Essay on section size, shape and thickness selection in Design of Solar Trackers

A course in "Design for Manufacturing" and "mechanical optimization" will give a mathematical approach for selection of most optimal shape, selection size and thickness of the structural member, resulting in the smallest tonnage for the tracker.

Torsion Members:

The "torsion + bending" member in a solar tracker is the torque-tube. The design of the tube is based on the strength of the tube in resisting the torsion and bending. The area moment of inertia of the tube section is the metric used to gauge the resistance of the member to the bending and torsion. This metric is roughly linearly proportional to the thickness of the section and directly proportional to the cube of the major dimension of the section in the direction of bending.
Mass of tube, per meter of length (ignoring holes, dimples and other imperfections) is the only contributor towards tonnage, and finally cost of the tracker. The mass per meter of tube is given in the following tables.

Circular tube

		Thickness					
		2.5	3	3.5	4	5	mm
Dia	130	8.02	9.62	11.22	12.83	16.03	kg/m
	135	8.32	9.99	11.65	13.32	16.65	kg/m
	140	8.63	10.36	12.09	13.81	17.27	kg/m
	145	8.94	10.73	12.52	14.31	17.88	kg/m
	150	9.25	11.10	12.95	14.80	18.50	kg/m
	Mm	kg/m	kg/m	kg/m	kg/m	kg/m	

Square Tube

		Thickness					
		2.5	3	3.5	4	5	mm
Side of Square	100	7.851	9.4212	10.9914	12.5616	15.702	kg/m
	110	8.6361	10.36332	12.09054	13.81776	17.2722	kg/m
	120	9.4212	11.30544	13.18968	15.07392	18.8424	kg/m
	130	10.2063	12.24756	14.28882	16.33008	20.4126	kg/m
	140	10.9914	13.18968	15.38796	17.58624	21.9828	kg/m
	Mm	kg/m	kg/m	kg/m	kg/m	kg/m	

Hexagonal Tube							
		Thickness					
		2.5	3	3.5	4	5	mm
Face to Face	110	7.32	8.74	10.15	11.54	14.29	kg/m
	120	8.00	9.56	11.10	12.63	15.66	kg/m
	122.5	8.17	9.76	11.34	12.91	16.00	kg/m
	130	8.68	10.37	12.05	13.72	17.02	kg/m
	135	9.02	10.78	12.53	14.27	17.70	kg/m
	Mm	kg/m	kg/m	kg/m	kg/m	kg/m	

Octagon Tube							
		Thickness					
		2.5	3	3.5	4	5	mm
Face to Face	120	7.75	9.30	10.86	12.41	15.51	kg/m
	125	8.08	9.69	11.31	12.92	16.15	kg/m
	130	8.40	10.08	11.76	13.44	16.80	kg/m
	135	8.72	10.47	12.21	13.96	17.45	kg/m
	140	9.05	10.86	12.66	14.47	18.09	kg/m
	mm	kg/m	kg/m	kg/m	kg/m	kg/m	

Polar moment of inertial (2nd moment of area) for the section is given in the following table is the selection criteria for the bending and torsion resistance of the beam.

Circular tube							
		Thickness					
		2.5	3	3.5	4	5	Mm
Dia	130	43,13,799.41	51,76,559.29	60,39,319.18	69,02,079.06	86,27,598.82	mm^4
	135	48,30,935.02	57,97,122.02	67,63,309.02	77,29,496.03	96,61,870.03	mm^4
	140	53,87,831.40	64,65,397.68	75,42,963.96	86,20,530.24	1,07,75,662.80	mm^4
	145	59,85,961.19	71,83,153.43	83,80,345.67	95,77,537.90	1,19,71,922.38	mm^4
	150	66,26,797.00	79,52,156.40	92,77,515.81	1,06,02,875.21	1,32,53,594.01	mm^4
	mm	mm^4	mm^4	mm^4	mm^4	mm^4	

Square Tube							
		Thickness					
		2.5	3	3.5	4	5	mm
Side of Square	100	16,66,666.67	20,00,000.00	23,33,333.33	26,66,666.67	33,33,333.33	mm^4
	110	22,18,333.33	26,62,000.00	31,05,666.67	35,49,333.33	44,36,666.67	mm^4
	120	28,80,000.00	34,56,000.00	40,32,000.00	46,08,000.00	57,60,000.00	mm^4
	130	36,61,666.67	43,94,000.00	51,26,333.33	58,58,666.67	73,23,333.33	mm^4
	140	45,73,333.33	54,88,000.00	64,02,666.67	73,17,333.33	91,46,666.67	mm^4
	Mm	mm^4	mm^4	mm^4	mm^4	mm^4	

Hexagonal Tube							
		Thickness					
		2.5	3	3.5	4	5	Mm
Face to Face	110	2990582.81	3539724.52	4073252.02	4591464.12	5583123.00	mm^4
	120	3904862.81	4627217.28	5330810.47	6015970.10	7332285.00	mm^4
	122.50	4159372.50	4930082.75	5681199.86	6413058.75	7820327.06	mm^4
	130	4988765.81	5917391.47	6823820.09	7708408.24	9413475.00	mm^4
	135	5598837.19	6643897.60	7664934.83	8662319.88	10587603.00	mm^4
	Mm	mm^4	mm^4	mm^4	mm^4	mm^4	

Octagon Tube							
		Thickness					
		2.5	3	3.5	4	5	Mm
Face to Face	120	35,53,287.21	42,10,604.25	48,50,849.20	54,74,320.26	66,72,120.31	mm^4
	125	40,26,329.04	47,73,571.38	55,02,211.25	62,12,559.99	75,79,616.25	mm^4
	130	45,39,600.64	53,84,617.18	62,09,435.21	70,14,379.18	85,65,929.69	mm^4
	135	50,94,744.04	60,45,712.10	69,74,819.91	78,82,405.06	96,34,344.69	mm^4
	140	56,93,401.27	67,58,826.57	78,00,664.20	88,19,264.90	1,07,88,145.31	mm^4
	Mm	mm^4	mm^4	mm^4	mm^4	mm^4	

The index for selection of the most optimal section will be represented by the product of the inverse of the weight per meter of the section and the polar moment of inertia of the section. The index is given below:

Circular tube

		Thickness					
		2.5	3	3.5	4	5	mm
Dia	130	0.508	0.502	0.496	0.490	0.479	cm^4/kg
	135	0.549	0.543	0.537	0.531	0.519	cm^4/kg
	140	0.591	0.585	0.579	0.573	0.560	cm^4/kg
	145	0.636	0.629	0.623	0.616	0.603	cm^4/kg
	150	0.681	0.675	0.692	0.688	0.681	cm^4/kg
	mm	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	

Square Tube

		Thickness					
		2.5	3	3.5	4	5	mm
Side of Square	100	0.394	0.388	0.382	0.376	0.365	cm^4/kg
	110	0.480	0.473	0.467	0.460	0.448	cm^4/kg
	120	0.574	0.567	0.560	0.553	0.539	cm^4/kg
	130	0.677	0.669	0.662	0.654	0.639	cm^4/kg
	140	0.789	0.780	0.772	0.764	0.747	cm^4/kg
	mm	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	

Hexagonal Tube

		Thickness					
		2.5	3	3.5	4	5	Mm
Face to Face	110	0.409	0.405	0.401	0.398	0.391	cm^4/kg
	120	0.488	0.484	0.480	0.476	0.468	cm^4/kg
	122.50	0.509	0.505	0.501	0.497	0.489	cm^4/kg
	130	0.575	0.570	0.566	0.562	0.553	cm^4/kg
	135	0.621	0.616	0.612	0.607	0.598	cm^4/kg
	mm	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	

Octagon Tube

		Thickness					
		2.5	3	3.5	4	5	Mm
Face to Face	120	0.458	0.453	0.447	0.441	0.430	cm^4/kg
	125	0.498	0.492	0.487	0.481	0.469	cm^4/kg
	130	0.540	0.534	0.528	0.522	0.510	cm^4/kg
	135	0.584	0.578	0.571	0.565	0.552	cm^4/kg
	140	0.629	0.623	0.616	0.609	0.596	cm^4/kg
	mm	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	cm^4/kg	

Let us say we need a lower limiting value of 40,00,000 mm^4
Looking at the values in the table, following choices can be made:

Shp.	Tube	J Value	Wt./m	Savings in kg	Saving in Rs. (per MW)	Index
Sq	100x3.5	41,99,133	10.99	8,751.15	7,00,091.94	0.382
Sq	110x2.5	41,43,229	8.636	1,823.80	1,45,903.70	0.480
Cir	130x2.5	40,71,246	8.02	-	-	0.508
Oct	125x2.5	40,26,329	8.08	179.87	14,389.46	0.498
Hex	122.5x2.5	41,59,373	8.17	447.36	35,788.88	0.509

So, for going towards the most optimal size of tube, and assuming that, the tooling costs to be incurred are 10L for new rollers and new bearing inserts, the payback shall start sooner than expected.

While the values considered are only rough, it may be seen that with further optimization or refinements in diameters, the tonnage saving in torque tubes can be of significant value, even including dies and tooling.

So, the guidelines for the designer should rather instruct on increasing the section size and choosing better shapes, rather than increasing the thickness which is a practice that we have been following at MSPL.

Important thumb-rule is: the section modulus is proportional to the cube of the major dimension of the HSS, and only linearly proportional to the thickness of the tube. Further, it may be observed, that the increase in weight per meter, by increasing the major dimension by 10 mm increase the weight by 1 kg for square and 5mm in dia for circle by 0.5 kg per meter. But an increase in thickness by 0.5mm increases the per meter weight of the section by 2 kg.

The measurement index for this is the product of inverse of the mass of the beam and the polar moment of inertia.

A better comparison of structural members based on shapes can be made by keeping the coil width of the base sheet equal for shapes being compared and check the structure index:

Coil Width	400			
Thickness	1.5			
	Major Dim	M	J	P
Square	100.0	4.71	19,11,786.50	0.41
Hexagon	66.7	4.65	2137442.09	0.46
Octagon	50.0	4.68	22,25,797.42	0.48
Circular	127.3	4.71	23,47,106.79	0.50

Coil Width	600			
Thickness	1.5			
	Major Dim	M	J	ρ
Square	150.0	7.07	65,50,186.50	0.93
Hexagon	100.0	7.01	7308520.24	1.04
Octagon	75.0	7.02	76,06,312.41	1.08
Circular	191.0	7.07	80,15,659.67	1.13

Coil Width	400			
Thickness	3			
	Major Dim	M	J	ρ
Square	100.0	9.42	36,54,184.00	0.39
Hexagon	66.7	9.19	4110517.15	0.45
Octagon	50.0	9.36	42,87,765.14	0.46
Circular	127.3	9.42	45,30,314.90	0.48

Coil Width	600			
Thickness	3			
	Major Dim	M	J	ρ
Square	150.0	14.13	1,27,11,384.00	0.90
Hexagon	100.0	13.90	14240634.16	1.02
Octagon	75.0	14.04	1,48,37,741.14	1.06
Circular	191.0	14.13	1,56,56,611.49	1.11

It can be seen from the above tables, that for the same coil width, the shape of the member makes a lot of difference in the structural property. It can also be seen, that the properties change positively with the section size and negatively with the sheet thickness used.

Pure Bending Members:

A similar approach is used for selecting the most optimal section in bending of beams using the mass per meter of the beam and the area-moment of inertia in axis pertaining to the direction of bending. It may be noted that this is a more simplistic explanation, and hence factors such as radius of gyration for buckling etc. are not considered in this analysis. It may also be noted that a cut off value of radius of gyration can be used as an eligibility criterion and included in the analysis, but is not in the scope of this essay.

The moment of inertia about the minor axis (larger value of moment of inertia) is assumed to be the active direction of bending. The per-meter mass of the beam selected is also calculated and the ratio of moment of inertia and the per meter weight of the beam forms the metric for comparison in this case. The larger the ratio, the better is the utilization of the material. It is assumed that the other checks such as strength in shear and tension/compression are accounted for in separate calculations. The tables of comparison of sections are given in the following tables, and are used for comparing the various sections used by various tracker designers.

Hot-rolled Standard I-Section Beams:

Beam Series	Beam ID	Weight	Ixx	Iyy	ρx	ρy
Junior	ISJB 150	7.1	322	9.2	45.35	1.30
	ISJB 200	9.9	781	17.3	78.89	1.75
Light	ISLB 100	8	168	12.7	21.00	1.59
	ISLB 150	14.2	690	55.2	48.59	3.89
	ISLB 200	19.8	1700	115	85.86	5.81
	ISLB 250	27.9	3720	193	133.33	6.92
	ISLB 300	37.7	7330	376	194.43	9.97
Medium	ISMB 100	8.9	183	12.9	20.56	1.45
	ISMB 150	15	718	46.8	47.87	3.12
	ISMB 200	24.2	2120	137	87.60	5.66
	ISMB 250	37.3	5130	335	137.53	8.98
	ISMB 300	46	8990	486	195.43	10.57
Heavy	ISHB 150	27.1	1460	432	53.87	15.94
	ISHB 200	37.3	3660	967	98.12	25.92
	ISHB 250	51	7740	1960	151.76	38.43
	ISHB 300	58.8	12600	2200	214.29	37.41
Wide Flange	ISWB 150	17	839	94.88	49.35	5.58
	ISWB 200	28.8	2620	329	90.97	11.42
	ISWB 250	40.9	5940	858	145.23	20.98
	ISWB 300	48.1	9820	990	204.16	20.58
Column Section	ISSC 100	20	436	236	21.80	11.80
	ISSC 150	37.1	1970	700	53.10	18.87
	ISSC 200	60.3	5530	1530	91.71	25.37
	ISSC 250	85.6	12500	3260	146.03	38.08

Hot Rolled Standard C-section Beams:

Beam Series	Beam ID	Weight	Ixx	Iyy	ρx	ρy
Medium	ISMC 100	9.56	192	26.7	20.08	2.79
	ISMC 150	16.8	788	103	46.90	6.13
	ISMC 200	22.3	1830	141	82.06	6.32
Medium Parellel Flange	ISMCP 100	9.56	194	29.4	20.29	3.08
	ISMCP 150	16.8	794	120	47.26	7.14
	ISMCP 200	22.3	1840	156	82.51	7.00
Junior	ISJC 100	5.8	124	14.9	21.38	2.57
	ISJC 150	9.9	472	37.9	47.68	3.83
	ISJC 200	14	1160	84.2	82.86	6.01

Light	ISLC 100	7.9	165	24.8	20.89	3.14
	ISLC 150	14.4	699	103	48.54	7.15
	ISLC 200	20.6	1730	147	83.98	7.14

Cold-formed C-with-Lip type beams:

Beam Dimensions	Thickness	Weight	Ixx	Iyy	ρx	ρy
150x100x25	2	6.089	300.39	110.6	49.33	18.16
	3.15	9.4	455.09	165.26	48.41	17.58
	4	11.76	561.3	201.69	47.73	17.15
180x80x25	2	5.931	390.32	96.35	65.81	16.25
	3.15	9.154	591.17	102.8	64.58	11.23
	4	11.449	782.88	124.67	68.38	10.89
170x50x20	2	4.672	249.61	20.27	53.43	4.34
	3.15	7.171	373.96	29.12	52.15	4.06
	4	8.93	456.58	34.47	51.13	3.86

Rectangular Hollow Sections:

H	B	t	Weight	Ixx	Iyy	ρx	ρy
100	50	2.5	5.6985	95.2	32.0	16.70	5.62
120	50	2.5	6.4845	149.7	37.7	23.08	5.81
140	50	2.5	7.2705	220.7	43.3	30.35	5.96
100	60	2.5	6.0915	107.0	48.3	17.57	7.93
120	60	2.5	6.8775	166.9	56.6	24.27	8.22
140	60	2.5	7.6635	244.3	64.8	31.88	8.46
100	80	2.5	6.8775	130.8	92.7	19.02	13.48
120	80	2.5	7.6635	201.5	107.7	26.29	14.05
140	80	2.5	8.4495	291.6	122.7	34.51	14.52
100	50	5	11.004	173.7	56.2	15.78	5.10
120	50	5	12.576	276.3	66.3	21.97	5.27
140	50	5	14.148	411.0	76.5	29.05	5.41
100	60	5	11.79	196.3	86.3	16.65	7.32
120	60	5	13.362	309.4	101.4	23.16	7.59
140	60	5	14.934	456.6	116.6	30.57	7.81
100	80	5	13.362	241.4	169.4	18.07	12.68
120	80	5	14.934	375.6	197.6	25.15	13.23
140	80	5	16.506	547.8	225.8	33.18	13.68
100	50	6	13.01616	200.9	63.9	15.43	4.91
120	50	6	14.90256	321.1	75.6	21.55	5.07
140	50	6	16.78896	479.2	87.3	28.54	5.20
100	60	6	13.95936	227.4	98.9	16.29	7.08
120	60	6	15.84576	360.1	116.5	22.73	7.35

140	60	6	17.73216	533.1	134.0	30.07	7.56
100	80	6	15.84576	280.5	196.1	17.70	12.37
120	80	6	17.73216	438.2	229.0	24.71	12.92
140	80	6	19.61856	640.9	261.9	32.67	13.35

For a required bending strength, the beams of all the sections should be checked for their efficient material usage and the beam with the largest ρx should be selected, to ensure the most optimal usage of material.

This essay is written by *Ninad Hemant Watve* and is his opinion. The accuracy of numbers can and should be debated. The logic is clear and easy. The numbers can be used as a reference during selection of sections and thickness.
