Analysis of The Optimal slenderness ratio for Power Transmission Tower

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Abstract: Through theoretical analysis, this paper deduced the optimal slenderness ratio and calculated length of the angle steel. According to the actual stress conditions, this paper figure out the optimal slenderness ratio and calculated length of the large angle steel, large double angle steel, ordinary double angle steel and ordinary quadruple angle steel. In order to provide a basis to replace the large angle steel with the combined angle steel, the slenderness ratio and calculated length which are suitable for engineering applications are given.

Foreword

At present, the limb width of the steel angle tower is mostly 200mm and below, the main member of the steel angle tower body with great bearing force in the ultra-high voltage and some same tower double/multiple circuits super-high voltage line engineering apply the double splice or multiple splice angle steel combination, which makes structure of the power transmission tower complicated and consumption of the steel quantity increased. Introduction of the 220mm and 250mm large angle steel makes foundation for application of the large steel angle in the steel tower in the power transmission line. Compared to the ordinary double splice or quadruple splice angle steel members, the large angle steel has good force integrity and evenness. Bending torque at the end of the bar which is generated after structural forcing is very small, its forcing is closer to the two force bar member compared to the combination angle steel. Because section area of the large angle steel is very great and bearing force is also very high, it can substitute the member which shall apply the double splice angle steel in original design.

Bearing capability of the angle steel member in the power transmission tower is mainly affected by strength and stability two factors. When bearing force of the member is controlled by strength, it isn’t related to the slenderness ration. When its bearing force of the member is controlled by stability, its bearing force is related to slenderness ratio of the member. When strength bearing force of the member equals to stable bearing force, it will be related to optimal slenderness ratio issue.

Optimal slenderness ratio

Bearing capability of the steel tower member is determined by strength bearing force and stable bearing force two factors. Strength bearing force depends on net area (section area is subtracted area of the hole) of the member, quality and section thickness of the steel material; stable bearing force depends on calculation length and section area of the member, section area, yield strength of the material and rotary radius of the section. In which, strength bearing force is a primary condition which must be met by the member. Reduced hole number of the section shall be determined firstly in order to determine strength bearing force of the member, so as to determine reduction condition of the section area of the member, and then obtain the stability coefficient, slenderness ratio and calculation length which can meet requirements of stable bearing force. When strength and stable calculation stress are equivalent, forcing of the member is reasonable. Now the calculation length is optimal calculation length, the corresponding slenderness ratio is the optimal slenderness ratio, the stability coefficient is the optimal stability coefficient. When the slenderness ratio of the member is less than the optimal slenderness ratio, bearing force of the member is controlled by strength. When the slenderness ratio of the member is greater than the optimal slenderness, bearing force of the member is controlled by stability. Followings are process to determine the optimal slenderness ratio:

Strength calculation formula of the axle center forcing member:

$$N/A_n \leq m \cdot f \qquad (1)$$

In which: N is design value of axle centre pressure, N; A_n is net section area of the member, mm^2; m is strength reduction coefficient of the member; f is strength design value of the material, N/mm^2.

Stability calculation formula of the axle centre compression member:

$$N/(\varphi \cdot A) \leq m_n \cdot f \qquad (2)$$

In which: φ is stability coefficient; A is area of the rough section of the member, mm^2; m_n is strength reduction coefficient.

When strength bearing force of the member equals to the stability bearing force:

$$A_n \cdot f = \varphi \cdot A\, m_n \cdot f \qquad (3)$$

$$\varphi = A_n/(A \cdot m_n) \qquad (4)$$

$$K\lambda = K \cdot L_o/r \qquad (5)$$

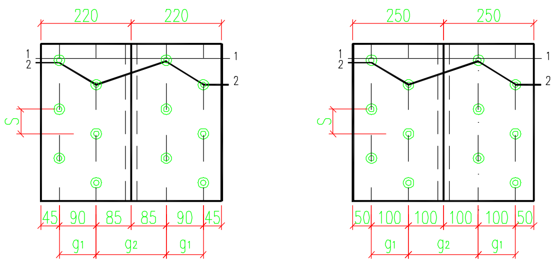
In which: λ is slenderness ratio of the member; L_o is calculation length of the member, m.

Analysis of reduced hole number

Learn from DL/T5442-2010《Drawing and construction regulation of steel tower in power transmission line》, the large specification steel angle can be arranged as double rows or three rows bolts on demand. Compared to the ordinary specification angle steel, the limb width of the large specification angle steel is very great, its reduced hole number shall be calculated again. According to regulations of 《Design manual of high voltage power transmission line in power engineering》, the saw tooth shaped destruction sections of the double rows and three rows of the bolts are assumed as shapes in figure 1 and figure 2 when the large specification angle steels are drawn （the bolt in the figure is M24, and span S=60）, the reduced hole number of the angle steel takes large one of the calculated reduced hole number of every destruction section. The net section area of the drawn board equals to multiply of the net width and the board thickness of the board. Net width of the board shall be value that whole width is subtracted by amount of the diameters of all bolt holes, and plus $S^2/(4g)$ on the span of every hole. Net width b_n of the drawn board is:

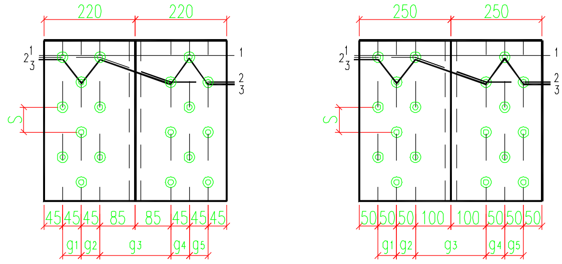
$$b_n = b - n_o \cdot d_o + \sum_{i=1}^{n_o - 1} \frac{S_i^2}{4g_i}$$

In which: b is width of the drawn board, mm; n_o is number of the bolt hole on the saw tooth section; d_o is diameter of the bolt hole, mm; S_i is span between two adjacent horizontal holes, mm; g_i is span between two adjacent transversal holes, mm。



（a）∠220　　　（b）∠250

Figure 1　Schematic figure of destruction section of large specification angle steel double rows of bolts



（a）∠220　　（b）∠250

Figure 2　Schematic figure of destruction section of large specification angle steel three rows of bolts

Table 2-1 Calculated reduced hole number of every destruction section when large specification angle steel double rows of bolts are drawn

Specification of angle steel	Section area (cm^2)	1-1 Reduced hole number of section 2		2-2Reduced hole number of section 3.1	
		Net area (cm^2)	Reduction coefficient	Net area (cm^2)	Reduction coefficient
L220×16	68.664	60.50	0.88	56.01	0.82
L220×26	108.264	95.00	0.88	87.77	0.81
L250×18	87.842	78.66	0.90	73.61	0.84
L250×35	163.402	145.55	0.89	135.91	0.83

Note: When it is destructed along 2-2 section, calculation formula of reduced hole number is $n=4-\frac{S^2}{4d_0}\left(\frac{1}{g_1}+\frac{1}{g_2}+\frac{1}{g_3}\right)$; In which: $g_2=2d_1-t$, d_1 is distance between first alignment line to the limb back of the angle steel.

Learn from table 2-1, maximum reduced hole number can take 3.1 when the large specification steel angles ∠220 and ∠250 are arranged as the double rows of the bolts, it is slightly greater than reduced hole number 2.33 during double rows bolts arrangement of the ordinary specification angle steel, reduction coefficient of the section area is about 0.81~0.84.

Table 2-2 Calculation reduced hole number of every destruction area when three rows of the bolts of the large specification steel angle are drawn

Specification and size	Section area (cm^2)	1-1 Reduced hole number of section 3		2-2 Reduced hole number of section 3.81		3-3 Reduced hole number of section 2.98	
		Net area (cm^2)	Reduction coefficient	Net area (cm^2)	Reduction coefficient	Net area (cm^2)	Reduction coefficient
L220×16	68.664	56.42	0.82	53.28	0.78	57.92	0.84
L220×26	108.264	88.37	0.82	83.37	0.77	90.91	0.84
L250×18	87.842	74.07	0.84	70.37	0.80	74.15	0.84
L250×35	163.402	136.63	0.84	129.61	0.79	136.96	0.84

Note: when it is destructed along the 2-2 section, calculation formula of the destruction reduced hole number is $n=4-\frac{S^2}{4g_3d_0}$; in which: $g_3=2d_1-t$; when it is destructed along the 3-3 section, calculation formula of the destruction reduced hole number is $n=6-\frac{S^2}{4d_0}\left(\frac{1}{g_1}+\frac{1}{g_2}+\frac{1}{g_3}+\frac{1}{g_4}+\frac{1}{g_5}\right)$. In which, d_0 is diameter of the bolt hole, mm.

Learn from table 2-2, maximum reduced hole number can take 3.81 when the large specification angle steel ∠220 and ∠250 are arranged as three rows of the bolts, the reduction coefficient of the section area is about 0.77~0.80, it is seen weakness of three rows of the bolts on the section are very serious.

Calculation value of optimal slenderness ratio f angle steel

The strength destruction of the bar member consists of drawn strength destruction and compression strength destruction. Reduced hole number of drawn destruction is calculated according to formula of the saw tooth type destruction. Calculation result shows drawn reduced hole number can reach 2~3.1 when arrangement of the large specification angle steel applies two rows of the bolts. Drawn reduced hole number can reach 3~3.8 pieces when three rows of the bolts are arranged. Because compression force transfer of the hole wall and the bolt shall be considered during compression strength destruction, destruction type of the section is different to above mentioned saw tooth type destruction, therefore the compression reduced hole number can be reduced suitably. Reduced hole number for compression strength destruction during engineering design is 2 pieces for the single limb and 4 pieces for the double limb.

When the large specification angle steel applies the double rows of the bolts for connection, refer to table 2-3 for optimal slenderness ratio calculation results of the common double splice angle steel and the large specification angle steel of Q420 materials and M24 bolts:

Table 2-3 Calculation table of Q420 ordinary double splice angle steel and large specification angle steel with double rows of bolt connection

Specification of angle steel	Section area (cm^2)	Strength reduction coefficient	Net section area (cm^2)	Optimal stability coefficient	Optimal slenderness ratio	Optimal calculation length (m)	Baring force (kN)
2L160×16	98.14	1	81.82	0.834	41.0	2.529	3109
2L180×18	123.90	1	105.54	0.852	38.1	2.651	3799
2L200×24	181.32	1	156.84	0.865	35.9	2.743	5646
L220×18	76.752	1	67.572	0.880	33.3	1.448	2433
L220×26	108.264	1	95.004	0.878	33.7	1.447	3420
L250×20	97.045	1	86.845	0.895	30.7	1.518	3126
L250×35	163.402	1	145.552	0.891	31.4	1.527	5240

Learn from table 2-3, when the M24 bolt connection is applied, compression reduced hole number of the single member is 2, compression reduced hole number of the double splice member is 4, optimal slenderness ratio of the Q420 large specification angle steel is mostly ranged between 0.7 and 33.7 （the limb thickness is very thin, application of specification ∠220×16 and ∠250×18 is very a few）, optimal calculation length is commonly ranged between 1445mm and 1527mm, and compression bearing force is ranged between 2299kN and 5240 kN; the optimal slenderness ratio of the angle steel combination of Q420 double common specification is commonly ranged between 34.4 and 41.0, the optimal calculation length is commonly ranged between 2159mm and 2750mm, and compression bearing force is ranged between 2748kN and 4774kN. It is seen that bearing force of the large specification angle steel basically covers bearing force of the common specification double splice angle steel （except 2∠200×24）. But the optimal slenderness ratio and the optimal calculation length of the large specification angle steel are commonly small than the double splice angle steel. More auxiliary materials are required to divide the node space small during design, so as to play maximum bearing force of the material.

When the large specification angle steel applies two rows of the bolts for connection, optimal slenderness ratio calculation results of the common four splice angle steel and the large specification double splice angle steel of Q420 material and M24 bolt are shown as table 2-4:

Table 2-4 Calculation table of Q420 ordinary angle steel and large specification double splice angle steel with double row bolt connection.

Specification of angle steel	Section area (cm^2)	Strength reduction coefficient	Net section (cm^2)	Optimal stability coefficient	Optimal slenderness ratio	Optimal calculation length (m)	Bearing force (kN)
4L160×16	196.28	1	163.64	0.834	41.0	2.942	6218
4L180×18	247.80	1	211.08	0.852	38.1	3.060	7599
4L200×24	362.64	1	313.68	0.865	35.9	3.203	11292
2L220×18	153.504	1	135.144	0.880	33.3	2.846	4865
2L220×26	216.528	1	190.008	0.878	33.7	2.831	6840
2L250×20	194.09	1	173.69	0.895	30.7	2.987	6253
2L250×35	326.804	1	291.104	0.891	31.4	2.972	10480

Learn from table 2-4, when M24 bolt connection is applied, compression reduced hole number of the double splice member is 4, compression reduced hole number of the four splice member is 8, optimal slenderness ratio of the Q420 double splice large specification angle steel combination is same as that of the single angle steel, which is commonly ranged between 30.7 and 33.7（the limb thickness is very thin, application of the specification ∠220×16 and ∠250×18 is a few）, the optimal calculation length is commonly ranged between 2831mm and 2987mm, compression bearing force is ranged between 4598 kN and 10480 kN; the optimal slenderness ratio of the Q420 four splice ordinary specification angle steel combination is same as the optimal slenderness ratio of the double splice specification angle steel combination, which is commonly ranged between 34.4 and 41.0, the optimal calculation length is commonly ranged between 2456mm and 3203mm, and compression bearing force is ranged between 4761kN and 11292 kN. It is seen bearing force of the double splice large specification angle steel combination basically covers bearing force of the four splice common specification angle steel combination（except 4∠200×24）. Compared to the single large specification angle steel, the double splice large specification angle steel combination can obtain the optimal calculation length which is greater than the four splice common specification angle steel combination.

Table 2-5 Calculation table of Q420 large specification angle steel and double splice angle steel with three rows of bolt connection

Specification of angle steel	Section area (cm^2)	Strength reduction coefficient	Net section are (cm^2)	Optimal stability coefficient	Optimal slenderness ratio	Optimal calculation length (m)	Bearing force (kN)
L220×26	108.264	1	88.374	0.816	43.7	1.878	3181
L250×35	163.402	1	136.627	0.836	40.7	1.978	4919
2L220×18	153.504	1	125.964	0.821	42.9	3.671	4865
2L220×26	216.528	1	176.748	0.816	43.7	3.674	6840
2L250×20	194.09	1	163.49	0.842	39.6	3.861	6253
2L250×35	326.804	1	273.254	0.836	40.7	3.849	10480

Lear from table 2-5, when the M24 three rows of bolt connection is applied, compression reduced hole number of the single member is 3 and compression reduced hole number of the double splice member is 6, the optimal slenderness ratio of the Q420 large specification angle steel is commonly ranged between 32.6 and 43.7（the limb thickness is very thin, application of specifications ∠220×16 and ∠250×18 is a few）, the optimal calculation length is commonly ranged between 1874mm and 1978mm, the compression bearing force is ranged between 2144kN and 4919 kN; the optimal slenderness ratio of the Q420 double splice large specification angle steel combination is commonly ranged between 32.6 and 43.7, the optimal calculation length is commonly ranged between 3671mm and 3858mm, and compression bearing force is ranged between 4598kN and 10480 kN.

Suggestion value of slenderness ratio and calculation length of angle steel

Calculation of the optimal slenderness ratio of the high strength angle steel can be applied to determine the optimal calculation length between the nodes of the main material, which can provide reference for arrangement between the nodes of the main material during design of the steel tower. The large specification angle steel is generally applied when the height between the nodes is very great, the slenderness ratio of the main material is greater than the optimal value, bearing force doesn't reach maximum value. In order to make forcing of the power transmission steel tower more reasonable when the large specification angle steel, the large specification double splice angle steel, the common combination angle steel and the common four splice angle steel apply M24 bolt connection, suggestion values of the slenderness ratio and the calculation length of the main material with above various specification angle steel are shown as following:

1.When the large specification angle steel applies the double rows of the bolts for connection, the slenderness ratio can take about 33 and the calculation length can take about 1.5m during design of the large specification angle steel; when the large specification angle steel applies three rows of the bolts for connection, the slenderness ratio can take about 43 and the calculation length can take about 2.0m during design of the large specification angle steel;

2.When the large specification double splice angle steel applies the double rows of the bolts for connection, the slenderness ratio can take about 33 and the calculation length can take about 3.0mm during design of the large specification double splice angle steel. When the large specification double splice angle steel applies three rows of the bolts for connection, the slenderness ratio can take about 43 and the calculation length can take about 4.0m during design of the large specification of the double splice angle steel;

3.The slenderness ratio of the common double splice angle steel main material can take about 40, and the calculation length can take about 2.8m;

4.The slenderness ratio of the common four splice angle steel main material can take about 40, the calculation length can take about 3.0m.

Conclusion

It is learn from analysis of this paper, it can avoid using the combination angle steel when the large specification of the angle steel is applied, so as to realize purpose on reducing manufacturing quantity and the tower weight, which has very high economic benefit. When the section area of the large specification angle steel is equivalent to that of the combination angle steel, the rotary radius is very small, the auxiliary material shall be added to reduce the length between the nodes in order to reduce its slenderness ratio. Compared to the single angle steel tower, the combination angle steel tower has uneven forcing between the angle steels and additional secondary bending torque etc problem, and the member of the combination angle steel is complicate. The combination member which is connected together through the filling board isn't a complete integrity. Bearing force of every member isn't consistent completely, a certain safety tolerance shall be reserved when the main material applies the combination angle steel.

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