	-393	-302	-424
East Mount Load (lbf)	455	120	669	-560	43	-772	277	111	431	-291	-10	-424

The load case leading to maximum bending moment is “Region A&B- Max Uniform- Uplift”. However, when “Max Torque Uplift” loads are resolved to interior dimensions, the single-side torsional load governs the design.

5 Primary Component Limits

The following sub-sections provide summary calculations for each of the three primary structural components in this assembly: the Clamp Body, Torque Tube Straps, and Module Clips.

5.1 Clamp Body

The Clamp Body is designed for “Max Uniform Up”, “Max Uniform Down”, “Max Pressure Up”, “Max Pressure Down”, “Max Torque Up” and “Max Uniform Down” load cases.

“Max Uniform” load cases lead to maximum stresses in the clamp body and design calculation for the same is shown below. The design calculation below provides a limit for elastic deformation.

The part is determined to be in flexure and checked for failure in terms of material strength.

A	=	Section area	$= 2.703 \times 10^{-4}\ m^2\ (0.419in^2)$
I	=	area moment of inertia of the section	$= 7.825 \times 10^{-8}\ m^4\ (0.188in^4)$
Y	=	distance from the elastic neutral axis to the most extreme fiber	= 0.03094m (1.218in)
F_y	=	specified minimum yield stress of material	= 413.7 MPa (60ksi)

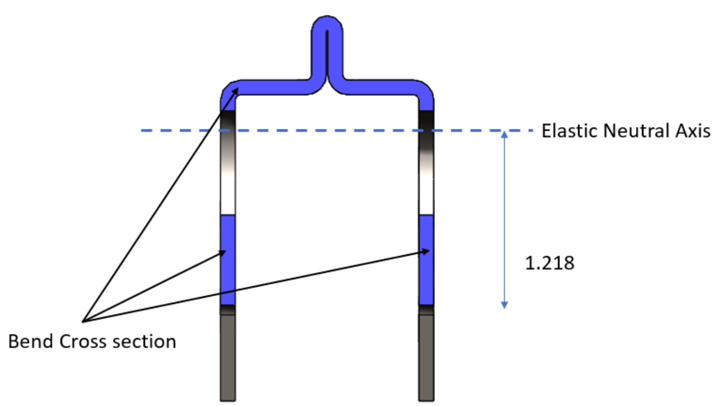


Figure 16: Clamp Body Neutral Axis

The bending moment that results in elastic deformation for the clamp body's weekest section is

$$M = F_y I \,/\, Y$$

= 1050 N·m (9.32 kip-in)

However, elastic deformation is not a failure mode for this component. Plastic deformation of the clamp body would constitute a failure, and the plastic limit is substantially higher than the elastic limit. To determine the plastic bending moment limit, physical testing was performed and is recorded in DVT-20026-03. The clamp body was also analyzed for buckling as a mode of failure. Nonlinear buckling analysis was performed within ANSYS and physical testing was performed and is recorded under the same report. Physical testing demonstrates that the component meets all physical deformation criteria up to a limit of at least

M = 1165 N·m (10.31 kip-in).

5.2 Torque Tube Straps

The torque tube straps are evaluated both for flexural yield and for bearing strength at the fastener mounting holes. While flexural yield is calculated here, plastic flexural yield is actually required for a proper clamping connection to the torque tube.

5.2.1 Flexural Yield

The torque tube straps are subject to flexure of the web where the straps are bolted together.

This analysis uses ANSI/AISC 360-16, Chapter F6: I Shaped Members and Channels Bent About Their Minor Axis. The nominal flexural strength (M_n) of the component is the lower value of either yielding or flange local buckling. The calculations below reference the dimensions noted in Figure 4.

First evaluating the yielding failure mode:

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 0.6 \times F_y S_y$$

where

I	= area moment of inertia of the section	= 2.776 x 10^{-9} m^4 (0.00667in^4)
Y	= distance from the neutral axis to the most extreme fiber	= 0.00965m (0.380in)
F_y	= specified minimum yield stress of the material	= 344.7MPa (50ksi)
S_y	= elastic section modulus taken about the y-axis	= 2.868 x 10^{-7} m^3 (0.0175in^3)
Z_y	= plastic section modulus taken about the y-axis	= 5.227 x 10^{-7} (.0319in^3)

thus

$M_{n,\ yield}$ = 180.17 Nm (1.595 kip-in) plastic, or
59.32 Nm (0.525 kip-in) elastic

Plastic yielding is considered the governing failure mode for this design, as elastic yielding is required to attain clamping around the torque tube.

For flange local buckling,

$$M_{n,buckling} = M_p - \left(M_p - 0.7 \times F_y S_y\right)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)$$

$$\lambda = \frac{b}{t_f}$$

where,

b = the full nominal dimension of the flange = 0.014m (0.551in)

t_f = thickness of the flange = .00313m (0.1233in)

λ_{pf} = λ_p, the limiting slenderness for a compact flange, defined below = 9.15

λ_{rf} = λ_r, the limiting slenderness for a noncompact flange, defined below = 24.08

E = modulus of elasticity = 200 GPa (29000 ksi)

$$\lambda_p = 0.38 \times \sqrt{\frac{E}{F_y}}$$

$$\lambda_r = 1.0 \times \sqrt{\frac{E}{F_y}}$$

thus:

$M_{n,buckling}$ = 217.38 Nm (1.924 kip-in)

If the flange were to be considered slender, then:

$$M_n = F_{cr} S_y$$

$$F_{cr} = \frac{0.69E}{\left(\frac{b}{t_f}\right)^2}$$

Thus,

$M_{n,slenderbuckling}$ = 2298.1 Nm (20.34 kip-in)

The governing failure mode for the lower strap is yielding, with a moment of 180.17 Nm 1.595 kip-in.

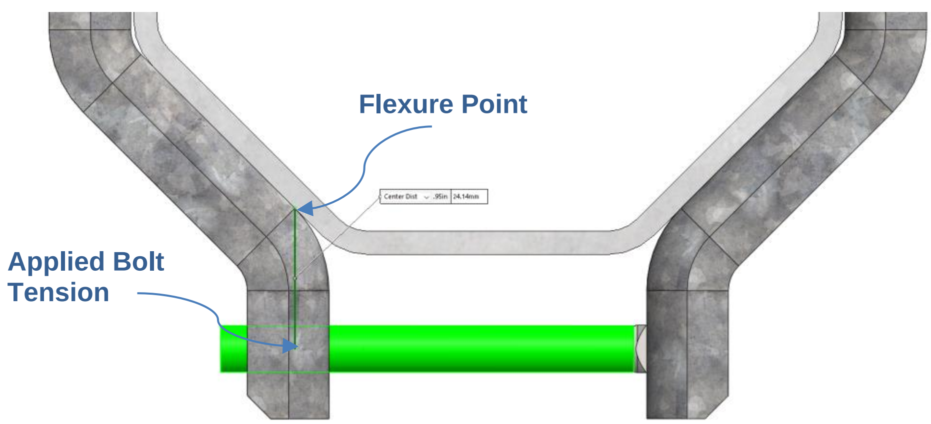


Figure 17: Flexural Point of the Torque Tube Straps

With a distance to the load application of 24.1mm (0.95in) and two torque tube straps to distribute the load, the governing load at the bolt location is 2 x 180.17 / 0.0241 = 14.95kN (3.36 kips). The 5/16-18 grade 5 bolt has a maximum pretension of 14.86 kN (3.34 kips), resulting in a utilization ratio of the torque tube strap of 99.4%. But while the base material of the torque tube strap has a yield strength of 344.7 MPa (50ksi), work hardening during the forming process increases the yield strength of the material around the bends, which is also the region of the flexure point. Thus, the work hardened material has a higher utilization ratio than noted above. Additionally, plastic deformation of the torque tube strap does not constitute a failure. Rather, it applies the necessary clamping load to the torque tube and relaxes the bolt pretension. Furthermore, the flexure region of the torque tube strap does not generally experience additional loading due to wind effects. The frictional faying forces of the straps on the torque tube provide resistance to wind loading, and flexure point on the straps themselves remain only exposed to the bolt tension.

5.2.2 Bearing Capacity

The torque tube strap is attached to the clamp body with a 9.5mm (0.375in) diameter pin.

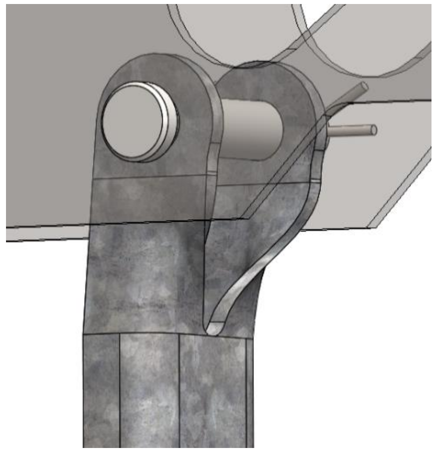


Figure 18: Torque Tube Strap Bearing Connection

The minimum material thickness between the hole and edge of the strap is 6.38mm (0.251in) and the two pins are separated by a distance of 122.5mm (4.823in). Each strap contains two bearing faces to distribute the respective load, and section J3.10 of AISI 360 provides the following guidance.

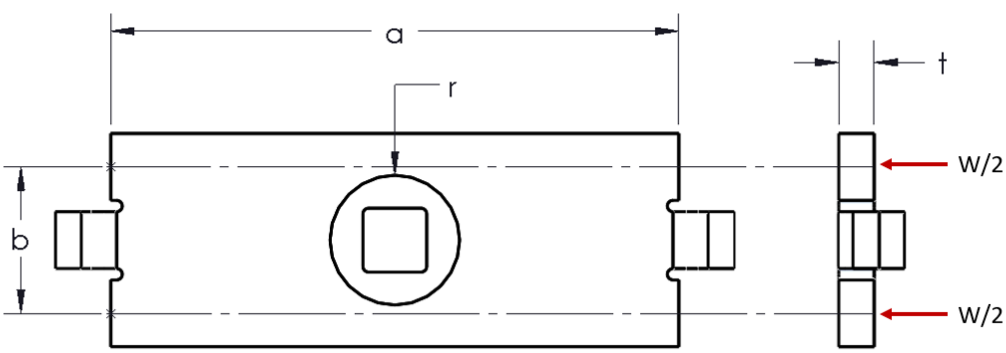
When deformation at the bolt hole at service load is a design consideration

$$R_n = 2.4dtF_u$$

Rn = 32 kN (7.2 kips) per hole or 64 kN (14.4 kips) per connection.

5.3 Module Clips

The module clips are supported uniformly under the bolt head with a radius, r, of 9.1mm (0.36in). Worst case loading on the clip is in the max torque uplift condition, with the module frames spaced at a maximum separation distance of b = 24mm (0.95in). The bending stress on the module clips is calculated using Roark's formulas for stress on flat plates with constant thickness.



For a rectangular plate with a length, a, of 80mm (3.15in) and thickness, t, of 5mm (0.197in), bending stress at the center of the clamp is calculated as follows:

$$\sigma_{\max} = \frac{3W}{2\pi t^2}\left[(1+v)ln\frac{2b}{\pi r_0}+\beta\right]$$

where;

W = total applied force

v = poisson's ratio = 0.33

β = 1, for a/b ≥ 2.

The design stress for tensile yielding, σ_{max}, is 0.9*Fy = 173.7 MPa (25.2 ksi), therefore solving for W, the design uplift force on each clamp is 5.39 kN (1.212 kips).

6 Hardware Limits

ANSI/AISC 360-16 was used to calculate tensile and shear capacity for each of the fastener sets. Per the code, the allowable tensile or shear strength, R_n, is provided by

$$R_n = F_n A_b$$

where:

A_b = nominal unthreaded body area of bolt or threaded part, in^2

F_n = nominal tensile stress, F_{nt}, or shear stress, F_{nv}, ksi

6.1 Body/Strap Fasteners

The straps are connected to the clamp body using two 9.5mm (0.375in) diameter clevis pins with a minimum tensile strength of 344.7 MPa (50 ksi). Per ANSI/AISC 360-16, the pins have a nominal shear stress of 194.4 MPa (28.2 ksi).

The body/strap fasteners are loaded in double shear. Thus, the design shear strength, ΦR_{nv} = 0.75 x 2 x F_n x A_b = 20.64 kN (4.64 kips).

The hole-to-hole spacing of these fasteners is 122mm (4.82 in). The worst-case loading on these bolts is in the max-torque uplift scenario.

6.2 Torque Tube/Strap Fasteners

The straps are connected to the torque tube using a 5/16"-18 grade 5 carriage bolt. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 620.5 MPa (90 ksi).

Thus, the design tensile strength, ΦR_{nt} = 0.75 x F_n x A_b = 614.6 kN (3.51 kips).

The torque tube/strap fastener is loaded in tension. From the free body diagram in Figure 19, considering the load on strap, P, the tension on the bolt, T_b, can be calculated as,

$$P = R_{tY} = R_{tX}$$

$F_F = 0.3R_t$ for galvanized steel

$$\sum M_0 = (0.589\,P) + (3.891\,P) - (0.589 \times 0.3\,P) - (3.891\ \times 0.3\,P) - (5.361\,T_b) = 0$$

Therefore,

$$T_b = 0.58\,P$$

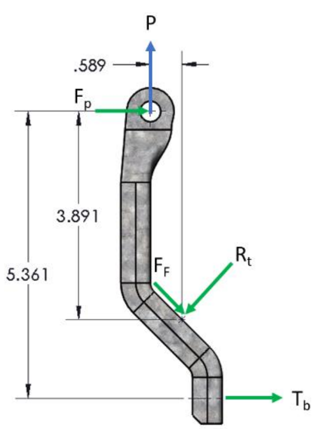


Figure 19: Free Body Diagram of Torque Tube Strap

6.3 Module Attachment Fasteners

The module clip connection is made using a 5/16”-18 grade 5 carriage bolt. Per ANSI/AISC 360-16, grade 5 bolts have a nominal tensile stress of 620.5 MPa (90 ksi).

The module attachment fasteners are loaded in tension. Thus, the design tensile strength,

$\Phi R_{nt} = 0.75 \times F_n \times A_b = 15.61$ kN (3.51 kips).

The hole-to-hole spacing of these fasteners is 550mm (21.65 in). The worst-case loading on these bolts is in the max-torque uplift scenario.

7 Summary of Results

Below is a summary of the calculations and results discussed herein. For comparative purposes, an example site condition is provided below. This example passed testing and is recorded in Array document DVT-20026-3. In this example, a 61.2 m/s (130mph) wind velocity is assumed. The module dimensions are in accordance with the example calculations in Section 4. The governing load cases are max uniform up and max torque up. The results in

Table 4 summarize the allowable load and the loads experienced at each of the components at the example site for both Max Uniform and Max Torque cases.

Table 4: Summary Results

Failure Mode	Limiting Load	Calculation Location	Test Case Uniform Load	Test Case Torque Load	Test Case Utilization Factor
Clamp Body	1165 N m (10.3 kip-in)	5.1	1165 N m (10.3 kip-in)	1053 N m (9.3 kip-in)	100%
Torque Tube Strap Flexural Yield[1]	14.95 kN (3.36 kips)	5.2	14.86 kN (3.34 kips)	14.86 kN (3.34 kips)	99%[1]
Torque Tube Strap Bearing Load	64.05 kN (14.4 kips)	5.2.2	3.4 kN (0.77 kips)	12.5 kN (2.81 kips)	20%
Module Clips Flexural Yield	5.38 kN (1.21 kips)	5.3	1.7 kN (0.77 kips)	1.6 kN (0.70 kips)	32%
Body/Strap Fasteners, Shear	20.64 kN (4.64 kips)	6.1	3.4 kN (0.77 kips)	12.5 kN (2.81 kips)	60%
Torque Tube/Strap Fasteners, Tension	15.61 kN (3.51 kips)	6.2	1.97 kN (0.44 kips)	7.25 kN (1.63 kips)	46%
Module Attachment Fasteners, Tension	15.61 kN (3.51 kips)	6.3	1.7 kN (0.77 kips)	1.6 kN (0.70 kips)	11%

[1] The torque tube strap relies on some flexural yield to clamp the module mounting system to the torque tube. This flexural yield does not constitute a failure of the clamp.

Revision History:

Release Date	Revision	Description	Name
1/11/2021	A	Original Release	NS, NK, BF

1 Executive Summary

The 200mm FS7 Module Mount (21015) is rated for *service loads* corresponding to at least the following conditions:

- Max Normal Force, Uplift: -503 lbf (-2,237 N)
- Max Normal Force, Downforce: 529 lbf (2,352 N)
- Max Moment: 503 ft·lbs (682 N·m)

Under these conditions, the clamp assembly will pass testing when loaded as described in Section 4. The governing failure modes of this product are flexural yielding of the Module Rail, and flexural yielding of the strap or fasteners, resulting in loosening of bolted connections.

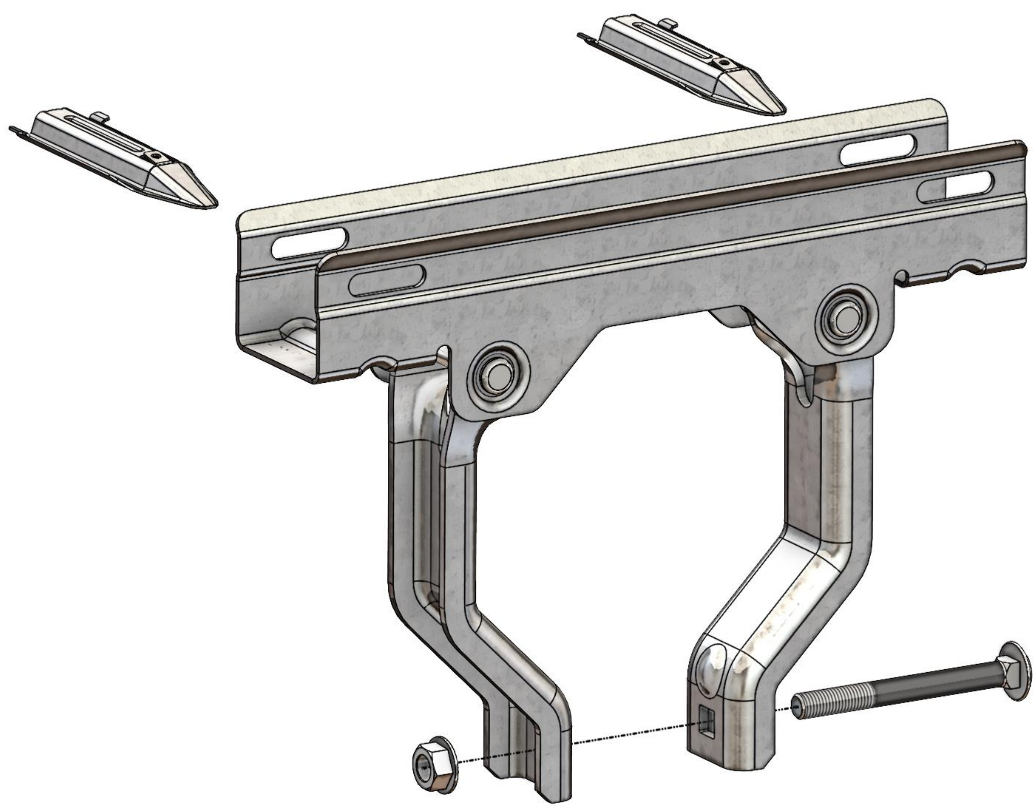


Table of Contents

2 Assembly Description

Array's 200mm FS7 Module Mount, 21015-901, attaches the photovoltaic (PV) modules to an octagonal steel torque tube. This arrangement is presented in Figure 1. This document provides a summary of the governing design limits of the product and their methods of calculation.

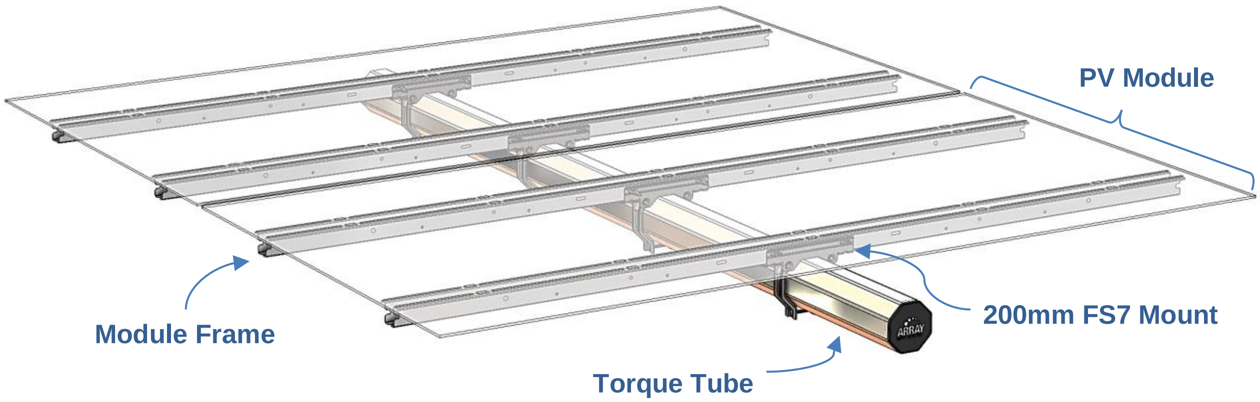


Figure 1: 200mm FS7 Module Mount with Torque Tube and Module

Figure 2 presents the components of the FS7 Module Mount. The primary steel components include a module rail and two straps. Fasteners includes module attachment clips, strap rivets, and torque tube/strap fasteners.

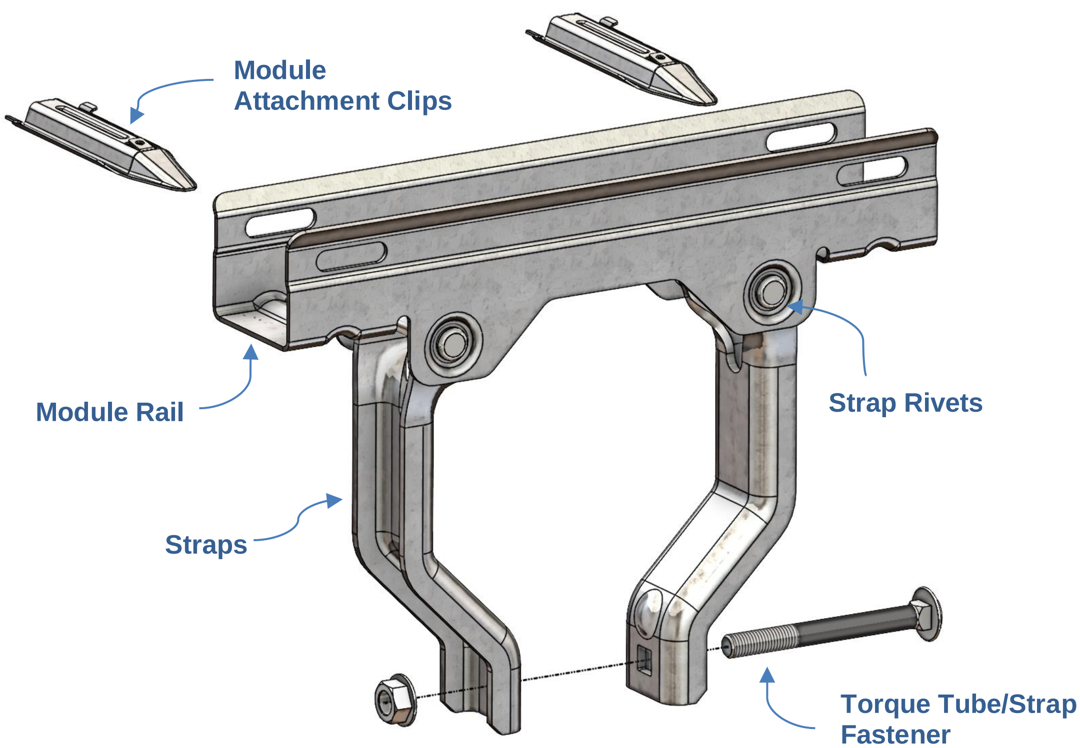


Figure 2: 200mm FS7 Module Mount

Applying pretension to the torque tube/strap fasteners secures the module rail to the torque tube. The module is installed by inserting the module attachment clips into the designated slots which secures the module frame to the mounting rails.

3 Detailed Description of Components

Each of the components in Figure 2 are described in this section, including material properties, bolt torques, manufacturing methods, and relevant dimensions.

3.1 Module Rail

The Module Rail (Figure 3) is stamped from 1.6mm (16 gauge) steel with a yield strength of 413 MPa (60ksi). The overall dimensions of the Module Rail are 250mm x 50mm x 62mm (9.8in x 1.9in x 2.4 in). The purpose of the module rail is to secure the module to the torque tube. It provides connection points to the module frame and to the torque tube straps interfacing with the torque tube. There are four slots on the top of the body for securing the module. The Module Rail also has four 8 mm (0.32in) holes for torque tube strap mounting.

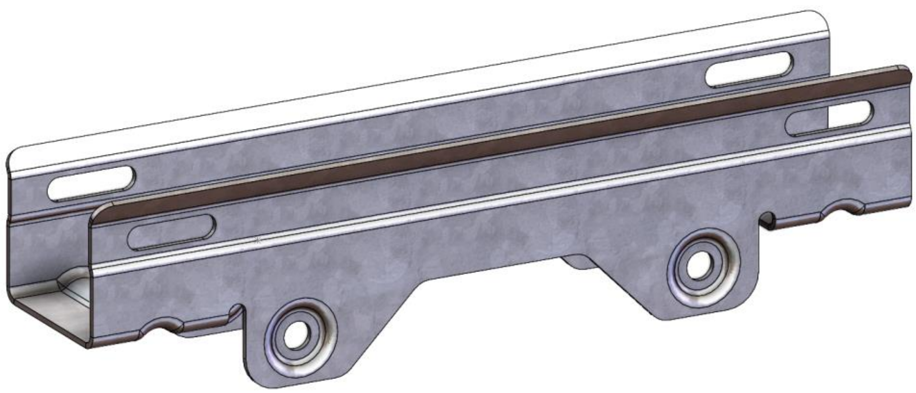


Figure 3: Module Rail

3.2 Torque Tube Straps

The torque tube straps (Figure 4) are a stamped steel component made from pre-galvanized sheet with a minimum yield strength of 413 MPa (60ksi). The sheet is made from 11-gauge steel, with a nominal thickness of 3.13mm (0.123in). Figure 4 presents the overall dimensions of the cross section. The rivet hole that connects to the module rail has a diameter of 8.2mm (0.323in) and a minimum edge distance of 6.38mm (0.251in). The square carriage bolt hole has a minimum edge distance of 7.65mm (0.301in) and a square opening with 8.71mm (0.343in) across the flats.

Figure 4: Torque Tube Strap and Section View

3.3 Strap Rivets

The strap rivets (Figure 5) secure the torque tube straps to the module rail, while allowing the straps to rotate freely for installation to the torque tube. The strap rivet is made from 7.94mm (0.3125”) diameter, 1018 or 1021 hot rolled steel or 302 stainless steel with a minimum yield strength of 345 MPa (50 ksi).

Figure 5: Strap Rivet

3.4 Torque Tube / Strap Fasteners

The torque tube/strap fasteners (Figure 6) include a 76mm (3.0in) long 5/16”-18 grade 8 carriage bolt and a serrated flange nut. The fastener assembly secures the clamp assembly to the torque tube by applying pretension to the bolt.

Figure 6: Torque Tube / Strap Fasteners

3.5 Module Attachment Clips

The module attachment clips (Figure 7) secure the module to the clamp assembly when driven through the slots on the module frame and rail. The clips are stamped from 0.78mm (0.031”) carbon steel with a minimum hardness of 44 HRC. The overall dimensions of the clip are 93mm x 27mm x 7.6mm (3.7in x 1.1in x 0.3 in).

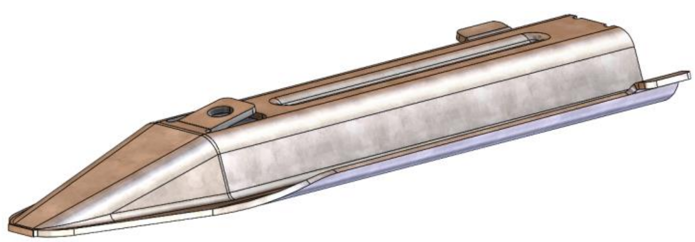


Figure 7: Module Attachment Clips

4 Load Inputs, Safety Factors, and Design Codes

The 200mm FS7 Module Mount is designed to meet the following code criteria:

A. Wind loading is calculated in accordance with ASCE 7-10, Method 3.

B. Steel is designed to comply with AISC 360-10 standard.

The wind loads acting on the PV module are calculated in accordance with the ASCE 7 procedure using aerodynamic coefficients from a wind tunnel study performed by Cermak Peterka Petersen, Inc. (CPP). The coefficients selected represent the worst-case loading condition from all wind directions within each region. The loading conditions evaluated include max pressure, max uniform load, and max torque in both uplift and downforce.

$$P = q_z \times GC_p$$

Where;

P is the design wind pressure acting on the module

q_z is the velocity pressure evaluated at height z for the selected exposure as per ASCE 7 procedure.

GC_p is a loading coefficient provided via the wind tunnel testing discussed above

There are six different load cases considered for the mount. Max Pressure is presented in Figure and Figure 9, Max Uniform is presented in Figure 10 and Figure 11, and Max Torque is presented in Figure 12 and Figure 5.

4.1 Max Pressure

Max Pressure is derived from the peak normal force coefficients resulting in the maximum force being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition. Wind tunnel data provides unique GC_p values for each of the four quadrants presented below.

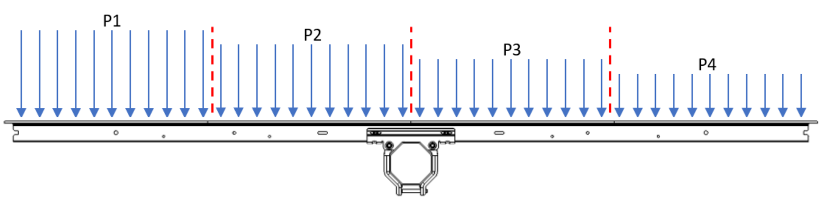


Figure 8: Max Pressure, Downforce

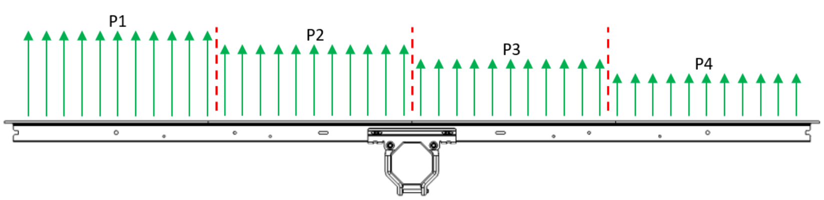


Figure 9: Max Pressure, Uplift

4.2 Max Uniform Pressure

Max Uniform is the area average of the max pressure load condition used to determine the design pressure in accordance with IEC 61215 MQT 16 static mechanical load test.

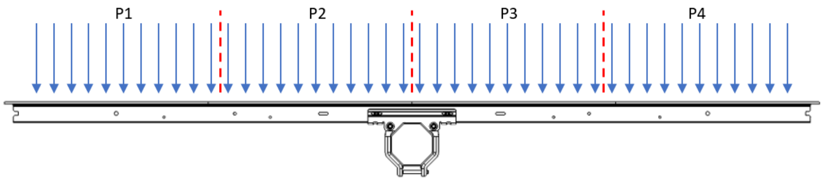


Figure 10: Max Uniform, Downforce

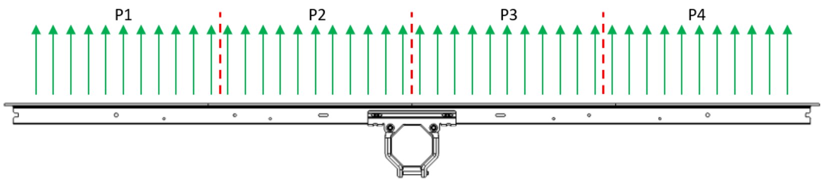


Figure 11: Max Uniform, Uplift

4.3 Max Torque

Max Torque is derived from the peak normal force coefficients resulting in maximum torque being applied to the clamp tributary area. The pressure is presented as four strips of equal area along the module length, resulting in an unbalanced load condition.

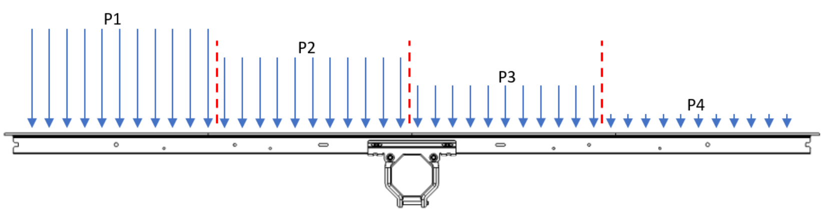


Figure 12: Max Torque, Downforce

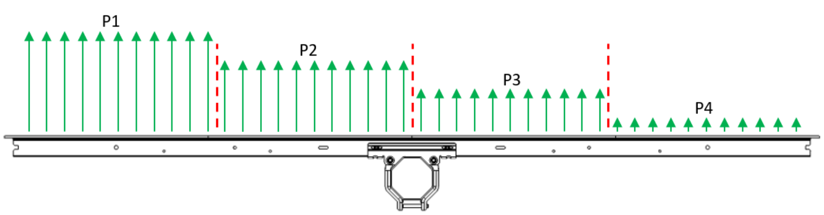


Figure 5: Max Torque, Uplift

The normal force and torque acting on the clamp are evaluated as:

$$F_N = (P_1A_1) + (P_2A_2) + (P_3A_3) + (P_4A_4)$$

$$M_{Torque} = \left[\left(\frac{3}{8}P_1A_1\right) + \left(\frac{1}{8}P_2A_2\right) - \left(\frac{1}{8}P_3A_3\right) - \left(\frac{3}{8}P_4A_4\right)\right]L$$

where;

A is the area of a strip equal to ¼ the module length times its width.

L is the cord length of the module.

The 200mm FS7 Module Mount was designed using the ASD load combinations from Section 2.4.1 of ASCE 7-10 presented in Table 1.

Table 1: ASD Load Combinations

Combo	D	L	W	S	E
1	1	0	0	0	0
2	1	1	0	0	0
3	1	0	0	1	0
4	1	0.75	0	0.75	0
5	1	0	0.6	0	0
6a	1	0.75	0.45	0.75	0
6b	1	0.75	0	0.75	0.525
7	0.6	0	0.6	0	0
8	0.6	0	0	0	0.7

In addition to the strength calculations detailed in this report, the structural performance of the 200mm FS7 Module Mount has been established through testing, from which the allowable strength, R_a, has been calculated as follows:

$$R_a = R_n/\Omega$$

where;

R_n = Average failure value of all test results

Ω = safety factor;

[1.5] for max uniform load,

[1.21] for max pressure and max torsion

Alternate combinations of module size and wind speed may result in similar loads, so neither the wind speed nor module size can be considered a maximum when evaluated in isolation. The module mount is qualified for the applied load, which varies with each project site. The PV module utilizes two frame rails inset from the edge of the glass, which are each supported by a mounting rail. Therefore, the loading inputs for the module rail assume a pressure tributary area equal to one half the width of the module, which is reflected in the calculations below.

Table 2: Calculation Inputs

Wind Speed, ASCE 7	123.6	mph
kz	0.85	-
kzt	1	-
kd	0.85	-
I	1	-
H/L Ratio	0.6	-
Clamp Width AB	200	mm
Clamp Width CDE	200	mm
Tributary Length	2300	mm
Tributary Width	608	mm
Tributary Area	1.40	m^2
Basic Wind Pressure	28.2	PSF
Uniform Loads Safety Factor	1.5	-
Non-Uniform Safety Factor	1.21	-
Service Factor	0.6	-
H/L Pressure Increase Factor	1.00	-
Module Length/Width Ratio	0.26	-

Table 3: Calculation Results

	Regions A&B					
	Downforce			Uplift		
Test Pressure	Pressure	Torque	Uniform	Pressure	Torque	Uniform
EE	2110	1691	2523	-2388	-2779	-2400
E	2070	1327	2523	-2287	-1033	-2400
W	1912	781	2523	-2160	-408	-2400
WW	1518	477	2523	-1953	-250	-2400
Test Loads Applied At Clamp Width (Metric)						
Total Force (N)	2658	1494	3525	-3070	-1562	-3353
Total Torque (N·m)	194	421	0	-144	-825	0
West Mount Load (N)	2300	2850	1762	-2254	-4905	-1677
East Mount Load (N)	359	-1356	1762	-816	3343	-1677
Test Loads Applied At Clamp Width (Imperial)						
Total Force (lbf)	598	336	792	-690	-351	-754
Total Torque (ft-lbs)	143	310	0	-106	-608	0
West Mount Load (lbf)	517	641	396	-507	-1103	-377
East Mount Load (lbf)	81	-305	396	-183	751	-377

The load case leading to maximum bending moment is “Region A&B- Max Uniform- Uplift”. However, when “Max Torque Uplift” loads are resolved to interior dimensions, the single-side torsional load governs the design.

5 Primary Component Limits

The following sub-sections provide summary calculations for the primary structural components in this assembly, the module rail and torque tube straps.

5.1 Module Rail

5.1.1 Module Rail Flexural Yield

The Module Rail is designed for “Max Uniform Up”, “Max Uniform Down”, “Max Pressure Up”, “Max Pressure Down”, “Max Torque Up” and “Max Uniform Down” load cases.

The “Max Torque Uplift” load case leads to maximum stresses in the Module Rail and design calculation for the same is shown below.

The part is determined to be in flexure and checked for failure in terms of material strength.

I	=	area moment of inertia of the section	$= 1.232*10^{-8}m^4$ ($0.0296in^4$)
Y	=	distance from the centroid to the most extreme fiber	= 0.018m (0.706in)
F_y	=	specified minimum yield stress of the steel	= 413.7 MPa (60ksi)
L_e	=	distance to load application	= 0.0195m (0.768in)

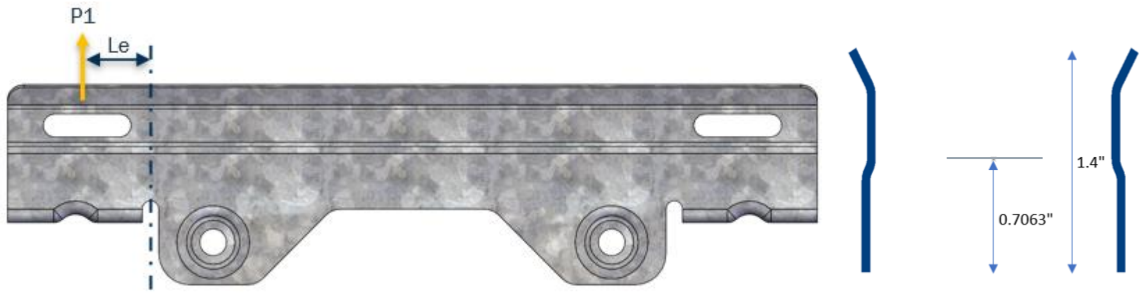


Figure 6: Module Rail Sectional Properties

S_y = elastic section modulus = 0.688×10^{-6} m^3 (0.042 in^3)

Z_y = plastic section modulus = 1.041×10^{-6} m^3 (0.0635 in^3)

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 1.6 \times F_y S_y$$

$M_{p,\ yield}$ = 430 Nm (3.81 kip-in) plastic

5.1.2 Module Rail Bearing Capacity, Holes

The torque tube straps are attached to the Module Rail using two 8.0mm (5/16") diameter rivets.

The minimum clear distance between the hole and edge of the strap is 8.8mm (0.347in) and the two pins are separated by a distance of 122.5mm (4.823in). Each side contains two bearing faces to distribute the respective load, and Section J of AISI 360 provides the following guidance.

The bearing strength at the rivet holes, when deformation at the bolt hole at service load is a design consideration

$$R_n = 1.2 l_c t F_u \leq 2.4 d t F_u$$

For local compressive yielding, the nominal bearing strength is;

R_n = 9.5 kN (2.14 kips) per hole or 19.0 kN (4.28 kips) per connection.

For shear yielding, the nominal bearing strength is;

R_n = 8.23 kN (1.85 kips) per hole or 16.4 kN (3.70 kips) per connection.

The worst-case loading on the rivet holes connection is in the max-torque uplift scenario.

5.1.3 Module Rail Bearing Capacity, Slots

The module frame is attached to the rail using two module attachment clips. The clips are inserted into two pairs of slotted holes located on the sides of the rail. Each slot measures 27mm (1.06 in) wide by 7.2mm (0.28in) high. To ensure adequate preload in the connection, an interference fit exists between the clips and the slotted holes in the module frame and mounting rail. After insertion, the resulting preload force on the clip is 1574 N (354 lbs.).

The center spacing between the slots is 200mm (7.87 in). The worst-case loading on the slots is in the max-torque uplift scenario.

The available bearing strength of the slots:

$R_n = 0.6 F_y A_{gv}$ for shear yielding

$R_n = 1.8 F_y A_{pb}$ for local compressive yielding

For shear yielding of the element, the nominal bearing strength is:

R_n = 6.49kN (1.458 kips) per slot, or 12.97kN (2.916 kips) per connection.

For local compressive yielding, the nominal bearing strength of the slots is:

Rn = 4.21kN (0.946 kips) per slot, or 8.42kN (1.892 kips) per connection.

5.2 Torque Tube Straps

The torque tube straps are evaluated both for flexural yield and for bearing strength at the fastener mounting holes. While flexural yield is calculated here, plastic flexural yield is required for a proper clamping connection to the torque tube.

5.2.1 Strap Flexural Yield

The torque tube straps are subject to flexure of the web where the straps are bolted together.

This analysis uses ANSI/AISC 360-16, Chapter F6: I Shaped Members and Channels Bent About Their Minor Axis. The nominal flexural strength (M_n) of the component is the lower value of either yielding or flange local buckling. The calculations below reference the dimensions noted in Figure 4.

First evaluating the yielding failure mode:

$$M_{n,yield} = M_{p,yield} = F_y Z_y \leq 1.6 \times F_y S_y$$

where

I	= area moment of inertia of the section	= 2.776 x 10^{-9} m^4 (0.00667in^4)
Y	= distance from the centroid to the most extreme fiber	= 0.00965m (0.380in)
F_y	= specified minimum yield stress of the material	= 413.7 MPa (60ksi)
L_e	= distance to load application	= 0.016m (0.639in)
S_Y	= elastic section modulus taken about the y-axis	= 2.868 x 10^{-7} m^3 (0.0175in^3)
Z_Y	= plastic section modulus	= 5.433 x 10^{-7} (0.0332in^3)

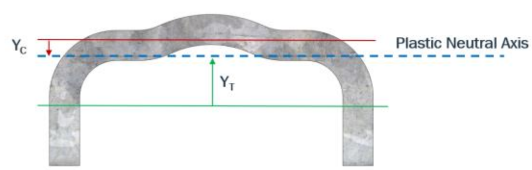


Figure 7: Strap Sectional Properties

Thus,

$M_{n, yield}$ = 225.1 Nm (1.99 kip-in) plastic, or

189.8 Nm (1.68 kip-in) elastic

Plastic yielding is considered the governing failure mode for this design, as elastic yielding is required to attain clamping around the torque tube.

For flange local buckling,

$$M_{n,buckling} = M_p - (M_p - 0.7 \times F_y S_y)\left(\frac{\lambda - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)$$

$$\lambda = \frac{b}{t_f}$$

where,

b	= the full nominal dimension of the flange	= 0.014m (0.551in)
t_f	= thickness of the flange	= .00313m (0.1233in)
λ_{pf}	= λ_p, the limiting slenderness for a compact flange, defined below	= 9.15
λ_{rf}	= λ_r, the limiting slenderness for a noncompact flange, defined below	= 24.08
E	= modulus of elasticity	= 200 GPa (29000 ksi)

$$\lambda_p = 0.38 \times \sqrt{\frac{E}{F_y}}$$

$$\lambda_r = 1.0 \times \sqrt{\frac{E}{F_y}}$$

thus:

$M_{n,buckling}$ = 257.91 Nm (2.283 kip-in)

If the flange were to be considered slender, then:

$$M_n = F_{cr} S_y$$

$$F_{cr} = \frac{0.69E}{\left(\frac{b}{t_f}\right)^2}$$

Thus,

$M_{n,slenderbuckling}$ = 1978.3 Nm (17.51 kip-in)

The governing failure mode for the lower strap is yielding, with a moment of 225.1 Nm (1.99 kip-in).

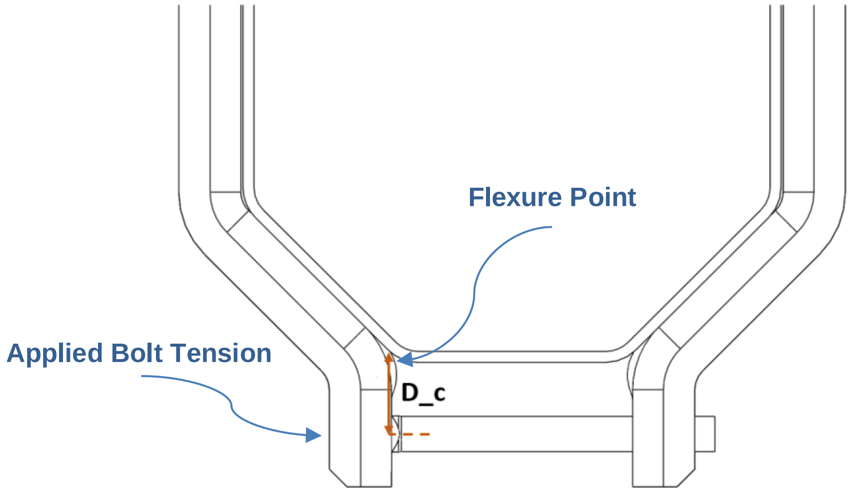


Figure 8: Flexural Point of the Torque Tube Straps

The 5/16-18 grade 8 bolt has a maximum pretension of 13.5 kN (3.04 kips), resulting in a utilization ratio of the torque tube strap of 97%. But while the base material of the torque tube strap has a yield strength of 413.7 MPa (60ksi), work hardening during the forming process increases the yield strength of the material around the bends, which is also the region of the flexure point. Thus, the work hardened material has a higher utilization ratio than noted above. Additionally, plastic deformation of the torque tube strap does not constitute a failure. Rather, it applies the necessary clamping load to the torque tube and relaxes the bolt pretension. Furthermore, the flexure region of the torque tube strap does not generally experience additional loading due to wind effects. The frictional faying forces of the straps on the torque tube provide resistance to wind loading, and flexure point on the straps themselves remain only exposed to the bolt tension.

5.2.2 Strap Bearing Capacity

The torque tube strap is attached to the Module Rail using an 8 mm (5/16 in) diameter pin.

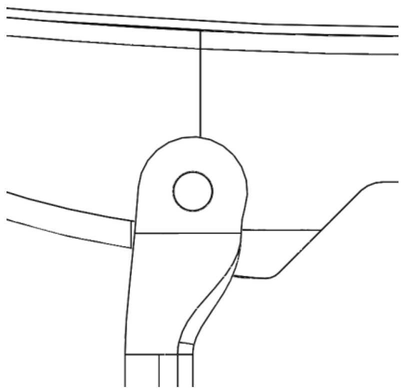


Figure 9: Torque Tube Strap Bearing Connection

The minimum material thickness between the hole and edge of the strap is 6.38mm (0.251in) and the two pins are separated by a distance of 122.5mm (4.823in). Each strap contains two bearing faces to distribute the respective load, and section J3.10 of AISI 360 provides the following guidance.

When deformation at the bolt hole at service load is a design consideration

$$R_n = 2.4dtF_u$$

R_n = 24.6 kN (5.54 kips) per hole or 49.2 kN (11.07 kips) per connection.

6 Hardware Limits

ANSI/AISC 360-16 was used to calculate tensile and shear capacity for each of the fastener sets. Per the standard, the allowable tensile or shear strength, R_n, is provided by

$$R_n = F_n A_b$$

where:

A_b = nominal unthreaded body area of bolt or threaded part, in^2

F_n = nominal tensile stress, F_{nt}, or shear stress, F_{nv}, ksi

6.1 Strap Rivets

The straps are connected to the Module Rail using two 8mm (5/16”) diameter rivets with a minimum tensile strength of 440 MPa (63.8 ksi). Per ANSI/AISC 360-16, the rivets have a nominal shear strength of 247.7 MPa (35.9 ksi).

The body/strap fasteners are loaded in double shear. Thus, their design shear strength is; 2 x F_n x A_b = 24.5 kN (5.51 kips).

The hole-to-hole spacing of these fasteners is 122mm (4.82 in). The worst-case loading on these bolts is in the max-torque uplift scenario.

6.2 Torque Tube Fastener

The straps are connected to the torque tube using a 5/16”-18 grade 8 carriage bolt. Per ANSI/AISC 360-16, grade 8 bolts have a nominal tensile stress of 775.7 MPa (113 ksi).

Thus, the design tensile strength is; F_n x A_b = 38.3 kN (8.63 kips).

The maximum preload on the carriage bolt is 25.8 N.m. (19 ft.lbs.)

6.3 Module Attachment Clips

The module is attached to the mounting rail using two module attachment clips (four per module). The clips are stamped from carbon steel with tensile yield strength of of 690 MPa (100 ksi).

The module attachment clips are loaded in shear. Thus, the nominal shear strength is;

$V_n = 0.6\, F_y A_w C_v$ = 3.9 kN (0.878 kips).

To ensure adequate preload in the connection, an interference fit exists between the clips and the slotted holes in the module frame and mounting rail. After insertion, the resulting preload force on the clip is 1574 N (354 lbs.).

The center spacing between the clips is 200mm (7.87 in). The worst-case loading on the clips is in the max-torque uplift scenario.

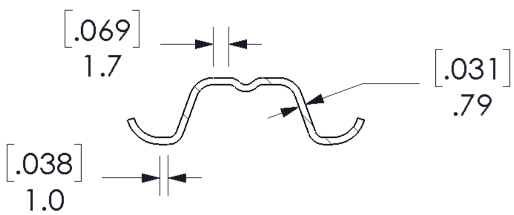


Figure 10: Section View of Module Attachment Clip

7 Summary of Results

Below is a summary of the calculations and results discussed herein. For comparative purposes, an example site condition is provided below. In this example, a 55.3 m/s (123.6 mph) wind speed is assumed. The module dimensions are in accordance with the example calculations in Section 4. The governing load cases are max uniform up and max torque up. The results in Table 4 summarize the allowable load and the loads experienced at each of the components at the example site for both Max Uniform and Max Torque cases.

Table 4: Results Summary

Component	Limiting Load	Calculation Location	Test Case Uniform Load	Test Case Torque Load	Test Case Utilization Factor
Module Rail, Flexural	430 Nm (3.81 kip-in)	5.1.1	34.3 N m (0.304 kip-in)	95.4 N m (0.85 kip-in)	22%
Module Rail, Holes, Bearing	16.4 kN (3.70 kips)	5.1.2	6.79 kN (1.53 kips)	12.63 kN (2.84 kips)	77%
Module Rail, Slots, Bearing	8.42kN (1.892 kips)	5.1.3	3.25 kN (0.731 kips)	6.49 kN (1.458 kips)	77%
Torque Tube Strap, Flexural	225.1 Nm (1.99 kip-in)	5.2.1	219.1 Nm (1.94 kip-in)	219.1 Nm (1.94 kip-in)	97%
Torque Tube Strap, Bearing	49.2 kN (11.07 kips)	5.2.2	12.63 kN (1.53 kips)	19.44 kN (2.84 kips)	26%
Rivets, Shear	24.5 kN (5.51 kips)	6.1	12.63 kN (1.53 kips)	19.44 kN (2.84 kips)	51%
Carriage Bolt, Tension	38.3 kN (8.63 kips)	6.2	14.19 kN (3.19 kips)	17.09 kN (3.84 kips)	71%
Module Attachment Clip, Shear	3.9 kN (0.878 kips)	6.3	0.89 kN (0.2 kips)	2.46 kN (0.55 kips)	63%

Revision History:

Release Date	Revision	Description	Name
1/12/2023	A	Original Release	BF