

EXPERIMENTAL STUDY OF MECHANICAL BEHAVIOUR OF ANGLES IN TRANSMISSION TOWERS UNDER FREEZING TEMPERATURE

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Received: 12 May 2017; Revised: 4 August 2017; Accepted: 25 November 2017

ABSTRACT: Compared with the lower-grade steel members, the application of steel angles made of Q420 greatly reduces the self-weight of lattice transmission tower and further leads to the saving of foundation cost. However, unlike the conventional transmission towers, the strength and brittleness of the towers using higher-grade steel are more sensitive to freezing temperature, especially in cold regions. It is noted that the studies on transmission line tower at cold region are limited in literature. In this paper, a series of tests such as Charpy impact test, uniaxial tensile test and tensile notch test were carried out at low temperatures to investigate the mechanical properties and toughness of steel angles made of Q235B, Q345B and Q420C as well as welded joints using Q420C. The results show that the toughness of steel angles decreases with the lowering temperature while the strength increases with the decreasing temperature. The heat affected zone in welded joints is more susceptible to fracture than the parent material. A strength reduction method is proposed for the design of transmission tower in cold regions with rich experimental data provided. The influence of stress concentration at low temperatures was also investigated for fracture resistant design.

Keywords: Steel angle, low temperature, transmission tower, toughness, notch sensitivity

DOI: 10.18057/IJASC.2018.14.3.9

1. INTRODUCTION

Steel materials of strength above 400 MPa become widely used in transmission line engineering due to its light weight and high loading capacity. More importantly, the high strength steel can avoid the largely use of compound sections in the design of transmission towers subjected to heavy loads, which not only brings a more reliable load transfer mechanism but also simplifies the fabrication work. Also, structural engineers may face problems when using the direct analysis to design transmission tower as the initial member imperfection of compound sections has not been given in the design codes such as AISC-LRFD [1] and EC3 [2]. The direct analysis method is a powerful and reliable tool which can well predict the structural behavior of transmission tower considering joint performance [3-4]. Generally speaking, the application of high strength steel can improve the safety and structural performance of transmission engineering with a reduction in fabrication and construction cost.

It should be pointed out that the mechanical properties and toughness of the high-strength steel may be quite different from that of normal steel, due to the different rolling process, crystal phases and chemical components. It is reported that the elongation decreases commonly with the increasing of steel strength, which indicates the lower plastic deformation capacity and ultimate-to-yield strength ratio for higher grade steel as the temperature decreases [5-8]. Obviously, the transmission tower

made of higher grade steel has higher load-carrying capacity than that made of normal steel. According to the theory of fracture mechanics, the higher strength steel is more sensitive to defect and therefore increases the risk of brittle fracture at low temperature [9-12]. This concern leads to the limited use of higher strength steels such as Q420 and Q460 in transmission towers especially in the low temperature area.

In the past decades, considerable number of steel structures collapsed in cold regions due to brittle fracture. It is reported that the number of tower collapsed at low temperature environment in China has increased several dozen times from 1988 to 2013. It seems that the use of higher strength steel causes severe brittle problems in cold regions of China. For all steel grades, the Chinese structural steel is classified into A, B, C and D. There is no requirement of Charpy impact test for Class A while the temperature of Charpy impact test is 20°C, 0°C and -20°C for Class B, C and D respectively. In Chinese market, the steel angles for transmission towers are generally made of Class B and C. Thus, there is an urgent need to verify the performance of steel angles at temperatures lower than -20°C for routine design or evaluation of existing tower in cold regions.

For UHV (Ultra High Voltage) and EHV (Extra High Voltage) transmission towers, their main legs usually consist of multiple angles which are connected by bolts for easy fabrication and transportation. In the process of drilling bolt hole, the commonly used method is punching process, which easily causes microcrack and crack source around the wall of hole. The microcrack will be quickly expanded when the temperature of steel angle is below the ductile-brittle transition temperature. This leads to the failure of bolted joints and further the collapse of the transmission tower.

A typical transmission tower contains four main legs which are the key members to transfer the external loads to the foundation. The brittle failure of main angles at low temperature will lead to the collapse of the tower and further endanger the safe and stable operation of the whole power system. Thus, there is an urgent need of experimental study of the mechanical properties, fracture toughness and notch sensitivity of steel angles used in transmission tower at low temperature. It is of great importance to the design and construction of UHV (Ultra High Voltage) and EHV (Extra High Voltage) transmission lines in cold regions. In this paper, a series of tests such as Charpy impact test, uniaxial tensile test and tensile notch test were carried out at low temperatures to investigate the mechanical properties and toughness of steel angles made of Q235B, Q345B and Q420C as well as welded joints using Q420C. From this study, the strength reduction method and some recommendations is proposed for the design of transmission tower in cold regions.

2. SETUP OF EXPERIMENTAL TESTS

In this paper, totally 31 transmission lines (500 kV and above) which are in operation or under construction at the regions of China with annual average temperature below 0°C are investigated. Among them, there are 24, 1 and 6 towers for 500 kV, 660 kV and 750 kV lines respectively. For the minimum temperature in the design stage, there are 9, 17 and 5 towers designed for -40°C, -35°C and -30°C respectively. These transmission lines are mainly made of steel angles except one named Qingyun-Jixi 500 kV double circuit which used Q345B steel tubes. Six line towers (two 500 kV lines, one 660 kV line and three 750 kV lines) are used Q420B and Q420C steel angles while the other towers are made of Q235B and Q345B steel angles.

Experimental study is the effective approach to investigate the mechanical behaviour of engineering structures [13-15]. To evaluate the actual performance of the towers mentioned above, a series of tests such as Charpy impact test, uniaxial tensile test and uniaxial tensile test with notch were carried out at low temperatures to investigate the mechanical properties and toughness of steel angles made

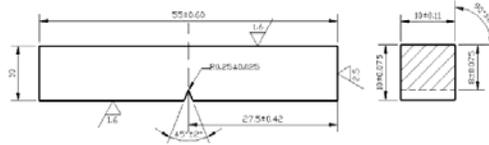
of Q235B, Q345B and Q420C. The welded joints using Q420C steel plate were also studied with consideration of different thicknesses to minimize the influence of these parameters due to randomness.

2.1 Low Temperature Impact Toughness Test

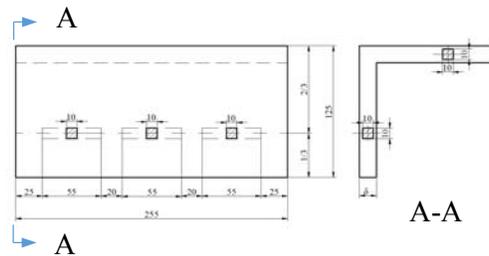
Various factors such as material processing, accuracy of testing machine, swing and frame fit, test temperature control and location of sample may lead to large discrepancy of the impact test results. Therefore, the number of test samples is generally not less than three.

The Q235B and Q345B steel materials are commonly used in transmission lines. In this paper, four groups of Charpy impact tests in terms of steel grade and member/joint were performed at specified temperature from 100°C to -60°C according to the standard GB/T 229-2007 [16]. The interval is 10°C for temperature from 0°C to 100°C while 5°C is used from -60°C to -5°C.

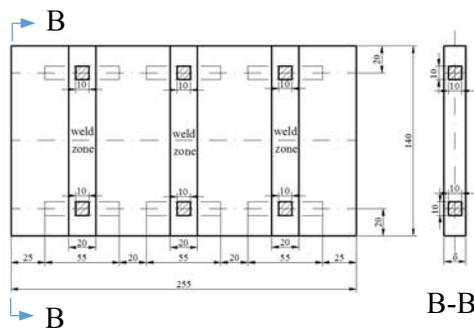
The locations and dimensions of the specimens (as seen in Figure 1a) of Q235B and Q345B steel angles for Charpy impact test are determined in accordance with the standard GB/T 229-2007 [16]. The specimens were sampled from the steel angle named L140×12 with the location shown in Figure 1b.



(a) Geometry of Impact Test Specimen



(b) Sampling of Steel Angle



(c) Sampling of Welded Joints

Figure 1. Sampling and Geometry of Impact Test Specimens

Similarly, the preparation of test specimens of Q420C for Charpy impact test is shown in Figure 1 in accordance with the standard GB/T 229-2007 [16]. The test specimens of Q420C were sampled from the steel angle named L125×12, L140×14 and L160×16 with plate thickness of 12 mm, 14 mm and 16 mm respectively. The Q420C welded joints were sampled from welding plates considering thickness of 12 mm, 14 mm and 16 mm. Three identical samples were made for each specified model and thickness and therefore, there are nine impact test specimens accounting for three different plate thicknesses. The tests were performed at each specified temperature points (i.e. 20, -20, -45, -60°C) according to the standard GB/T 229-2007 [16].

The impact tests are shown and listed in Table 1. In summary, the samples for Charpy impact test have accounted for the influence of steel grade, member/weld joint, plate thickness and temperature change.

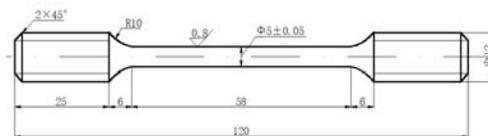
Table 1. Impact Test List

Steel grade	Type	Temperature range $T/^\circ\text{C}$	Temperature points n_T	Number of samples n_S
Q235B	Steel angle	100~0	10	10×4
		-5~-60	12	12×4
Q345B	Steel angle	100~0	10	10×4
		-5~-60	12	12×4
Q420C	Steel angle	20,-20,-45,-60	4	4×3×3
Q420C	Welded joint	20,-20,-45,-60	4	4×3×3

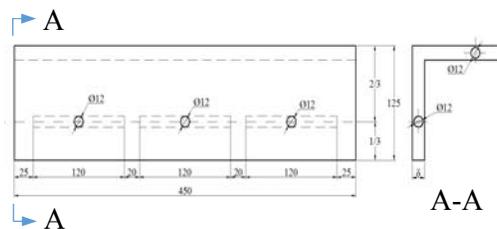
2.1 Low Temperature Tensile Tests

The locations and dimensions of the specimens (as seen in Figure 2a) of Q235B and Q345B steel angles for low temperature tensile test are determined in accordance with the standard GB/T 13239-2006 [17]. The specimens were sampled from the steel angle named L140×12 with the location shown in Figure 2b.

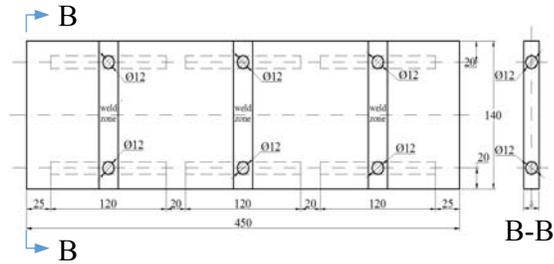
Five tensile test specimens were performed at each specified temperature from 20°C to -50°C (i.e. 20, 0, -10, -20, -30, -40, -50°C) according to the standard GB/T 13239-2006 [17].



(a) Specimen for Low Temperature Tensile Test



(b) Sampling of Steel Angle



(c) Sampling of Welded Joints

Figure 2. Sampling and Geometry of Tensile Test Specimens

Additionally, mechanical properties of Q420C high-strength steel and its welded joint were determined by smooth tensile test specimens as shown in Figure 2c, which were machined in accordance with the standard GB/T 13239-2006 [17]. Respectively, smooth tensile test specimens of Q420C high-strength steel were sampled from the steel angle named L125×12, L140×14 and L160×16 (marked as 12 mm, 14 mm and 16 mm), and its welded joints were sampled from welding plates with thickness of 12 mm, 14 mm and 16 mm respectively. Make three identical samples from each specified model and thickness. Then nine replicated tensile test specimens were performed at each specified temperature points (i.e. 20, -10, -20, -45°C) according to the standard GB/T 13239-2006 [17]. The smooth tensile test list is shown in Table 2.

Table 2. Smooth Tensile Test List

Steel grade	Type	Temperature points $T/^\circ\text{C}$	Number of samples ($n_T \times n_S$)
Q235B	Steel angle	20~-50	7×5
Q345B	Steel angle	20~-50	7×5
Q420C	Steel angle	20,-10,-20,-45	4×9
Q420C	Welded joint	20,-10,-20,-45	4×9

2.2 Notch Sensitivity Tests

The specimens of Q235B and Q345B for notch sensitivity tensile test were sampled from the steel angle named L140×12. The geometry of the test specimens made of Q235B and Q345B steel angles for notch tensile test is shown in Figure 3. They were prepared in accordance with the standard HB 5214-1996 [18]. The locations and dimensions of the specimens of Q235B and Q345B steel angles for notch tensile test can be seen in Figure 2b.

There were five tensile test specimens performed at each specified temperature from 20°C to -50°C (i.e. 20, 0, -10, -20, -30, -40, -50°C) according to the standard HB 5214-1996 [18]. The notch tensile tests are listed in Table 3.

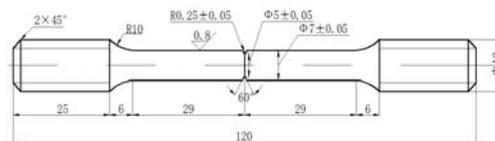


Figure 3. Geometry of Notch Tensile Test Specimens

Table 3. Notch Tensile Test List

Steels	Temperature points $T/^{\circ}\text{C}$	Number of samples ($n_T \times n_S$)
Q235B	20~-50	7×5
Q345B	20~-50	7×5

2.3 Experimental Equipment

As shown in Figure 4a, the machine for testing material properties at low temperature is SANS-50KN. The compressor is used for refrigeration and its lowest operating temperature is -90°C . The pendulum impact testing machine with maximum impact energy of 300J was adopted in the impact tests, as seen in Figure 5b. The cooling medium is alcohol and its lowest operating temperature is -60°C . These machines are suitable for large quantities of low temperature tests because of high speed and high precision of temperature control. Figure 5a shows a part of the specimens after impact test while Figure 5b demonstrates several specimens after tensile test.



(a) The Tensile Testing Machine



(b) The Pendulum Impact Testing Machine

Figure 4. Material Properties Testing Machines



(a) Specimens after impact test



(b) Specimens after Tensile Test

Figure 5. Specimens after Experimental Test

3. TEST RESULTS AND DISCUSSION

3.1 Low Temperature Impact Test

In structural engineering, the Charpy impact energy A_{kV} is widely employed as material toughness measurement in design as it partially reflects the fracture resistant ability of steel [19].

The Charpy impact tests of Q235B and Q345B were performed at 22 specified temperature points from 100°C to -60°C and the corresponding Charpy impact energy A_{kV} are listed in Table 4. Similarly, the Charpy impact tests of Q420C steel angles and the butt weld joints were performed at each specified temperature points (i.e., 20, 0, -20, -60°C) with the Charpy impact energy A_{kV} presented in Table 5.

In this paper, the relationship between the impact energy A_{kV} and temperature is regressed by Boltzmann function in Eq. 1 which is widely used for great dispersion of experimental data. Large quantities of experimental researches have shown that the Boltzmann function can well establish the correlation between impact energy and temperature [19], because it leads to minimal residuals with clear physical meanings of all parameters.

$$y = \frac{A_1 - A_2}{1 + e^{(t - t_0)/\Delta t}} + A_2 \quad (1)$$

Table 4. Charpy Impact Energy A_{kV} (J) of Q235B and Q345B Steel Angles

Q235B	$T/^\circ\text{C}$	100	80	70	60	50	40	30	20	10	0	-5	
		153	119	151	112	121	148	129	171	182	56	36	
		119	129	156	161	120	130	158	168	187	46	25	
		167	145	117	152	152	138	143	184	89	60	26	
	A_{kV}/J	112	116	154	143	112	138	160	174	165	42	29	
		-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60	
		23	17	12	8	4	8	5	6	6	3	3	
		14	14	11	9	9	7	8	4	7	3	4	
	A_{kV}/J	15	17	17	9	5	5	4	5	4	4	4	
		17	16	10	10	7	5	5	5	4	5	3	
Q345B		$T/^\circ\text{C}$	100	80	70	60	50	40	30	20	10	0	-5
			112	122	152	175	155	169	93	153	106	62	85
	161		132	151	173	150	175	169	141	131	56	58	
	185		164	174	113	125	163	164	153	103	54	60	
	A_{kV}/J	149	131	159	154	161	169	159	152	114	57	68	
		-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60	
		49	40	22	39	15	27	10	8	10	8	7	
		45	41	24	29	35	10	12	7	7	5	5	
	A_{kV}/J	45	55	35	25	12	16	11	9	6	6	5	
		46	33	22	30	16	7	11	8	8	7	6	

Table 5. Charpy Impact Energy A_{kV} (J) of Q420C Steel Angles and Welded Joints

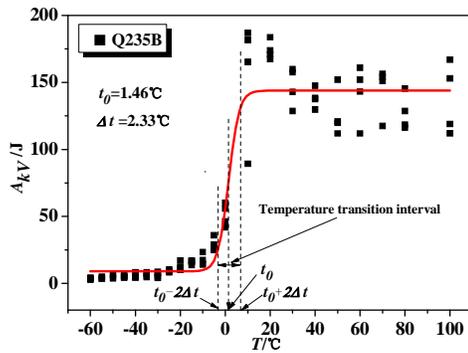
Steel grade/Type	Q420C/Steel angle				Q420C/Welded joint			
$T/^\circ\text{C}$	20	-20	-45	-60	20	-20	-45	-60
A_{kV}/J	92	105	40	22	158	46	33	7
	91	103	31	20	122	63	30	12
	143	101	36	15	163	52	25	13
	171	122	76	38	172	63	39	16
	177	140	57	60	152	39	26	19
	176	149	69	58	131	71	21	25
	153	131	83	22	126	58	35	29
	176	124	82	18	111	73	36	28
	176	115	39	61	154	57	48	27

In Eq. 1, y is the value of impact energy; t represents the temperature variable; A_1 and A_2 are the Charpy impact energy values of the lower and upper shelf respectively; t_0 is the transition temperature of ductile to brittle; Δt is the temperature transition interval, which reflects the ductile-brittle transition rate. The parameters A_1 , A_2 , t_0 and Δt are determined by curve-fitting technique with test data. The smaller of Δt , the narrower of the temperature range across the transition temperature region, and the material is easier from ductile to brittle.

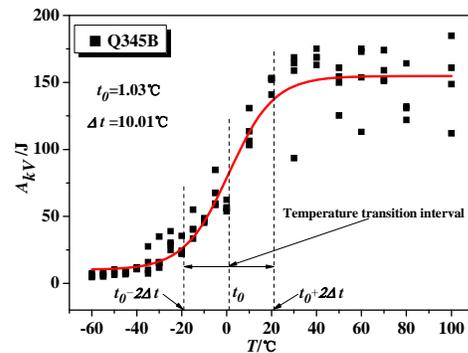
The Charpy impact test results of Q235B, Q345B and Q420C steel angles as well as Q420C welded joints at low temperature and the curves obtained by fitting Boltzmann function are plotted in Figure 6.

Table 6. Parameters in Boltzmann Function by Curve-fitting

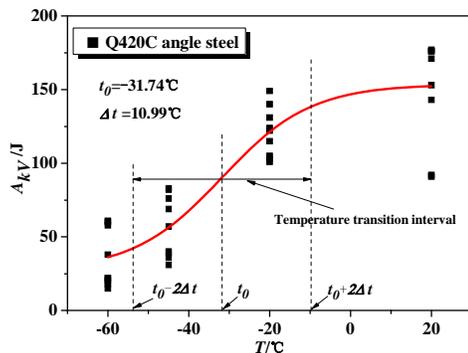
Steel grade	Type	The lower shelf A_1/J	The upper shelf A_2/J	Brittle-ductile transition temperature $t_0/^\circ\text{C}$	temperature transition interval $\Delta t/^\circ\text{C}$
Q235B	Steel angle	8.93	143.93	1.46	2.33
Q345B	Steel angle	10.02	154.75	1.03	10.01
Q420C	Steel angle	27.27	153.44	-31.74	10.99
Q420C	Welded joint	19.56	143.22	-12.69	10.22



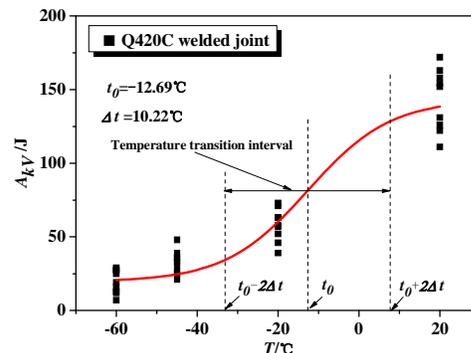
(a) Q235B Steel Angle



(b) Q345B Steel Angle



(c) Q420C Steel Angle



(d) Q420C Welded Joint

Figure 6. Low Temperature Impact Test Results

As shown in Figure 6, the impact energy of four kinds of materials decreases with the decrease of temperature starting at 20°C. The impact energy reduces rapidly with the decrease of temperature until reaching a certain temperature. The fitting results such as A_1 , A_2 , t_0 and Δt in Boltzmann function are listed in Table 6.

It is clearly shown in Figures 6a and 6b that the curve of the temperature transition interval of Q235B is more rapid than Q345B, which indicates that Q235B more likely becomes brittle at low temperature. From Table 6, it is also found that t_0 of Q345B steel angle is 0.44°C which is lower than Q235B; Δt of Q345B steel angle is 7.67°C which is higher than Q235B. Therefore, the ability to resist low temperature and cold brittleness of Q345B is higher than Q235B.

As shown in Table 6, the ductile-brittle transition temperature of Q235B, Q345B and Q420C steel angles are 1.46°C, 1.03°C and -31.74°C respectively. The ductile-brittle transition temperature of Q420C steel angles is about -33°C lower than Q235B and Q345B steel angle. Thus, the ability of Q420C steel angles to resist low temperature and cold brittleness is better than Q235B and Q345B steel angles.

The ductile-brittle transition temperature of Q420C steel angles and welded joints are -31.74°C and -12.69°C respectively. Clearly, the ability of Q420C welded joints to resist low temperature and cold brittleness is much lower than its parent material.

From the above, Q420C steel angles are recommended in the region at low temperature, but the use of Q420C welded joints should be minimized.

3.2 Low Temperature Tensile Tests

In the design of lattice transmission tower, the mechanical properties of angle steel such as yield strength σ_s and ultimate tensile strength σ_b as well as the ultimate-to-yield strength ratio are vital for the determination of load resistance of steel member.

The mechanical properties of Q235B and Q345B steel angles at 7 specified temperature points from 20°C to -50°C are presented. The values of yield strength σ_s and ultimate tensile strength σ_b as well as the ultimate-to-yield strength ratio for five tested specimens under seven temperature points are listed in Table 7. Similarly, the mechanical properties of steel angles and butt welded joints made of Q420C were performed at several specified temperature points (i.e. 20, 0, -20, -45°C). The values of yield strength σ_s and ultimate tensile strength σ_b as well as the ultimate-to-yield strength ratios for the nine tested specimens under four temperature points are listed in Table 8.

Extensive theoretical and experimental researches indicated that, in the temperature range from -70°C to 20°C, the variations of yield strength and ultimate tensile strength with temperature can be expressed by Eqs. 2 to 4 as follows [20],

$$\sigma_s = \sigma'_s e^{q_s(T'-T)} \quad (2)$$

$$\sigma_b = \sigma'_b e^{q_b T'-T)} \quad (3)$$

$$k = q_b/q_s \quad (4)$$

where σ_s , σ'_s and σ_b , σ'_b are the yield strength and ultimate tensile strength at temperature T and T' respectively; q_s and q_b are the temperature sensitive factors of yield strength and ultimate tensile strength respectively; k is the ratio of q_b and q_s .

In addition, the yield-to-ultimate strength ratio of angle steel with considering temperature can be derived from the Eqs. 2 and 3.

$$\frac{\sigma_s}{\sigma_b} = \frac{\sigma'_s}{\sigma'_b} e^{(q_s - q_b)(T'-T)} \quad (5)$$

Table 7. Mechanical Properties of Q235B and Q345B Steel Angles from Tensile Test

Steel grade	Property	T/°C						
		20	0	-10	-20	-30	-40	-50
Q235B	σ_b /MPa	418	406	452	460	473	488	491
		422	442	465	501	485	477	508
		402	443	474	516	461	500	512
		396	436	500	456	476	482	501
		368	450	501	461	467	486	483
	Mean	401.20	435.40	478.40	478.80	472.40	486.60	499.00
	σ_s /MPa	243	242	302	315	315	330	358
		298	288	279	396	337	337	369
		236	277	348	402	314	353	375
		224	311	394	295	292	358	374
		206	298	405	281	292	329	324
Mean	241.40	283.20	345.60	337.80	310.00	341.40	360.00	
σ_b/σ_s	1.66	1.54	1.38	1.42	1.52	1.43	1.39	
Q345B	σ_b /MPa	548	560	570	575	600	601	612
		549	569	576	588	573	609	612
		550	562	568	578	591	618	606
		543	560	578	577	589	605	608
		539	557	568	580	588	624	610
	Mean	545.80	561.60	572.00	579.60	588.20	611.40	609.60
	σ_s /MPa	348	344	386	371	437	408	397
		426	416	423	443	386	458	403
		407	348	378	379	391	437	390
		346	346	423	376	390	434	409
		361	377	362	382	385	468	407
Mean	377.60	366.20	394.40	390.20	397.80	441.00	401.20	
σ_b/σ_s	1.45	1.53	1.45	1.49	1.48	1.39	1.52	

The temperature sensitivity coefficients q_s and q_b and the ratio k in Eqs. 2 to 4 for Q235B, Q345B and Q420C steel angles as well as Q420C welded joints at six temperature points from 0°C to -50°C are determined from tests and listed in Table 9.

The mechanical properties such as yield strength σ_s and ultimate tensile strength σ_b of Q235B and Q345B steel angles at seven temperature points from -20°C to -50°C, and the average value curve of test results and their prediction curves from these equations are shown in Figure 7 and Figure 8. The mechanical property indices of Q420C angle steel and its welded joint test results at four temperature points (i.e. 20, 0, -20, -45°C) and their prediction curves of test results are shown in Figure 9.

As shown in Table 9, the temperature sensitivity coefficients q_s and q_b of Q235B and Q345B are all positive. According to Eqs. 2 and 3, the positive temperature sensitivity coefficients indicates that the yield strength σ_s and ultimate tensile strength σ_b of Q235B and Q345B angle steel are increased with decreasing of temperature. It also can be seen in Table 9 that, the parameter k of Q235B is less than 1 while the parameter k of Q345B is greater than 1. It means that for Q235B angle steel at low temperature the increment of σ_b is smaller than σ_s , while the increment of σ_b is larger than σ_s for Q345B angle steel.

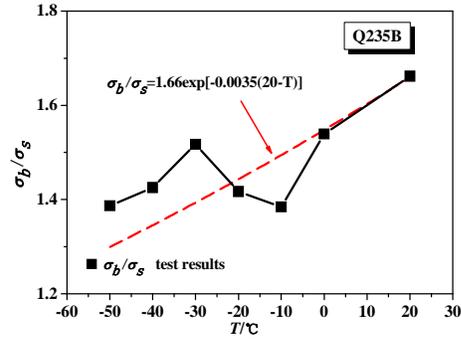
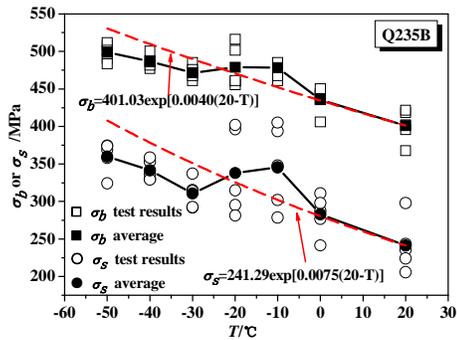
Table 8. Mechanical Properties of Q420C Steel Angles and Butt Welded Joints

Property	Q420C/Steel angle				Q420C/Welded joint			
T/°C	20	-10	-20	-45	20	-10	-20	-45
σ_b / MPa	654	671	690	699	557	541	587	584
	660	680	683	698	557	574	581	585
	657	677	693	702	553	528	573	550
	572	612	610	606	514	514	539	561
	571	594	604	598	510	526	530	546
	572	591	607	603	510	546	537	511
	620	640	641	663	600	575	636	643
	622	646	648	664	601	611	611	630
	613	639	646	665	585	564	611	646
Mean	615.67	638.89	646.89	655.33	554.11	553.22	578.33	584.00
σ_s /MPa	460	479	543	517	450	457	486	446
	474	496	519	522	444	443	471	460
	485	491	521	531	429	423	450	486
	413	441	496	445	412	433	452	468
	427	442	479	425	415	449	455	470
	448	447	469	432	398	397	440	451
	487	487	486	521	449	437	472	500
	477	492	503	505	455	446	464	484
	467	475	499	510	454	432	474	475
Mean	459.78	472.22	501.67	489.78	434.00	435.22	462.67	471.11
σ_b/σ_s	1.34	1.35	1.29	1.34	1.28	1.27	1.25	1.24

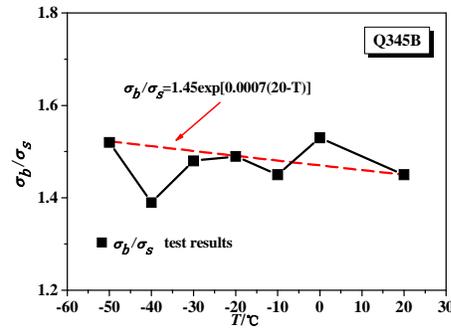
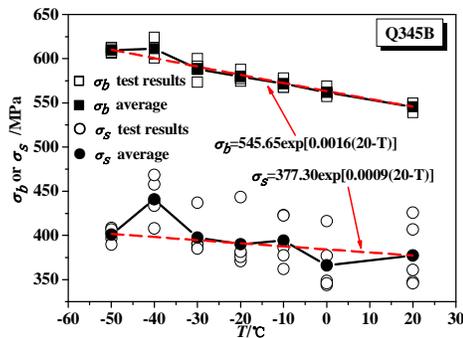
Table 9. Temperature Sensitivity Coefficients

Steel grade/Type	T/°C	$q_s/(10^{-3} \cdot ^\circ\text{C}^{-1})$ Mean	$q_b/(10^{-3} \cdot ^\circ\text{C}^{-1})$ Mean	k	
Q235B/ Steel angle	0	7.98	4.09	4.00	0.53
	-10	11.96	5.87		
	-20	8.40	4.42		
	-30	5.00	3.27		
	-40	5.78	3.22		
	-50	5.71	3.12		
Q345B/ Steel angle	0	-1.53	1.43	1.58	1.81
	-10	1.45	1.56		
	-20	0.82	1.50		
	-30	1.04	1.50		
	-40	2.59	1.89		
	-50	0.87	1.58		
Q420C/ Steel angle	-10	0.89	1.23	1.14	0.85
	-20	2.18	1.24		
	-45	0.97	0.96		
Q420C/ Welded joint	-10	0.09	-0.05	0.61	0.62
	-20	1.60	1.07		
	-45	1.26	0.81		

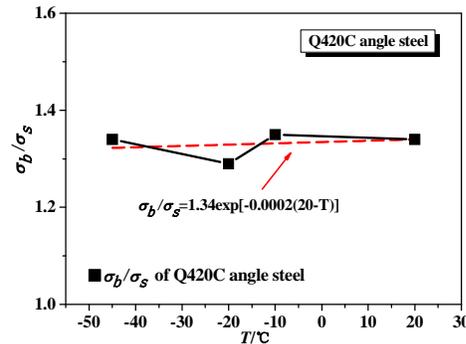
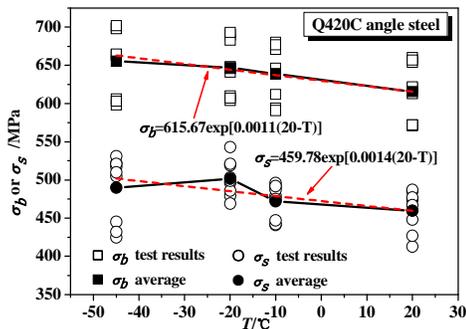
As shown in Table 9, the temperature sensitivity coefficients q_s and q_b of Q420C steel angles and its welded joint are also all positive, which indicate that the yield strength σ_s and ultimate tensile strength σ_b of Q420C angle steel and its welded joint are also increased with decreasing of temperature. The parameter k of Q420C steel angles and its welded joint at low temperature are all less than 1, which indicate that the increment of σ_b is smaller than σ_s .



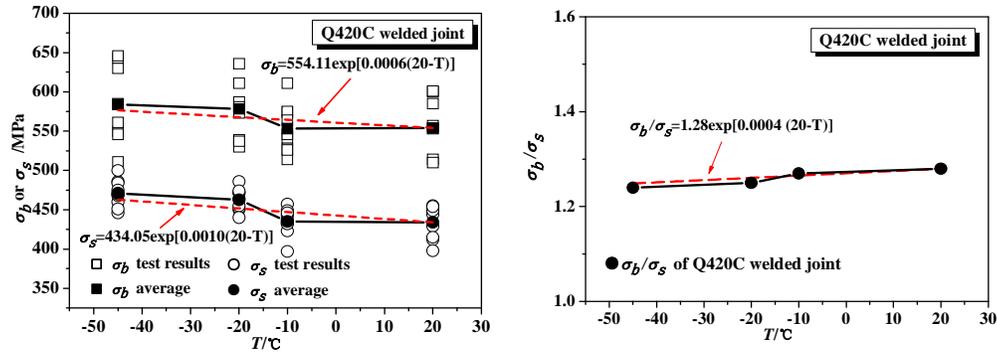
(a) Ultimate and Yield Tensile Strength (b) Ultimate-to-yield Strength Ratio
Figure 7. Mechanical Property Indices of Q235B Steel Angles



(a) Ultimate and Yield Tensile Strength (b) Ultimate-to-yield Strength Ratio
Figure 8. Mechanical Property Indices of Q345B Steel Angles



(a) Ultimate and Yield Tensile Strength (b) Ultimate-to-yield Strength Ratio
Figure 9. Mechanical Property Indices of Q420C Steel Angles



(a) Ultimate and Yield Tensile Strength (b) Ultimate-to-yield Strength Ratio

Figure 10. Mechanical Property Indices of Q420C Welded Joints

Figure 7 shows the mechanical property indices of Q235B steel angles from -50°C to 20°C including yield strength, ultimate tensile strength and ultimate-to-yield strength ratio as well as its prediction curves based on Eqs. 2 to 3. The yield strength σ_s and ultimate tensile strength σ_b of Q235B steel angle are increased from 241.40 MPa and 401.20 MPa to 360.00 MPa and 499.00 MPa respectively (see Figure 7a). It is clear that the yield strength and ultimate tensile strength are increased with increasing temperature. As shown in Figure 7b, the ultimate-to-yield ratios σ_b/σ_s of Q235B steel angle is dramatically decreased from 1.66 to 1.39 as the temperature decreased from 20°C to -50°C , which indicates the brittleness increased and plasticity decreased at low temperature.

Figure 8 shows the mechanical property indices as well as its prediction curves of Q345B steel angles from -50°C to 20°C . It can be seen in Figure 8a that, the yield strength and ultimate tensile strength are increased from 377.60 MPa and 545.80 MPa to 401.20 MPa and 609.60 MPa respectively. However, as shown in Figure 8b, the ultimate-to-yield ratios are changed and different from Q235B (see Figure 7b), which are varied between 1.45 and 1.53, and slightly increased with decreasing of temperature.

Figure 9 shows the mechanical property indices as well as its prediction curves of Q420C steel angles from -45°C to 20°C . As shown in Figure 9a, when the temperature decreases from 20°C to -45°C , the yield strength and ultimate tensile strength of Q420C steel angle are increased from 459.78 MPa and 615.67 MPa to 489.78 MPa and 655.33 MPa respectively. It can be seen in Figure 9b, the ultimate-to-yield ratios of Q420C steel angles are varied between 1.29 and 1.35, which is also different from Q235B.

Figure 10 shows the mechanical property indices as well as its prediction curves of Q420B weld joints from -45°C to 20°C . As shown in Figure 10a, with the temperature decreases from 20°C to -45°C , the yield strength and the ultimate tensile strength of Q420C welded joints are increased from 434.05 MPa and 554.10 MPa to 471.11 MPa and 655.33 MPa respectively. It can be seen in Figure 10b, the ultimate-to-yield ratios of Q420C welded joints are varied between 1.24 and 1.27.

As shown in Figures 7a, 8a and 9a, the yield strength and tensile strength of Q235B, Q345B and Q420C steel angles are all increased with the decrease of temperature. However, the temperature has more influence on the yield strength and tensile strength of Q235B steel angles than the Q345B and Q420C steel angles as the slope of the Q235B curves is greater than the others. It can be concluded that the influence of low temperature on yield strength and tensile strength will decrease with the increase of steel grade.

As shown in Figures 9a and 10a, the influence of low temperature on the yield strength and tensile strength of Q420C steel angles and its weld joints is quite similar. Taking yield strength for example, the yield strength of Q420C steel angles and its weld joints is slightly increased from 459.78 MPa and 434.05 MPa to 489.78 MPa and 471.11 MPa respectively with the temperature decreasing from 20°C to -45°C.

Figures 7b, 8b, 9b and 10b show the ultimate-to-yield ratio versus temperature curves of Q235B, Q345B and Q420C steel angles and Q420C weld joints. It can be seen from the figures, the influence of temperature on the ultimate-to-yield ratio is quite different. The ultimate-to-yield ratio of Q235B steel angle is dramatically decreased from 1.66 to 1.39, while Q345B and Q420C steel angles are varied between 1.45 and 1.53, 1.29 and 1.35 respectively. Hence, it is clear that the low temperature will dramatically increase the yield strength, tensile strength and brittleness of Q235B steel angles and decrease plasticity; but the low temperature has less influence on Q345B and Q420C steel angles and Q420C weld joints.

3.3 Notch Sensitivity Tests

The appearance of microcrack around bolt hole will affect the mechanical performance of steel angles at low temperature. In practice, steel members with notch become brittle under three-dimensional stress state and strain concentration occurs which is called the notch sensitivity. To evaluate the notch sensitivity of steel angles at low temperature, the notch sensitivity factor and the stress concentration coefficient of notch specimens are expressed in Eqs. 6 to 7 as follows [21,22],

$$q_t = \sigma_b / \sigma_{bH} \quad (6)$$

$$K_t = \sigma_{bH} / \sigma_s \quad (7)$$

where σ_b is the ultimate tensile strength of the smooth specimen, σ_{bH} is the ultimate tensile strength of specimen with notch, σ_s is the yield stress as the appearance of non-proportional elongation of smooth specimens. It can be seen from the equations, the notch sensitivity factor is defined as the ratio of σ_b and σ_{bH} , the stress concentration coefficient is the ratio of σ_{bH} and σ_s . Thus, the smaller of q_t and K_t , the smaller influence of notch.

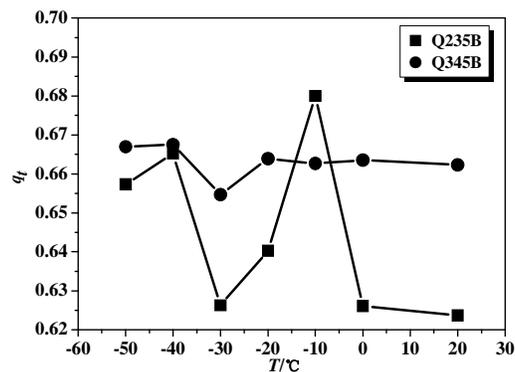


Figure 11. Notch Sensitivity Factors

The tensile tests of Q235B and Q345B steel angles were performed at seven specified temperature points from 20°C to -50°C. The values of ultimate tensile strength σ_b for 5 test specimens with 7 specified temperature points are listed in Table 11. According to the yield stress σ_s and ultimate tensile strength of the smooth specimen σ_b listed in Table 7, the notch sensitivity factor q_t and the

stress concentration coefficient K_t are calculated and listed in Table 10. Figure 11 shows the notch sensitivity factor versus temperature curves.

Table 10. Notch Tensile Test Results of Q235B and Q345B Steel Angles

Steel grade	Property	T/°C						
		20	0	-10	-20	-30	-40	-50
Q235B	Ultimate tensile strength	623	716	660	701	772	742	765
		636	651	695	720	739	705	748
		685	732	709	810	780	714	786
		638	715	728	770	720	781	749
	σ_{bH} /MPa	632	663	680	738	753	717	747
	q_t	642.8	695.4	694.4	747.8	752.8	731.8	759.0
	K_t	0.62	0.63	0.68	0.64	0.63	0.66	0.66
Q345B	Ultimate tensile strength	2.66	2.46	2.01	2.21	2.43	2.14	2.11
		823	836	863	878	917	947	916
		880	881	882	872	884	912	915
		813	846	864	880	906	939	912
	σ_{bH} /MPa	792	827	855	870	889	892	902
	q_t	812	843	851	867	896	889	925
	K_t	824.0	846.6	863.0	873.4	898.4	915.8	914.0
	0.66	0.66	0.66	0.66	0.65	0.67	0.67	
	2.18	2.31	2.19	2.24	2.26	2.08	2.28	

As shown in Figure 11, the notch sensitivity factor q_t of Q345B, which is changed between 0.65 and 0.67, is slightly increased with the decrease of temperature. Therefore, the temperature has little effect on the notch sensitive coefficient of Q345B steel angles. However, it is clear that the gap sensitive coefficient of Q235B steel angles, which is varied between 0.62 and 0.68, is much more sensitive to the decrease of temperature. Hence, it can be concluded that the sensitivity of the gap will increase with the increasing of steel grade of angel section. In other words, it should be taken more care on the use of high steel grade angle members at low temperature.

As shown in Table 10, the stress concentration coefficient K_t for Q235B steel angle varies between 2.01 and 2.66 while the range of K_t is from 2.08 to 2.31 for Q345B. It indicates that there is no clear increasing or decreasing tendency on the stress concentration of the two kinds of steel angles at low temperature. Thus, the effect of low temperature on K_t is insignificant. In practice, it is recommended that the stress concentration coefficient K_t of steel angles is taken as 3 to prevent the occurrence of brittle fault due to the possible existence of the notch at low temperature.

4. CONCLUSIONS

The application of higher strength steel such as Q420 can improve the safety and structural performance of transmission engineering with a reduction in fabrication and construction cost. However, the mechanical properties and toughness of the higher grade steel are different from that of commonly used steel such as Q235 and Q345, due to the different rolling process, crystal phases and chemical components especially under low temperature. The lack of support by experimental tests limits the use of Q420 and Q460 in transmission towers at the low temperature area. This paper fills the gap by carrying out a series of tests such as Charpy impact test, uniaxial tensile test and tensile notch test at low temperatures to investigate the mechanical properties and toughness of steel

angles made of Q235B, Q345B and Q420C as well as welded joints using Q420C. Several useful conclusions are made for design purpose and presented as follows:

- 1) The impact energy of steel materials decreases with the decreasing of temperature starting from 20°C. The ductile-brittle transition temperature of Q235B, Q345B and Q420C steel angles and Q420C welded joints are 1.47°C, 1.03°C, -31.74°C and -12.69°C, respectively. The ability to resist low temperature and cold brittleness of Q420C steel angles are better than Q235B and Q345B steel angles. Q420C steel angles are preferred in the cold region, but the welded joints of Q420C should be avoided.
- 2) The tensile strength σ_b and yield strength σ_s of Q235B, Q345B and Q420C steel angles and Q420C welded joints are increased with the decreasing of temperature. Also, the increment of σ_b at low temperature is smaller than σ_s for Q235B and Q420C steel angles and Q420C welded joints; but the increment of σ_b is greater than σ_s for Q345B steel angles. Welding process will significantly reduce the performance of Q420C steel angle and therefore, the welded joints of Q420C steel should be avoided at low temperature conditions.
- 3) In low temperature region, the design load resistance of steel angles can be calculated by the design strength specified in national design code with the reduction factor obtained from experimental test. The strength reduction factor of Q235B, Q345B and Q420C steel angles and Q420C welded joints are recommended as 0.90, 0.90, 0.75 and 0.70 respectively.
- 4) The effect of low temperature on stress concentration due to microcrack is insignificant. The stress concentration coefficient K_t of Q235B and Q345B steel angles is recommended as 3 for connection design of transmission tower. The notch sensitivity factor q_t of Q345B is larger than Q235B and therefore, it should take more care on the rolling process and fabrication works on the members made of higher steel grade such as Q420.

ACKNOWLEDGMENT

The authors acknowledge the financial support provided by the Natural Science Foundation of China (51408221), the Natural Science Foundation of Hebei Province of China (E2015502016), the Fundamental Research Funds for the Central Universities of China (2014ZD36). The third author is grateful to the financial supports by Innovation and Technology Fund of the Hong Kong SAR Government for the project “Development of an energy absorbing device for flexible rock-fall barriers (ITS/059/16FP)”.

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