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Experimental studies on the material properties of high-strength bolt connection at elevated temperatures

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Abstract. The high-temperature material properties of steel are very important to the fire resistance analysis of high-strength bolt connections. This paper reports on the results of the experimental studies on the high-temperature properties of 20 MnTiB steel which is widely used in high-strength bolts, and the friction coefficient of 16 Mn steel plates at elevated temperature which is a necessary parameter for bolted frictional connection analysis. The test data includes yield strength, limit strength, modulus of elasticity, elongation and expansion coefficient of 20 MnTiB steel at elevated temperature, and the friction coefficients between two 16 Mn steel plates under elevated temperatures and after cooling. Based on the data from the tests, the mathematical models for predicting the mechanical properties of 20 MnTiB steel and friction coefficients of 16 Mn steel plates have been established.

Key words: high-strength bolts; material properties; high-temperature; connections; friction coefficients.

1. Introduction

Steel structures are widely used for various constructions because of their advantages in lightweight, fast construction and favorable ability on seismic-resistance. However the fire resistance ability of steel structures is worse than concrete structures. In fire catastrophe, unprotected steel buildings may be subject to severe damage or even collapse. It is very important to know the high-temperature properties of steel when conducting the fire resistance investigation or design of steel structures.

The high temperature properties of steel may be obtained through tensile test at elevated temperatures. It was found in previous investigations that the steel experiences no obvious yield plateau and the mechanical properties such as yield strength, limit strength and modulus of elasticity vary greatly at elevated temperatures (Li, Jiang, and Lin 1999). Many European countries have made achievements on this aspect, which is represented by ECCS as the mathematical expressions of yield strength, modulus of elasticity and the reduction coefficient of yield strength at high temperatures (ECCS 1983). In EUROCODE 3 and BS5950 Part 8, the reduction coefficient of yield strength, proportional strength and modulus of elasticity at elevated temperatures are listed in tables (CEN 1995, BSI 1990). In addition, America (ASCE NO. 78), Australia (Crozier and Wong 1993) and Japan (Sun and Gao 1994) have also conducted research on the high-temperature properties of steel systematically and have their own specification on the high-temperature properties of steel. Especially in resent years,

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Table 1 Chemical compositions of 16 Mn steel and 20 MnTiB steel

Material	Chemical compositions (%)						
	C	Si	Mn	P	S	Ti	B
16 Mn	0.12~0.20	0.20~0.60	1.20~1.60	≤0.045	≤0.050	/	/
20 MnTiB	0.17~0.24	0.17~0.37	1.30~1.60	≤0.035	≤0.035	0.04~0.10	0.0005~0.0035

Table 2 Mechanical properties of 16 Mn steel and 20 MnTiB steel at room temperature

Material	Yield strength (MPa)	Limit strength (Mpa)	Elongation (%)
16 Mn	≥345	≥510	≥21
20 MnTiB	≥940	1040~1240	≥10

Japan has investigated on the high-temperature properties of high-strength fire-resistant bolts for fire-resistant steel construction (Sakumoto *et al.* 1993). Their experiments include tension, relaxation and shear tests at elevated temperatures and after cooling.

In China, Lu Zhou-Dao has done research on the high-temperature mechanic properties of steel bars (1989) (Lu 1989), Lv Tong-Guang has investigated on the strength and deformation of reinforcing bars under high-temperatures (1996) (Lv 1996) and Tan Wei has studied the high-temperature mechanic properties of Q235 steel (1998) (Tan 1998). They all established the mathematical model for predicting the yield strength, limit strength, modulus of elasticity and elongation of specified steel at elevated temperatures.

In China, 20 MnTiB steel is widely used in high-strength bolts and 16 Mn steel plates treated by sandblast are widely used for high-strength bolt connections. The chemical compositions and mechanical properties of 16 Mn steel and 20 MnTiB steel at normal temperature are listed in Table 1 and Table 2 respectively. In this paper, we report on the results of the experimental studies on the high-temperature properties of 20 MnTiB steel and the high-temperature friction coefficient of 16 Mn steel plates treated by sandblast. The data obtained from our experiments include yield strength, limit strength, modulus of elasticity, elongation and expansion coefficient of 20 MnTiB steel at elevated temperature, and the friction coefficients between two 16 Mn steel plates under elevated temperatures and after cooling. Based on the data, the mathematical models for predicting the material properties of high-strength bolt connections at elevated temperatures have been established.

2. Mechanical property tests

2.1. Facility and specimens

The experiment facility for the mechanical property tests is AUTOGRAPHICS-25 omnipotent material test machine, the loading capacity of which is 250 kg. The test can be implemented by loading at fixed temperature or heating at fixed load. The stress-strain curve of the specimen can be recorded automatically during the test. The specimens are made according to the requirements of the mechanical

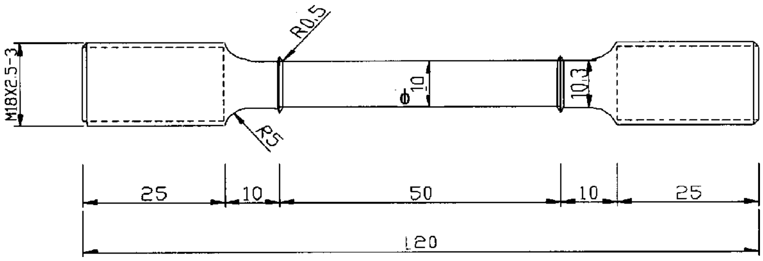


Fig. 1 Dimensions of 20 MnTiB steel specimen for mechanical property test

properties test. The dimensions of the specimen are shown in Fig 1. The specimens are made of materials experiencing the same heat treatment as in real bolt manufacture process to eliminate the effects of manufacture process on the material properties at elevated temperatures.

2.2. Loading and test procedure

The loads on the specimens are applied according to the Method for Tensile Test on Metals at High Temperature (GB4338-84) and the Method for Tensile Test on Metal (GB228-87) of the Chinese Standards. The mechanical property tests are the tensile tests at various fixed temperatures on 20MnTiB steel. The test temperatures are fixed at room temperature, 200°C, 300°C, 350°C, 400°C, 450°C, 500°C, 550°C, 600°C and 700°C respectively. Three specimens, each at a definite test temperature are employed for the tests. All together there are 30 specimens. The strain rate for this test is 0.1/min.

2.3. Test observations

1. When the temperature fixes at 200°C in a test, the surface color of the specimen has no change with that at the room temperature. However, the color of the fracture zone is golden, which is different from that at room temperature. The specimen has obvious neck contract phenomenon at failure. The stress-strain curve has obvious elastic and plastic phase.
2. When the temperature fixes at 300°C, the surface color of the specimen is blue and the color of the fracture zone is purple or brown. The specimen has obvious neck contract phenomenon at failure. The stress-strain curve is similar to that at the room temperature.
3. When the temperature rises to between 400°C and 450°C, the surface color of the specimen becomes dim blue and the color of the fracture zone becomes black or black green. The specimen has obvious neck contract phenomenon at failure.
4. When the temperature fixes at 600°C, both the surface color of the specimen and the color of the fracture zone are black. The black becomes deeper when the temperature becomes higher. The fracture zone contracts to a point. The specimen has plastic flow at failure and has a large elongation. There is nearly no elastic phase in the stress-strain relationship.
5. When the temperature is less than 400°C, obvious sound can be heard at failure. When the temperatures become higher, the fracture sound becomes weaker. When the temperature reaches 600°C, the fracture sound can hardly be heard.

Specimens after the test at different temperatures are showed in Fig 2.

Table 3 Test observations of mechanical property tests

Temperature	Surface color	Fracture zone color	Neck contract	Fracture sound
20°C~200°C	-	Golden	Obvious	Loud
300°C	Blue	Purple	Obvious	Loud
350°C	Purple	Blue	Obvious	Loud
400°C~450°C	Blue	Black-green	Obvious	Loud
500°C	-	Black-green	Obvious	Light
550°C	-	Black	Obvious	Light
600°C	Black	Black	-	No
700°C	Black	Black	-	No

A summary of the test observations is made in Table 3

Table 4 Average mechanical properties of 20 MnTiB steel at elevated temperatures

Specimen No.	Yield strength f_y (Mpa)	Limit strength f_u (Mpa)	Modulus of elasticity E ($\times10^5$Mpa)	Ultimate deformation S (mm)	Elongation δ_u (%)
20	1129.7	1175.3	2.01	5.65	11.3
200	1005.7	1180.0	1.76	6.86	13.0
300	944.0	1102.3	1.78	8.82	15.7
350	866.7	984.3	1.64	8.06	14.7
400	787.3	872.0	1.42	6.60	13.0
450	645.7	703.0	1.21	8.66	19.0
500	465.7	514.3	0.70	12.07	22.3
550	333.7	369.7	0.60	12.87	24.3
600	225.3	250.0	0.44	16.30	31.7
700	88.7	106.7	0.20	36.67	69.0

3. Results

The results obtained from experiments on the mechanical properties of 20 MnTiB steel at elevated temperatures are listed in Table 4.

The results of mechanical property tests show that: when the temperature increase, the yield strength, limit strength, modulus of elasticity of 20 MnTiB steel decrease and the elongation increase, and no obvious yield plateau of the steel are observed at high temperatures.

3.1. Mathematical model

The test data are used to establish the mathematical models of mechanical properties of 20 MnTiB steel at elevated temperatures for application in fire resistant calculation of steel structures. The formulas for yield strength, limit strength, modulus of elasticity, elongation are expressed in Eqs. (1)~(4) respectively, Fig. 3 shows the comparison of test data to the mathematical model for yield strength, limit strength, modulus of elasticity and elongation.

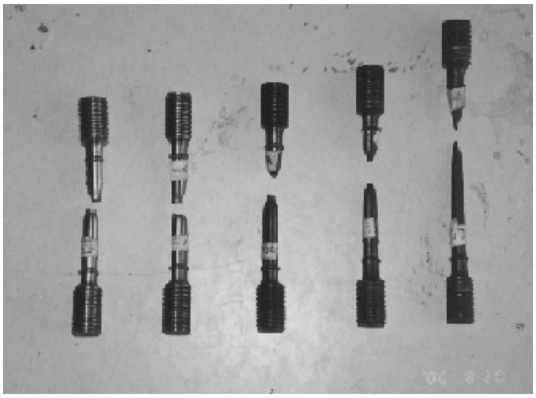


Fig. 2 Specimens after the test at different elevated temperatures (20ºC, 200 ºC, 400 ºC, 550 ºC, 700 ºC, respectively, from left to right)

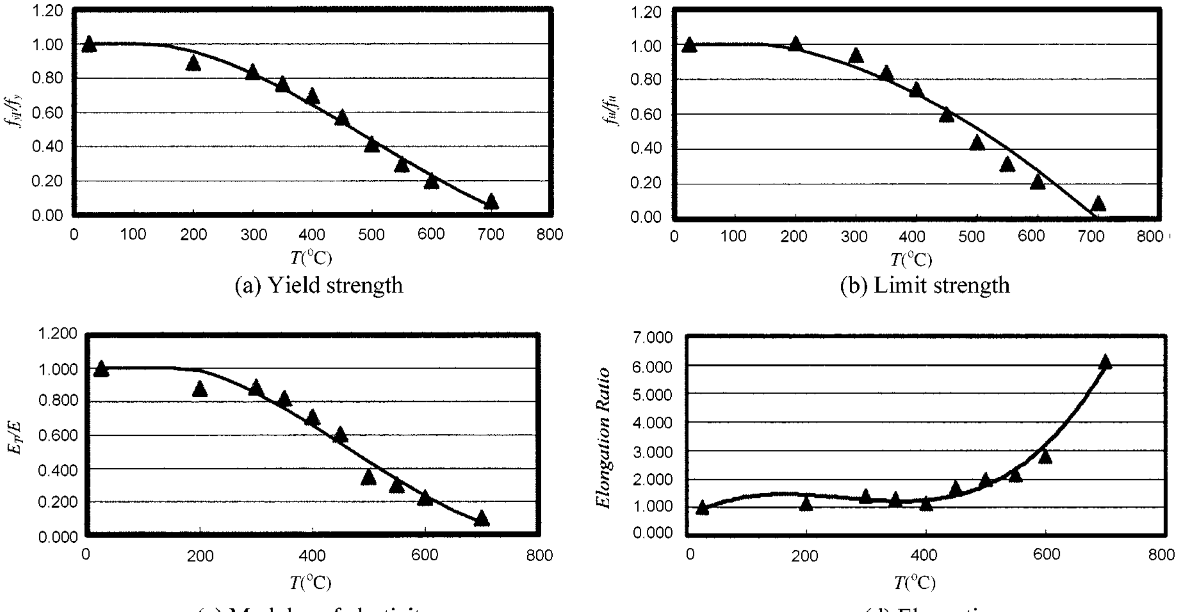


Fig. 3 Comparison of theoretical model to test results of yield strength

$$f_{yT}/f_y = 4\times10^{-9}\times T^3 - 6\times10^{-6}\times T^2 + 0.0011\times T + 0.9603 \le 1 \quad (1)$$

$$f_{uT}/f_u = -2\times10^{-6}\times T^2 + 7\times10^{-5}\times T + 1.0473 \le 1 \quad (2)$$

$$E_T/E = 6\times10^{-9}\times T^3 - 8\times10^{-6}\times T^2 + 0.0016\times T + 0.9403 \le 1 \quad (3)$$

$$\delta_T/\delta = 6\times10^{-8}\times T^3 - 5\times10^{-5}\times T^2 + 0.0113\times T + 0.6782 \quad (4)$$

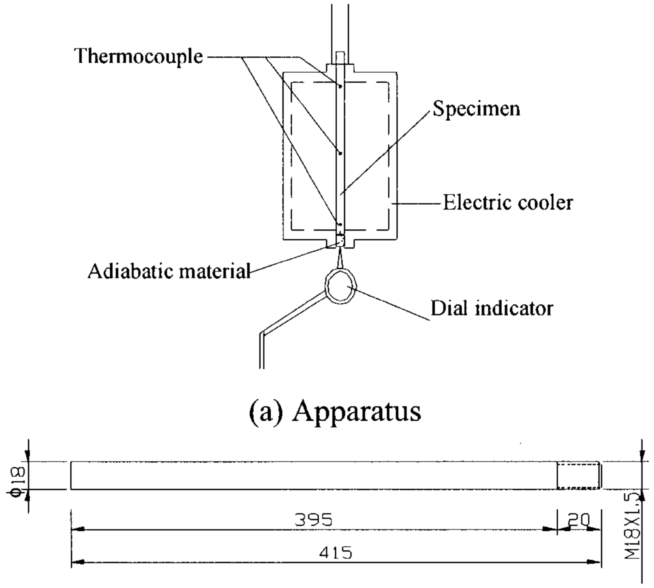
4. Thermal expansion coefficient tests

4.1. Test procedure

The thermal expansion coefficient tests are implemented on 20 MnTiB steel at elevated temperatures. The temperature of a specimen is measured by thermocouples located at the top, middle and bottom of the specimen. The top and bottom of the apparatus is covered by adiabatic material to reduce heat escape. In this test, the top of the specimen is fixed with the electric cooker, so the specimen can only move at the bottom. The movement at the bottom of the specimen can be recorded by a dial indicator, which is just the expansion of the specimen at various temperatures fixed at 200°C, 250°C, 300°C, 350°C, 400°C, 450°C, 500°C, 550°C, 600°C, 650°C and 700°C respectively. Each temperature lasts about 5~7 min until the specimen has fully expanded. Three specimens are employed for this group of test. The test apparatus and specimen is shown in Fig. 4 and 5.

4.2. Test observations

1. The specimen will not expand any more after about 5~7 minutes' heating at each temperature.
2. When the temperature is greater than 200°C, the expansion of the specimen at the same temperature interval increases.
3. When the specimen cools after the test, the length of the specimen recovers to its original length.



(b) Specimen

Fig. 4 Test apparatus and specimen of thermal expansion coefficient tests

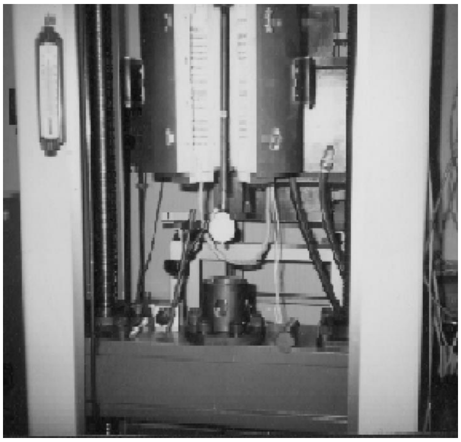


Fig. 5 Test apparatus of thermal expansion coefficient tests

4.3. Results

The results obtained from experiments on the thermal expansion of 20 MnTiB steel at elevated temperatures are listed in Table 5.

4.4. Mathematical model

The test data are used to establish the mathematical models of expansion coefficient of 20 MnTiB steel at elevated temperatures as expressed in Eqs. (5)~(6). Fig. 6. shows the comparison of test data to the mathematical model.

Table 5 Relative thermal expansion of 20MnTiB steel at elevated temperatures

Thermal expansion/bar length				Average
	Specimen No.			
Temperature (^{o}C)	1 (l_0 = 393 mm)	2 (l_0 = 397 mm)	3 (l_0 = 396 mm)	
100	7.38E-04	4.53E-04	6.31E-04	6.08E-04
200	1.78E-03	1.26E-03	1.72E-03	1.59E-03
250	2.52E-03	2.02E-03	2.58E-03	2.37E-03
300	3.33E-03	2.90E-03	3.36E-03	3.20E-03
350	4.20E-03	3.88E-03	4.24E-03	4.11E-03
400	5.11E-03	4.81E-03	5.15E-03	5.03E-03
450	6.01E-03	6.05E-03	6.16E-03	6.07E-03
500	7.00E-03	7.28E-03	7.27E-03	7.18E-03
550	8.17E-03	8.51E-03	8.46E-03	8.38E-03
600	9.34E-03	9.75E-03	9.67E-03	9.59E-03
650	1.08E-02	1.10E-02	1.09E-02	1.09E-02
700	1.20E-02	1.20E-02	1.22E-02	1.21E-02

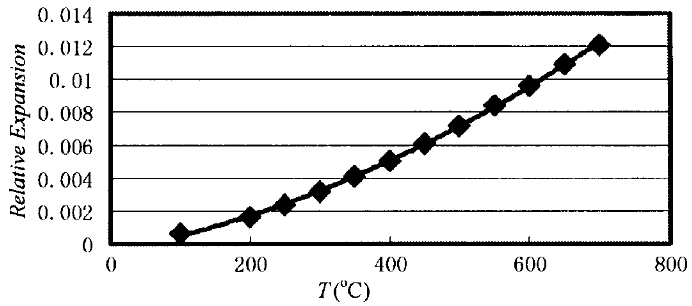


Fig. 6 Comparison of theoretical model to test results of relative expansion

Relative expansion $\Delta l = 1.45 \times 10^{-8} \times T^2 + 7.99 \times 10^{-6} \times T - 0.000464$ (5)

Expansion coefficient $\alpha = 2.90 \times 10^{-8} \times T + 7.99 \times 10^{-6}$ (m/m · °C) (6)

5. Comparison

Comparisons between the results for the yield strength, modulus of elasticity and expansion coefficient of steel at elevated temperatures specified in a number of codes and given by the models proposed hereinabove for 20 MnTiB steel are made in Figs. 7~9. It is illustrated that great difference exists between different specifications for high-temperature properties of steel. The reason for this relies in that different steel may have different high-temperature properties and different codes may employ different reliability criteria for determining the values used for design. Hence, it is very important to study the high-temperature properties for various steels and specify the design values in a code for a kind of specified steel.

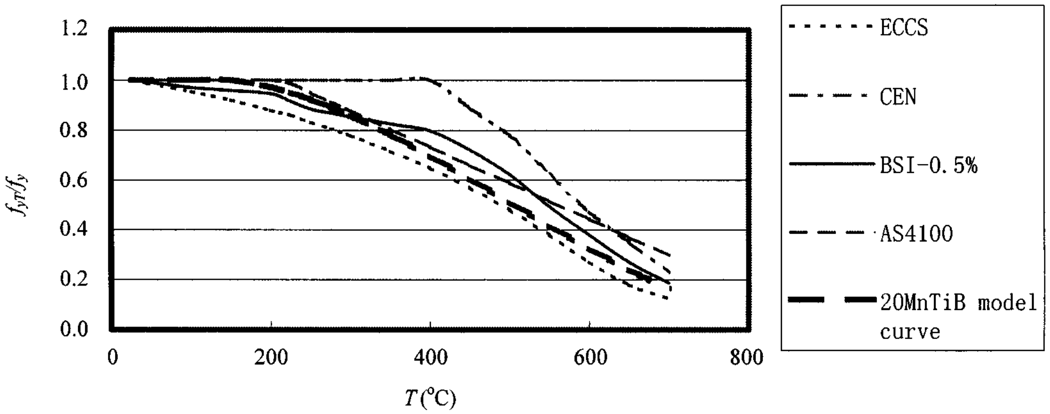


Fig. 7 Comparison of yield strength of steel at elevated temperatures between different specifications

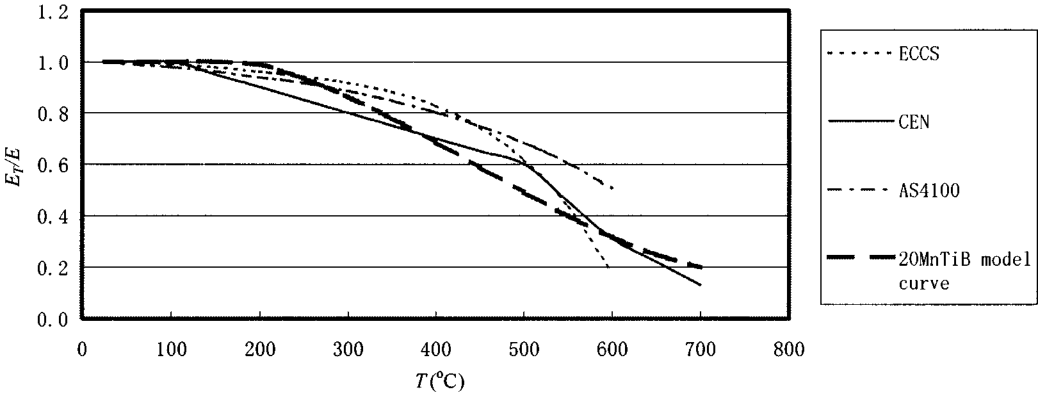


Fig. 8 Comparison of modulus of elasticity of steel at elevated temperatures between different specifications

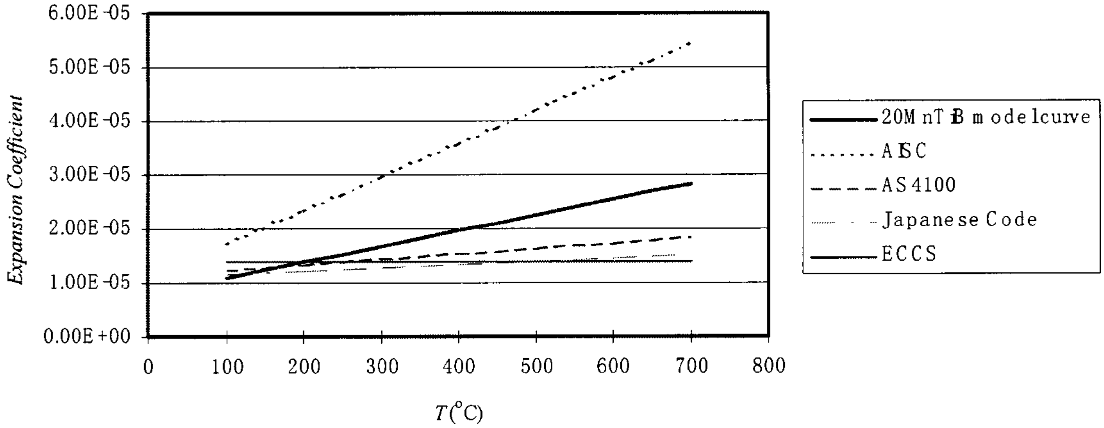


Fig. 9 Comparison of expansion coefficient of steel at elevated temperatures

6. Friction coefficient tests

6.1. Facility and test procedure

The facility for friction coefficient tests is shown in Fig. 10 and 11. The specimen for the tests are two 16 Mn steel plates, the size of the top and bottom plate is 600×400×8 mm^3 and 600×400×12 mm^3 respectively. The temperatures for the tests are fixed at room temperature, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C respectively. Five specimens at room temperature and three specimens each at all the other temperatures are employed for the tests. For all the specimen, the tests are re-done after cooling.

6.2. Test observations

1. At room temperature, 100°C and 200°C, the plates have no slip trail. At 300°C and 400°C, the plates have light slip trail. At 500°C, 600°C and 700°C, the plates have obvious slip trail.
2. At 300°C, the slip does not happen suddenly, which is different from other temperatures.

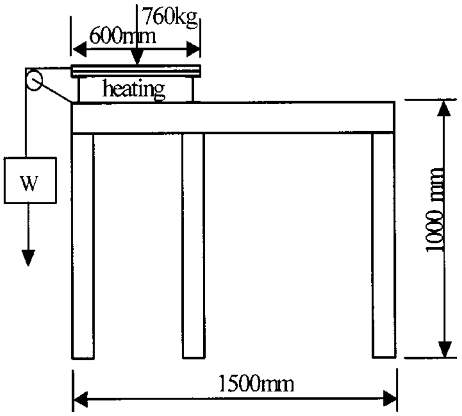


Fig. 10 Test facility of friction coefficient test

Table 6 Friction coefficient of 16Mn steel plates at elevated temperatures and after cooling

Specimen no.	At elevated temperatures			After cooling		
	Slip force (kg)	Friction coefficient	Average	Slip force (kg)	Friction coefficient	Average
30-1	457.50	0.602				
30-2	495.00	0.651				
30-3	607.50	0.799	0.605			
30-4	427.50	0.563				
30-5	315.00	0.414				
100-1	390.00	0.513		255.00	0.336	
100-2	480.00	0.632	0.543	277.50	0.365	0.378
100-3	367.50	0.484		330.00	0.434	
200-1	637.50	0.839		427.50	0.563	
200-2	675.00	0.888	0.836	427.50	0.563	0.520
200-3	592.50	0.780		330.00	0.434	
300-1	592.50	0.780		592.50	0.780	
300-2	742.50	0.977	0.908	555.00	0.730	0.763
300-3	735.00	0.967		592.50	0.780	
400-1	555.00	0.730		427.50	0.563	
400-2	772.50	1.016	0.921	555.00	0.730	0.684
400-3	772.50	1.016		577.50	0.760	
500-1	776.25	1.021		502.50	0.661	
500-2	742.50	0.977	0.992	427.50	0.563	0.661
500-3	742.50	0.977		577.50	0.760	
600-1	866.25	1.140		480.00	0.632	
600-2	840.00	1.105	1.110	480.00	0.632	0.681
600-3	825.00	1.086		592.50	0.780	
700-1	937.50	1.234		540.00	0.711	
700-2	930.00	1.224	1.224	540.00	0.711	0.694
700-3	922.50	1.214		502.50	0.661	

Note: At 30^{o}C, the average is obtained by the three middle value. The first value of specimen no. is temperature.

6.3. Results

The results obtained from the friction coefficient tests of 16 Mn steel plates at elevated temperatures and after cooling are listed in Table 6.

From the test data above, we discover that in the whole the friction coefficient increases when the temperature increases. When the temperature is greater than 300°C, the friction coefficient after cooling is about 0.69, which is a bit greater than that at normal temperature.

6.4. Mathematical model

The test data are used to establish the mathematical models for predicting the friction coefficient of 16Mn steel plates at elevated temperatures and after cooling, which are expressed in Eqs. (7)~(8). The comparison of test data to the mathematical model is shown in Fig. 12.

At elevated temperature $$f_{rT} = -3\times 10^{-7}\times T^2 + 0.0011\times T + 0.5438 \tag{7}$$

After cooling $$f'_{rt} = \begin{cases} 0.0015\times T + 0.24 & 100^{\circ}\text{C} \le T \le 300^{\circ}\text{C} \\ 0.69 & T > 300^{\circ}\text{C} \end{cases} \tag{8}$$

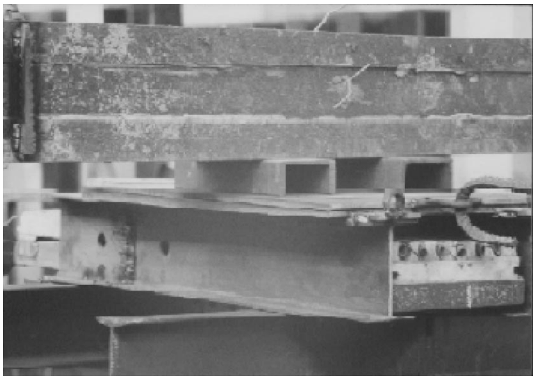


Fig. 11 A part of test facility of friction coefficient tests

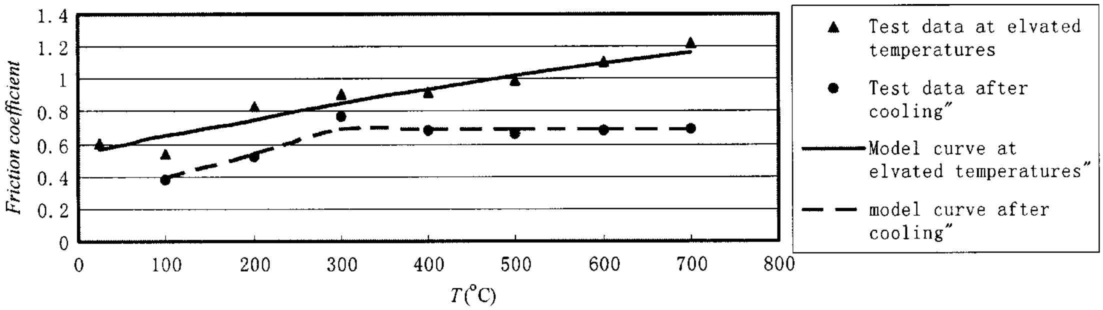


Fig. 12 Comparison of theoretical model to test results of friction coefficient

7. Conclusions

1. The investigation on material properties of high-strength bolt connections, using the most popular steels in China, at elevated temperatures are presented in this paper. Based on the data obtained from experiments, mathematical models are established for calculating yield strength, limit strength, modulus of elasticity, elongation, thermal expansion coefficient of bolts and friction coefficient of steel plates at elevated temperatures, which are the fundamental parameters for the fire-resistant analysis of high-strength bolt connections.

2. It is found from our studies that the behavior of high-strength bolt connection will change a lot at elevated temperatures. When temperature increase, the yield strength, limit strength, modulus of elasticity of 20 MnTiB steel used for high-strength bolts decrease while the elongation and thermal expansion coefficient increase. It is also observed that the friction coefficient of 16Mn plates used for high-strength bolt connections increases in the whole when temperature increases.

3. It is found that different steel may have different high-temperature properties. Hence, it is very important to study the high-temperature properties for various steels and specify the values at elevated temperatures for a specified steel for the purpose of fire-resistant design of structures using the steel.

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