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Behavior of High Strength Structural Steel at Elevated Temperatures

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Abstract: This paper presents the mechanical properties of high strength structural steel and mild structural steel at elevated temperatures. Mechanical properties of structural steel at elevated temperatures are important for fire resistant design of steel structures. However, current design standards for fire resistance of steel structures are mainly based on the investigation of hot-rolled carbon steel with normal strength, such as mild steel. The performance of high strength steel at elevated temperatures is unknown. Hence, an experimental program has been carried out to investigate the mechanical properties of both high strength steel and mild steel at elevated temperatures. The high strength steel BISPLATE 80 (approximately equivalent to ASTM A 514, EN 10137-2 Grade S690Q, and JIS G 3128) and the mild steel XLERPLATE Grade 350 (approximately equivalent to ASTM 573-450) were tested using steady and transient-state test methods. The elastic moduli and yield strengths were obtained at different strain levels, and the ultimate strength and thermal elongation were evaluated at different temperatures. It is shown that the reduction factors of yield strength and elastic modulus of high strength steel and mild steel are quite similar for the temperature ranging from 22 to 540°C. The test results were compared with the predictions obtained from the American, Australian, British, and European standards.

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CE Database subject headings: Temperature; Fire resistance; High strength steel; Mechanical properties; Steel structures.

Introduction

The current design standard for structural steel buildings in the United States (AISC 2005), explicitly allows for the use of quenched and tempered structural steel plate, which is the most common form of high strength structural steel produced. The ASTM standard specifies a nominal yield stress of $690\ \mathrm{N/mm^2}$ (100 ksi) for quenched and tempered steel which is the equivalent high strength steel used in plate form (Bjorhovde 2004). Further, the Hong Kong Standard defines high strength steel as having a nominal yield stress between 460 and $690\ \mathrm{N/mm^2}$ (67 and 100 ksi) (Hong Kong Buildings Department 2005). The newly released European Standard has an implied delineation point of $460\ \mathrm{N/mm^2}$ (67 ksi) to distinguish between mild and high strength steel. High strength structural steel in Australia is defined as a steel material which currently exceeds the maximum yield stress of $450\ \mathrm{N/mm^2}$ (65 ksi) (AS 1998). High strength quenched and tempered structural steel which is manufactured as steel plate in Australia currently has a nominal yield stress of $690\ \mathrm{N/mm^2}$ (100 ksi). This material is manufactured from mild steel plate which possesses a nominal yield stress of $300\ \mathrm{N/mm^2}$ (45 ksi). This material is rapidly heated and quenched in a cooling bath, a process which provides the steel with its high strength characteristics. The plate is then reheated and allowed to slowly cool which then allows the steel to redevelop its ductile nature. It is the quenching and tempering process which has been questioned as perhaps leading to compromised behavior of this material at high temperatures. This study has been commissioned to investigate this aspect as the use of high strength structural steel has received considerable attention and significant application in landmark tall buildings of late. However, the issue on residual strength of steel structures from a post-fire perspective steel was not considered in this study and this may need further investigation (Tide 1998).

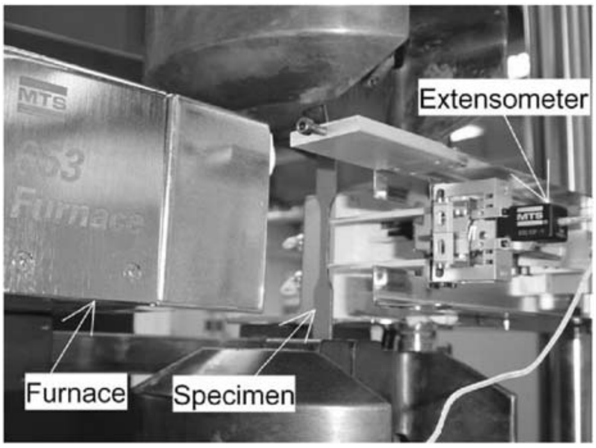

Fig. 1. Testing device

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Table 1. Arrangement of Steady- and Transient-State Tests

Test method	High strength steel	Mild steel	Total
Steady state	18	23	41
Transient state	16	—	16

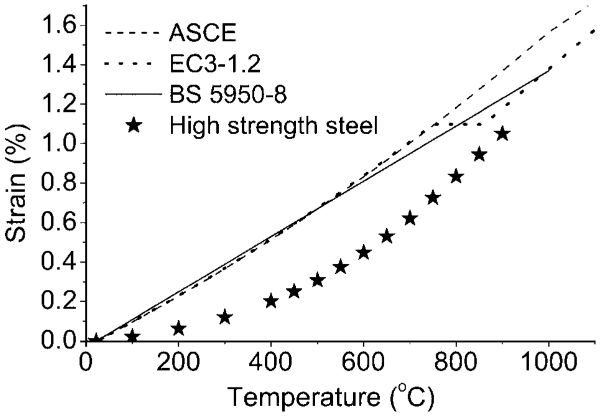

Fig. 2. Comparison of thermal elongation predicted by ASCE, BS 5950-8, and EC3-1-2 with test results of high strength steel

Experimental Investigation

Testing Device

The tensile testing machine used in this study was an MTS 810 Universal testing machine of 100 kN capacity. The heating device used was an MTS Model 653 high temperature furnace with a maximum temperature of 1,400°C, as shown in Fig. 1. The furnace was controlled by an MTS model 409.83 temperature controller. An MTS Model 632.53F-11 axial extensometer was used to measure the strain of the central region of the coupon specimens. The test devices are detailed in Chen and Young (2004).

Test Specimen

The coupon test specimens were obtained from structural steel sheets. The structural steel sheets included high strength steel BISPLATE 80 (approximately equivalent to ASTM A 514, EN 10137-2 Grade S690Q, and JIS G 3128) and mild steel XLERPLATE Grade 350 (approximately equivalent to ASTM 573-450) with a nominal plate thickness of 5.0 mm. A total of 57 tests (41 steady-state tests and 16 transient-state tests) were conducted in this study and the arrangement of the tests is shown in Table 1. The chemical composition of the tested high strength steel and mild steel is shown in Table 2. The test specimens were prepared in accordance with the ASTM Standard E 21-92 (1997) and Australian Standard AS 2291 (1979). The actual dimensions of the cross-sectional areas of the coupon specimens within the gauge length were measured using a micrometer. The measured dimensions were used to determine the cross-sectional area of each coupon.

Testing Procedure

Steady-State Test

In the steady-state tests, the specimen was heated up to a specified temperature then loaded until it failed while maintaining the same temperature. In this study, thermal expansion of the specimen was allowed by maintaining zero tension load during the heating process. After reaching the preselected temperature, approximately 2 min was required for the temperature to stabilize and after another 15 min, the tensile load was applied to the specimen. This would allow the heat to transfer into the specimen. The external thermocouple indicated that the variation of the specimen temperature within the gauge length was less than 6°C (±3°C) during the tests. In the steady-state tests, strain control was used in the tensile testing machine. A constant tensile loading rate of 0.2 mm/min was used and the strain rate obtained from the extensometer was approximately 0.006/min, which is within the range 0.005±0.002/min as specified by the ASTM Standard E 21-92 (1997).

Transient-State Test

In the transient-state tests, the specimen was under constant tensile load whereas the temperature was raised. The stress levels selected in the tests were 1, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, and 700 MPa. The temperatures specified in the temperature controller ranged from 100 to 1,000°C at an interval of 100°C. The strain of the specimen at a given temperature was recorded using the extensometer 10 min after the temperature reached the specified value. The ultimate strength of the specimen was defined as the point at which strain kept increasing at a given value of temperature. In the tests, there are two reasons for the temperature to rise step by step. First, there is a rapid loss of strength for the loaded specimen and the loading machine could not follow the sudden load drop under load control. Second, the strain data for different specified temperatures should be obtained, because the results of the transient-state tests need to be converted to stress–strain curves.

Table 2. Chemical Composition of High Strength Steel and Mild Steel Used in Tests

Chemical composition (Typical)	C	P	Mn	Si	S	Cr	Mo	B	CE (IIW)	PCM
BISPLATE 80	0.16	0.010	1.10	0.20	0.003	—	0.20	0.0010	0.40	0.25
Chemical composition (Maximum)	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	Al
XLERPLATE Grade 350	0.22	0.55	1.70	0.040	0.030	0.30	0.50	0.40	0.35	0.100
Chemical composition (Maximum)	Ti		niobilumn+vanadium		CE					
XLERPLATE Grade 350	0.040		0.03%		0.48					

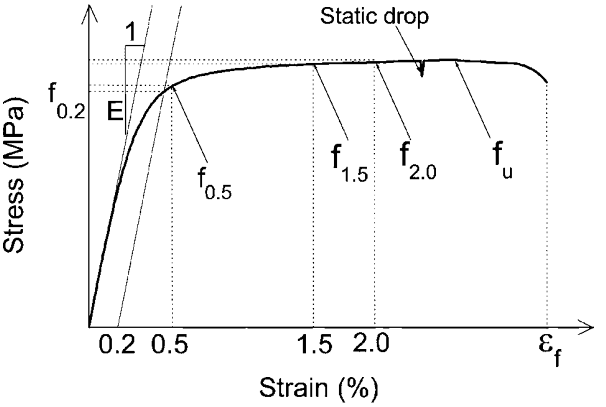

Fig. 3. Definition of symbols

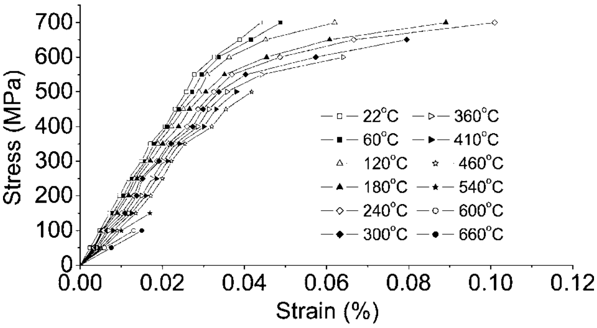

Fig. 4. Stress–strain curve of high strength steel at different temperatures obtained from transient-state test results

Thermal Elongation in Transient-State Test

Thermal elongation of the specimens was determined at a tensile stress level of 1 MPa (0.15 ksi), which is close to free thermal expansion, and compared with the thermal elongation calculated according to the ASCE Manual (1992), British Standard 5950-8 (1998), and European Code 3 Part 1.2 (2001) in Fig. 2. The thermal elongation of the strain in percentage (%) terms was plotted on the vertical axis of the graph and the horizontal axis represents varying temperatures. The comparison indicates that the test values of thermal elongation of high strength steel are less than the values predicted by the ASCE (1992), BS 5950-8 (1998), and EC3-1-2 (2001). Although the 1 MPa (0.15 ksi) tensile stress was almost negligible at ambient temperature for determining the thermal elongation, it however slightly affected the elongation when the temperature increased. As the thermal elongation was determined for specimens loaded at a stress level of 1 MPa (0.15 ksi), the elastic modulus obtained from the transient-state tests was slightly underestimated.

Determination of Strength and Elastic Modulus

The yield strengths at strain levels of 0.2, 0.5, 1.5, and 2.0% were obtained for the purposes of comparison with design standards prediction since these strain levels are widely accepted. The 0.2% yield strength ($f_{0.2}$) is the intersection point of the stress–strain curve and the proportional line offset by 0.2% strain. The yield strengths of $f_{0.5}$, $f_{1.5}$, and $f_{2.0}$ at the strain levels of 0.5, 1.5, and 2.0, respectively, are those values corresponding to the intersection points of the stress–strain curve and the vertical lines specified at given strain levels, as shown in Fig. 3. Serration of the stress–strain curve was observed at high temperatures and the intersection point was the mean value determined from the serration. The elastic modulus was determined from the stress-strain curve based on the tangent modulus of the initial elastic linear curve.

For the transient-state tests, the results are first converted into stress–strain curves, as shown in Fig. 4. The specimens were loaded to a given stress level, and the elastic moduli at different temperatures of each specimen can be determined from the stress-strain curves obtained from the transient-state tests. The data for each specimen at varying temperatures was normalized with respect to the initial elastic modulus at ambient temperature (normal room temperature) of each specimen, so that the influence of elastic modulus variation could be eliminated. Some repeat tests were conducted and the deviations between these test results were quite small with a maximum difference of 4%.

Comparison of Test Results with Design Standards Predictions

Yield Strength

The material properties obtained from the tests for high strength steel and mild steel at normal room temperature are presented in Table 3. The reduction factors ($f_{0.2,T}/f_{0.2,\text{normal}}$, $f_{0.5,T}/f_{0.5,\text{normal}}$, $f_{1.5,T}/f_{1.5,\text{normal}}$, $f_{2.0,T}/f_{2.0,\text{normal}}$) determined from the ratio of different yield strengths at different temperatures to that at ambient temperature (22°C) for the four strain levels of 0.2, 0.5, 1.5, and 2.0%, respectively, are presented in Tables 4 and 5. The test results for 0.2% yield strength of high strength steel and mild strength steel are plotted in Fig. 5. The vertical axis of the graph presents the reduction factor $f_{0.2,T}/f_{0.2,\text{normal}}$ and the horizontal axis represents the variation in temperature.

The reduction factors of 0.2% yield strength obtained from the tests were compared with the AISC Specification (2005), *ASCE Manual* (1992), and Australian Standard AS 4100 (1998) predictions, as shown in Fig. 5. The comparison indicates that the prediction from the AISC Specification is generally adequate, but unconservative for the temperatures of 410 and 460°C. It can be seen that the prediction from the *ASCE Manual* (1992) is generally conservative for both high strength steel and mild steel, but slightly unconservative for temperatures of 60, 120, 770, and 830°C for high strength steel. It is also shown that the AS 4100

Table 3. Material Properties of High Strength Steel and Mild Steel at Normal Room Temperature

Steel	$f_{0.2,\text{normal}}$ (MPa)	$f_{0.5,\text{normal}}$ (MPa)	$f_{1.5,\text{normal}}$ (MPa)	$f_{2.0,\text{normal}}$ (MPa)	$f_{u,\text{normal}}$ (MPa)	E_{normal} (GPa)	ε_f (%)
High strength steel	789	790	813	823	847	223	7
Mild steel	401	409	445	465	552	220	30

Table 4. Reduction Factors of Yield Strength and Elastic Modulus of High Strength Steel

T (°C)	E_T/E_{normal}	$f_{0.2,T}/f_{0.2,\text{normal}}$	$f_{0.5,T}/f_{0.5,\text{normal}}$	$f_{1.5,T}/f_{1.5,\text{normal}}$	$f_{2.0,T}/f_{2.0,\text{normal}}$
22	1.00	1.00	1.00	1.00	1.00
60	1.04	0.95	0.96	0.96	0.96
120	1.01	0.94	0.94	0.96	0.96
150	1.04	0.96	0.95	0.98	0.99
180	1.02	0.92	0.92	0.97	0.97
240	0.98	0.89	0.89	0.99	1.00
300	0.99, 1.00*	0.90, 0.88*	0.91, 0.89*	0.98, 0.97*	0.99, 0.98*
410	0.92	0.87	0.87	0.94	0.94
460	0.94	0.80	0.81	0.85	0.84
540	0.87	0.75	0.75	0.76	0.74
600	0.73	0.60	0.61	0.56	0.59
660	0.73	0.43	0.44	0.43	0.42
720	0.51	0.21	0.21	0.22	0.22
770	0.49	0.14	0.14	0.15	0.14
830	0.33	0.08	0.08	0.08	0.09
940	0.12	0.05	0.05	0.05	0.05

Note: *=second test.

provides a conservative prediction for the test results of high strength steel for temperatures ranging from 300 to 660°C and greater than 830°C, but is unconservative for temperatures ranging from 720 to 830°C and less than 300°C. The AS 4100 conservatively predicted the behavior of mild steel for the temperatures greater than or equal to 300°C, but unconservatively predicted for the temperatures less than 300°C.

The reduction factors of yield strength for strain levels of 0.5, 1.5, and 2.0% are compared with the EC3-1-2 (2001) and BS 5950-8 (1998), as shown in Figs 6–8. The reduction factors of 0.5%, yield strength predicted by the BS 5950-8 are conservative for both the test results of high strength steel and mild steel for temperatures ranging from 240 to 940°C, but unconservatively predicted for temperatures less than 240°C. The reduction factors of 1.5 and 2.0% yield strength predicted by the BS 5950-8 are conservative for the test results of high strength steel for temperatures ranging from 240 to 940°C, but unconservatively predicted for temperatures below 240°C. The reduction factors of 1.5 and 2.0% yield strength predicted by the BS 5950-8 are conservative for the test results of mild steel for temperatures ranging from 540 to 940°C, but unconservatively predicted for temperatures below 540°C. The reduction factors of 2.0% yield strength predicted by the EC3-1-2 is conservative for high strength steel for temperatures ranging from 240 to 940°C, as well as being conservative for mild steel for temperatures ranging from 540°C to 940°C, but unconservatively predicted for high strength steel for temperatures below 240°C and mild steel for temperatures below 540°C. The reduction factors of yield strength for the strain level of 2.0% are compared with the transient-state test results of structural steel S350GD+Z, S355, and S460M conducted by Outinen et al. (2001). It is shown that the test results obtained in this study generally agree well with the test results obtained by Outinen et al. (2001), except that the test results by Outinen et al. are generally lower than the test results in this study for temperatures ranging from 240 to 720°C.

Table 5. Reduction Factors of Yield Strength and Elastic Modulus of Mild Steel

T (°C)	E_T/E_{normal}	$f_{0.2,T}/f_{0.2,\text{normal}}$	$f_{0.5,T}/f_{0.5,\text{normal}}$	$f_{1.5,T}/f_{1.5,\text{normal}}$	$f_{2.0,T}/f_{2.0,\text{normal}}$
22	1.00	1.00	1.00	1.00	1.00
60	1.00	0.96	0.95	0.96	0.96
120	0.95	0.95	0.94	0.96	0.96
150	0.96	0.94	0.95	0.96	0.96
180	0.98, 0.97*	0.92, 0.92*	0.92, 0.93*	0.95, 0.97*	0.95, 0.97*
240	1.03	0.90	0.95	1.05	1.05
300	0.95	0.95	0.99	1.11	1.11
360	0.93	0.86	0.89	1.03	1.04
410	0.93, 0.89*	0.90, 0.90*	0.94, 0.94*	1.04, 1.04*	1.03, 1.03*
460	0.89	0.81	0.85	0.93	0.93
540	0.90	0.78	0.82	0.87	0.86
600	0.82	0.71	0.74	0.76	0.74
660	0.77	0.56	0.58	0.57	0.55
720	0.65	0.35	0.36	0.32	0.31
830	0.48	0.15	0.15	0.14	0.13
940	0.27, 0.26*	0.09, 0.09*	0.09, 0.09*	0.09, 0.09*	0.09, 0.08*

Note: *=second test.

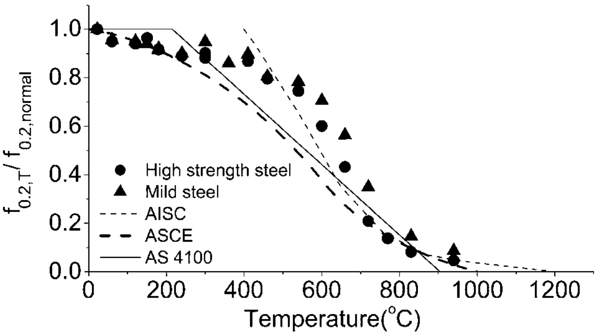

Fig. 5. Comparison of reduction factors of 0.2% yield strength predicted by AISC, ASCE, and AS 4100 with test results

Elastic Modulus

The reduction factors of elastic modulus of high strength steel and mild steel obtained from steady and transient-state tests were compared with AISC (2005), ASCE (1992), AS 4100 (1998), and EC3-1-2 (2001) predictions, as shown in Fig. 9. The reduction factors of elastic modulus of high strength steel obtained from the transient-state tests were also presented in Table 6. It can be seen that the reduction factors of elastic modulus of high strength steel obtained from the steady-state tests are higher than those obtained from the transient-state tests, as shown in Fig. 9. The reduction factors of elastic modulus of high strength steel obtained from the steady-state tests are similar to those of mild steel. The prediction of the reduction factors of elastic modulus obtained from the AISC (2005) are close to those predicted by EC3-1-2. The prediction of the reduction factors of elastic modulus obtained from the ASCE (1992) are identical to those predicted by AS 4100 (1998). This is due to the ASCE (1992) and AS 4100 (1998) adopting the same elastic modulus relationships with varying temperatures. It can be seen that the reduction factors predicted by AISC (2005), ASCE (1992), AS 4100 (1998), and EC3-1-2 (2001) are generally conservative for the steady-state test results obtained from this study for both high strength steel and mild steel, except for mild steel at a temperature of 120°C. The reduction factors of elastic modulus predicted by the AISC and EC3-1-2 are unconservative for the high strength steel obtained from transient-state tests, except for temperatures ranging from 540 to 660°C. It is shown that the predictions of elastic modulus using the approach of ASCE (1992) and AS 4100 (1998) are unconservative for the high strength steel obtained from the transient-state tests. The transient-state test results of the elastic modulus of high strength steel obtained in this study are different to those transient-state test results conducted by Outinen et al. (2001), as shown in Fig. 9. It is shown that the reduction factors of elastic modulus obtained from steady-state tests are generally higher than those transient-state test results.

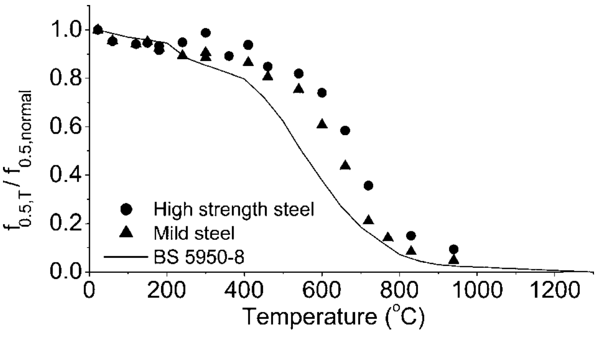

Fig. 6. Comparison of reduction factors of 0.5% strength predicted by BS5950-8 with test results

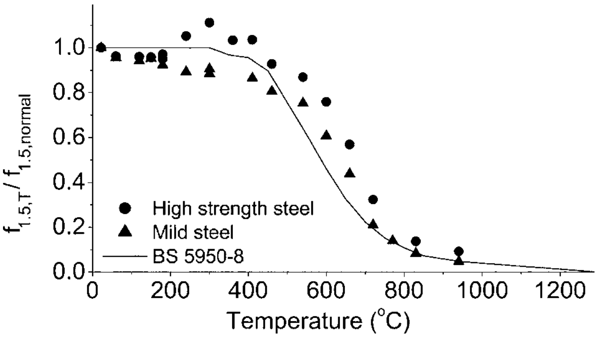

Fig. 7. Comparison of reduction factors of 1.5% strength predicted by BS5950-8 with test results

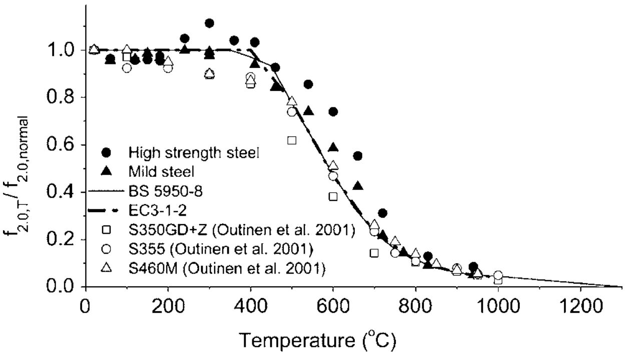

Fig. 8. Comparison of reduction factors of 2.0% strength predicted by BS5950-8 and EC3-1-2 with test results

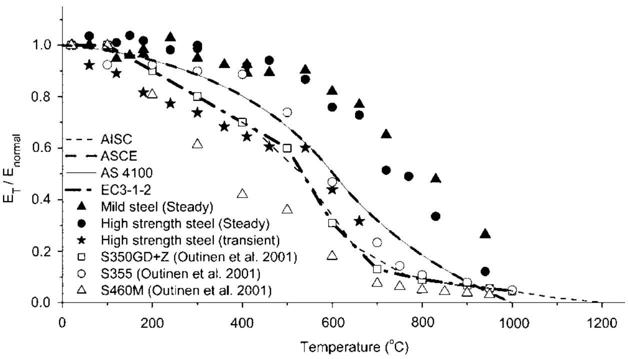

Fig. 9. Comparison of elastic modulus predicted by AISC, ASCE, AS 4100, and EC3-1-2 with test results

The reduction factors of yield strength and elastic modulus of the high strength steel and mild steel are compared in Table 7. The mean value of $(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{High}}/(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{Mild}}$ and $(E_T/E_{\text{normal}})_{\text{High}}/(E_T/E_{\text{normal}})_{\text{Mild}}$ ratios are 0.88 and 0.93 with the corresponding coefficients of variation (COV) of 0.200 and 0.187, respectively. It is shown that the reduction factors of yield

Table 6. Elastic Modulus of High Strength Steel Obtained from Transient-State Tests

Temperature (°C)	22	60	120	180	240	300	360	410	460	540	600	660
E_T (GPa)	209.2	192.9	186.5	170.7	161.7	154.3	142.9	134.9	126.6	125.8	92.0	66.3
E_T/E_{normal}	1.00	0.92	0.89	0.82	0.77	0.74	0.68	0.64	0.61	0.60	0.44	0.32

Table 7. Comparison of Yield Strength and Elastic Modulus between High Strength Steel and Mild Steel

	High strength steel		Mild steel		Comparison	
T (°C)	$\left(\frac{f_{0.2,T}}{f_{0.2,\text{normal}}}\right)_{\text{High}}$	$\left(\frac{E_T}{E_{\text{normal}}}\right)_{\text{High}}$	$\left(\frac{f_{0.2,T}}{f_{0.2,\text{normal}}}\right)_{\text{Mild}}$	$\left(\frac{E_T}{E_{\text{normal}}}\right)_{\text{Mild}}$	$\frac{(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{High}}}{(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{Mild}}}$	$\frac{(E_T/E_{\text{normal}})_{\text{High}}}{(E_T/E_{\text{normal}})_{\text{Mild}}}$
22	1.00	1.00	1.00	1.00	1.00	1.00
60	0.95	1.04	0.96	1.00	0.99	1.04
120	0.94	1.01	0.95	0.95	0.99	1.06
150	0.96	1.04	0.94	0.96	1.02	1.08
180	0.92	1.02	0.92	0.98	1.00	1.04
240	0.89	0.98	0.90	1.03	0.99	0.95
300	0.89	1.00	0.95	0.95	0.94	1.05
410	0.87	0.92	0.90	0.91	0.97	1.01
460	0.8	0.94	0.81	0.89	0.99	1.06
540	0.75	0.87	0.78	0.90	0.96	0.97
600	0.60	0.73	0.71	0.82	0.85	0.89
660	0.43	0.73	0.56	0.77	0.77	0.95
720	0.21	0.51	0.35	0.65	0.60	0.78
830	0.08	0.33	0.15	0.48	0.53	0.69
940	0.05	0.12	0.09	0.27	0.56	0.44
				Mean	0.88	0.93
				COV	0.200	0.187

strength and elastic modulus of the high strength steel and mild steel are quite similar for temperatures ranging from 22 to 540°C with a maximum variation of 8%. The reduction factors of yield strength and elastic modulus of the high strength steel are consistently smaller than those of the mild steel for temperatures greater than 540°C with a maximum variation of 56%. In addition, the values of $(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{High}}/(f_{0.2,T}/f_{0.2,\text{normal}})_{\text{Mild}}$ and $(E_T/E_{\text{normal}})_{\text{High}}/(E_T/E_{\text{normal}})_{\text{Mild}}$ ratios decrease when the temperature increases for temperatures greater than 540°C, as shown in Table. 7.

Ultimate Strength

The ultimate strength of the specimen is defined as a specified load for the temperature reached, at which the specimen undergoes a continuous elongation at an appreciable rate. This specified load was considered as the ultimate strength of the specimen at that particular temperature in the transient-state tests. In Table 8, the ultimate strengths of the high strength steel obtained from the transient-state tests ($f_{t,u,T}$) are compared with the ultimate strengths obtained from the steady-state tests ($f_{u,T}$) with and without consideration of the static drop. A static drop of the stress–strain curve is obtained by pausing the applied strain for one minute. This allowed the stress relaxation associated with plastic strain to take place; hence, the effect of loading rate can be eliminated, as shown in Fig. 2. The ultimate strength obtained from steady-state tests with the consideration of the static drop are closer to the results obtained from the transient-state tests compared with the results without the consideration of the static drop, as shown in Table 8.

Table 8. Comparison of Ultimate Strength Obtained from Transient- and Steady-State Tests for High Strength Steel

Temperature (°C)	$f_{t,u,T}$ (MPa)	$f_{u,T}$ (MPa)	$f_{u,T}$-drop (MPa)
22	>700	856, 838*	838, 820*
60	>700	812	793
120	>700	822	811
150	>700	840	824
180	>700	833	812
240	>700	846	812
300	>700	853, 830*	809, 786*
410	600–650	787	735
460	500–550	694	642
540	350–400	620	550
600	150–200	498	407
660	100–150	357	250
720	50–100	178	109
770	50–100	119	57
830	1–50	75	34
940	<1	43	22

Note: *=second test.

Conclusions

A test program for the behavior of high strength steel and mild steel at elevated temperatures has been presented. The test program included two types of hot-rolled steel, namely high strength steel BISPLATE 80 (approximately equivalent to ASTM A 514, EN 10137-2 Grade S690Q, and JIS G 3128) and mild steel XLERPLATE Grade 350 (approximately equivalent to ASTM 573-450) with plate thickness of 5.0 mm. Steady and transient-state tests were conducted at different temperatures. The yield strengths, elastic moduli, and thermal elongation obtained from the tests were compared with the American, Australian, British, and European predictions. Generally, it is shown that the yield strengths predicted by the American, Australian, British, and European standards are conservative for temperatures up to approximately 1,000°C. It is also shown that the elastic modulus predicted by the American, Australian, and European standards are generally unconservative for the high strength steel test results obtained from transient-state tests, and conservatively predicted for both high strength steel and mild steel test results obtained from the steady-state tests in this study. The yield strength and elastic modulus of the high strength steel and mild steel test results at elevated temperatures have been compared. It is shown that the reduction factors of yield strength and elastic modulus of high strength steel and mild steel are quite similar for the temperatures ranging from 22 to 540°C, but this is not the case for temperatures greater than 540°C.

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Notation

The following symbols are used in this paper:

E = elastic modulus;
E_{normal} = elastic modulus at normal room temperature;
E_T = elastic modulus at temperature T (°C);
$f_{t,u,T}$ = ultimate strength at temperature T (°C) obtained from transient-state test;
f_u = ultimate strength at normal room temperature obtained from steady-state test;
$f_{u,T}$ = ultimate strength at temperature T (°C) obtained from steady-state test;
$f_{0.2}$ = 0.2% yield strength;
$f_{0.2,\mathrm{normal}}$ = 0.2% yield strength at normal room temperature;
$f_{0.2,T}$ = 0.2% yield strength at temperature T (°C);
$f_{0.5}$ = 0.5% yield strength;
$f_{0.5,\mathrm{normal}}$ = yield strength corresponding to 0.5% strain level at normal room temperature;
$f_{0.5,T}$ = yield strength corresponding to 0.5% strain level at temperature T (°C);
$f_{1.5}$ = 1.5% yield strength;
$f_{1.5,\mathrm{normal}}$ = yield strength corresponding to 1.5% strain level at normal room temperature;
$f_{1.5,T}$ = yield strength corresponding to 1.5% strain level at temperature T (°C);
$f_{2.0}$ = 2.0% yield strength;
$f_{2.0,\mathrm{normal}}$ = yield strength corresponding to 2.0% strain level at normal room temperature;
$f_{2.0,T}$ = yield strength corresponding to 2.0% strain level at temperature T (°C);
T = value of temperature; and
ε_f = strain corresponding to fracture point of the specimen.

References

American Institution of Steel Construction (AISC). (2005). "Specification for structural steel buildings." *ANSI/AISC 360–05*, Chicago.

ASCE. (1992). "Structural fire protection." *ASCE manual and reports on engineering practice No. 78*, New York.

ASTM. (1997). "E21–92: Standard test methods for elevated temperature tension tests of metallic materials." *Annual book of ASTM standards, Vol. 03.01: Metals-mechanical testing; elevated and low-temperature tests; metallography*, West Conshohochken, Pa.

Australia Standards (AS). (1979). "Methods for the tensile testing of metals at elevated temperatures." *AS 2291:1979*, Sydney, Australia.

Australia Standards (AS). (1998). "Steel structures," *AS 4100:1998*, Sydney, Australia.

Bjorhovde, R. (2004). "Development and use of high performance steel." *Journal of Constructional Steel Research*, 60(3–5), 393–400.

British Standards Institution (BSI). (1998). "Structural use of steelwork in building—Part 8: Code of practice for fire resistant design." *BS 5950–8:1990*, London.

Chen, J., and Young, B. (2004). "Mechanical properties of cold-formed steel at elevated temperatures." *Proc., 17th Int. Spec. Conf. on Cold-Formed Steel Structures*, Univ. of Missouri-Rolla, Rolla, Mo., 437–466.

European Code 3 (EC3). (2001). *Eurocode 3: Design of steel structures—Part 1.2: General rules—Structural fire design*, European Committee for Standardization, DD ENV 1993–1-2:2001, CEN, Brussels.

Hong Kong Buildings Department. (2005). *Code of practice for the structural use of steel*, The Government of the Hong Kong Special Administrative Region, Kowloon, Hong Kong.

Outinen, J., Kaitila, O., and Mäkeläinen, P. (2001). "High-temperature testing of structural steel and modelling of structures at fire temperatures." *Research Rep. No. TKK-TER-23*, Helsinki Univ. of Technology Laboratory of Steel Structures, Helsinki, Finland.

Tide, R. H. R. (1998). "Integrity of structural steel after exposure to fire." *Eng. J.*, First Quarter, 26–38.