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Thermal and Mechanical Properties of Structural Steel SN400 at Elevated Temperatures

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Abstract

The accurate estimation of thermal and mechanical properties is a prerequisite for the reliable fire-resistant design of steel structures, considering that steel is used as one of the main materials for buildings due to fast construction, light weight, and high seismic resistance. For this reason, an experimental study was performed to examine the thermal and mechanical properties of SN400, one of structural steels for buildings, at various temperatures ranging from 20 to 900ºC. For thermal properties, thermal conductivity, specific heat, and expansion of SN400 were investigated. For mechanical properties, steady-state tension coupon tests were conducted. The yield strength, elastic modulus, ultimate tensile strength, and stress-strain relationships of SN400 were investigated. The measured properties of SN400 were compared with those of other mild-strength steels and predictions by current design guidelines.

Keywords: high-temperature properties, SN400, thermal properties, mechanical properties, reduction factors

1. Introduction

Two kinds of mild-strength structural steel have been intensively studied and widely used in Korea: SS steels (Korean Standard, 2016a) and SM steels (Korean Standard, 2016b) as specified in Korean Standard (KS), where SS and SM steels are rolled steels for general structure and welded structure, respectively. However, SS steels have no limitation on the chemical composition except for phosphorus (P) and sulfur (S), which are classified as impurities. In addition, SM steels have no limitation on the upper yield strength. Therefore, the use of new type of steel for seismic resistance of building structure, SN steels (Korean Standard, 2016c), equivalent to JIS G 3136 (Japanese Standard, 2012), has been increased. As a result, the properties of SN steels have come under close scrutiny.

Except for type A according to the classification of KS D 3861 (Korean Standard, 2016c), the standard for SN steels specifies its mechanical properties, such as the upper and lower limits of yield strength, yield ratio, charpy absorbed energy, and through-thickness performance (only for type C) as summarized in Table 1. It is different from SS steel or SM steel, because of the clear statement on a narrow range between the lower and upper limits of yield, as specified in Table 2. For high seismic performance, seismic design requirements are applied to SN steels, and some requirements are intensified, including assurance of weldability and limitation of impurity.

The use of SN steels has significantly increased with the growth of demand for structural steel in building construction. Moreover, building design develops toward the high-rise and long-spanned structures made of large-sized members. The demand for materials with high ductility and weldability is continuously increasing, since the structures need to withstand high seismic loads and to satisfy serviceability requirements. In this trend, SN steels are required to meet the higher standards for reliable performance.

Attention has been paid to structural fire safety, one of the major issues in steel structures. In particular, high fire-resistance is required in high-rise buildings, considering the sequence of catastrophic damage caused by fire. The temperature-dependent material properties of structural steel are important factors determining the fire-resistance of steel structures, and they need to be investigated under realistic fire conditions. Hence, many experimental studies

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Table 1. Characteristics of SN400 steel (KS D 3861)

Type	Thickness (t) [mm]	Requirements
A	6-100	Upper limit of C=0.24% Range of ultimate tensile strength=400-510 MPa
B	6-100	Range of yield strength=235-355 MPa Yield ratio ≤0.8 Charpy absorbed energy ≥27 J at 0°C Either C_{eq} or P_{cm} should be defined. Sulfur ≤0.015% UT tests can be requested in case of t ≥13 mm
C	16-100	In addition to the requirements for Type B, Through-thickness contraction ≥25% Sulfur ≤0.008% UT tests should be performed.

(Harmathy and Stanzak, 1970; Kirby and Preston, 1988; Twilt, 1988; Sakumoto *et al*., 1992; Outinen, 1999; Kwon, 2002; Chen *et al*., 2006; Bentz and Prasad, 2007) have focused on the evaluation of high-temperature properties of structural steels, but the number of data is still limited, particularly for the high-temperature thermal and mechanical properties of thick steel plates (thickness ≥10 mm) used in building structures as main structural members. High-temperature mechanical properties can be affected by the manufacturing process. According to Sidey and Teague (1988), the loss of strength of cold-formed steel at elevated temperatures exceeds that of hot rolled steel plate by 10-20%, because cold-formed steel at elevated temperatures loses the increased strength obtained from cold-working process at ambient temperature.

This paper presents the experimental study on high-temperature thermal and mechanical properties of SN400 type B (Korean Standard 2016c; Nominal yield strength F_y=235-355 MPa, charpy absorbed energy ≥27 J at 0°C) obtained from 12 mm thick steel plate. A series of thermal property tests was conducted to measure its thermal conductivity, specific heat, and thermal elongation at various temperatures ranging from 20 to 900°C. High-temperature tensile tests were also conducted to investigate yield strength, elastic modulus, and ultimate tensile strength of SN400 at target temperatures from 20 to 900°C. The measured properties are compared with previous test data and predictions based on current design guidelines, such as Eurocode 3 (CEN, 2005), AISC specification (AISC, 2010), and ASCE manual (ASCE, 1992).

2. Overview: Properties of Steel At Elevated Temperatures

2.1. Thermal properties

The thermal properties of steel affect temperature distribution at any section of steel members. Therefore, high-temperature thermal properties are essential to predict the behavior of a steel structure under fire conditions. Thermal conductivity is defined as the multiplication of thermal diffusivity, specific heat, and density. Thermal diffusivity is estimated using the measured rate of heat transfer from an exposed surface to the inside of material. Specific heat is the measured amount of heat required to increase unit temperature for unit mass of material. In addition, the thermal expansion of solids usually represents the change in length of a member due to a change in temperature. In other words, it is defined as the expansion of unit length of material under the increase in temperature by 1°C.

2.2. Mechanical properties

The mechanical properties of structural steel, such as proportional limit, yield strength, ultimate tensile strength, and elastic modulus, are closely related to the loss of strength and stiffness at elevated temperatures, which may result in the unacceptable performance of a structure under fire conditions. Generally, the mechanical properties of steel at elevated temperatures are determined from high temperature tension test under steady-state or transient-state test condition. In steady-state test, the test specimen is heated up to a target temperature and then a tensile test is performed. Whereas, in transient-state test, the test specimen is loaded a constant load and then exposed to uniformly increasing temperature. Usually, the transient-state test is considered to be similar to an actual fire conditions. However, due to the fact that the steady-state test is more simple and easier to obtain stress-strain values at the target temperature, steady-state test method was adopted in this study.

Regardless of temperature, the concept and definition of mechanical properties are consistent in each design model. Eurocode 3 (CEN, 2005) and AISC specification (AISC, 2010) use proportional limit to reflect nonlinear behavior of steel at elevated temperature. Yield strength is defined at 2% strain level in these models. However, ASCE manual (ASCE, 1992) uses 0.2% offset strain level to define yield strength. More detailed comparisons are discussed in Section 5.2.

Table 2. Comparison of SS400, SM400, SM490, SN400 and SN490 (Korean Standard, t≤40 mm)

Steel grades	Yield strength (F_y) Min.-Max. [MPa]	Ultimate strength (F_u) Min.-Max. [MPa]	Yield ratio (YR)	Carbon equivalent (C_{eq}) [%]	Weld crack sensitivity (P_{cm}) [%]
SS400	235*	400-510	-	-	-
SM400	235*	400-510	-	-	-
SM490	315*	490-610	-	-	-
SN400 (Specimen)	235-355 (309)	400-510 (441)	≤0.80 (0.70)	≤0.36 (0.26)	≤0.26 (0.18)
SN490	325-445	490-610	≤0.80	≤0.44	≤0.29

*Only the lower bound is specified.

3. Test Material, Specimen and Program

3.1. Test material: SN400

All specimens were machined from 12 mm steel plate of SN400. Table 2 shows the measured material properties of specimen SN400 at room temperature. The major chemical composition of specimen SN400 is as follows: Carbon (C) 0.134%, Silicon (Si) 0.251%, Manganese (Mn) 0.693%, Phosphorus (P) 0.011%, and Sulfer (S) 0.005%.

3.2 Test program and specimens

3.2.1. Thermal conductivity and specific heat tests

Thermal conductivity is determined by the measured thermal diffusivity, specific heat, and density. The thermal diffusivity and specific heat capacity of SN400 were measured using Netzsch LFA 457 system, and Netzsch DSC 404C system, respectively. For both cases, disk-shaped specimens were used: 12.7 mm in diameter and 2 mm in thickness for thermal diffusivity; and 5 mm in diameter and 1 mm in thickness for specific heat. The range of elevated temperatures was from 20°C (room temperature) to 900°C. The rate of heating was 10°C/min.

3.2.2. Thermal expansion tests

The thermal expansion of SN400 was measured using a pushrod dilatometer measurement system, Netzsch DIL 402C. It measured the thermal strain of specimens at elevated temperatures. The cylindrical specimens were used, and the dimensions were 5 mm in diameter and 25 mm in length. The rate of heating was 10°C/min, with the temperature range of 20-1000°C. The chamber was filled with inert argon (Ar) gas to prevent oxidation.

3.2.3. High-temperature tension tests

The steady-state test in accordance with the International Standard ISO 6892-2 (ISO, 2011) was performed to investigate high-temperature mechanical properties of SN400. Each specimen had a circular section with the diameter of 6 mm and the gauge length of 30 mm. The details of the specimen are presented in Fig. 1.

Instron and MTS universal testing machines (UTM) were used in the tests. Both have the same capacity of 100 kN, and there was no significant difference in performance. The temperature of the temperature-controlled electrical furnace and that of the specimen were measured, while heating specimens in the furnace from room temperature to the target temperature at the rate of 10°C/min, which is in the recommended range of Eurocode 3 (CEN, 2005). The target temperatures were 20°C (room temperature), 100, 200, 300, 400, 500, 600, 700, 800, and 900°C. It is noted that additional 10 minutes were required after reaching each target temperature for a stable temperature distribution, which is uniform within the section of the specimen. Once stabilization was confirmed, strain-controlled tensile loading was applied to the specimen until failure. Regardless of temperature, the strain rate of 0.004/min was applied up to the yield point. After yielding, the strain rate was increased to 0.015/min. Three specimens were tested at each target temperature.

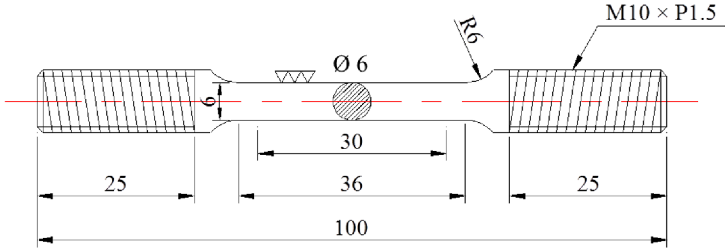


Figure 1. Dimensions of tensile test specimen (unit: mm).

Table 3. Measured thermal conductivity and specific heat of SN400

Temperature [°C]	Thermal diffusivity [mm²/s]	Specific heat [J/kg°C]	Thermal conductivity [W/m°C]	Density [kg/m³]
20	13.1	520.5	53.7	
50	13.7	487.7	51.6	
100	12.7	513.3	51.3	
200	11.5	535.7	48.3	
300	10.1	641.0	50.9	
400	8.8	656.3	44.9	7851
500	7.6	709.3	42.1	
600	6.2	843.3	41.1	
700	4.7	869.3	31.8	
800	4.3	741.3	24.9	
900	5.3	720.0	30.0	

4. Test Results

4.1. Thermal conductivity and specific heat tests

Table 3 summarizes the thermal properties obtained from the tests of SN400 at elevated temperatures. The thermal conductivity of SN400 decreased with the rise of temperature up to 800°C. The specific heat increased up to 700°C, and it fell back over 800°C. The increase of specific heat in the temperatures range from 700 to 800°C is widely known as the results from the phase change in steel. It is the atomic rearrangement from a face centered cubic structure to a body centered cubic structure, which requires considerable energy (Wang *et al*., 2012).

4.2. Thermal expansion tests

Figure 2 shows the change in the thermal strain of SN400 with the rise of temperature. The thermal strain increased linearly with temperature up to 750°C and then slightly decreased until 850°C. It increased again from 850 to 1000°C. It is noted that the temperature range with the strain fluctuation was similar to that of specific heat mentioned in 4.1, and it is mainly caused by the phase change. The thermal strain in Fig. 2 is the engineering strain.

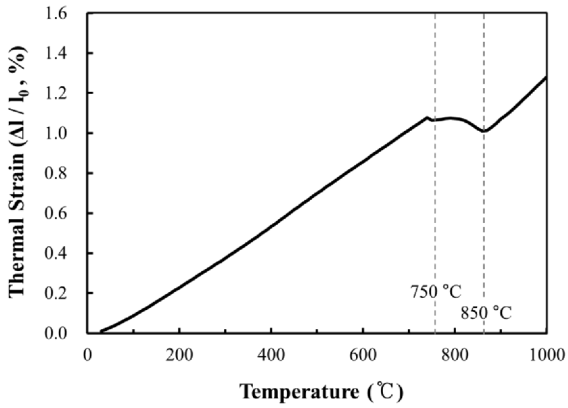


Figure 2. Thermal strain of SN400 at elevated temperatures

4.3. High-temperature tension tests

Figure 3 shows the photographs of specimens after steady-state high-temperature tension tests at each target temperature. Substantial necking was observed in the middle of most specimens, and they became darker or had less reflection on a surface at higher target temperature.

Figure 4 shows the stress-strain curves obtained at each target temperature. At 100°C, the yield strength and ultimate strength are slightly decreased. Between 200 and 300°C,

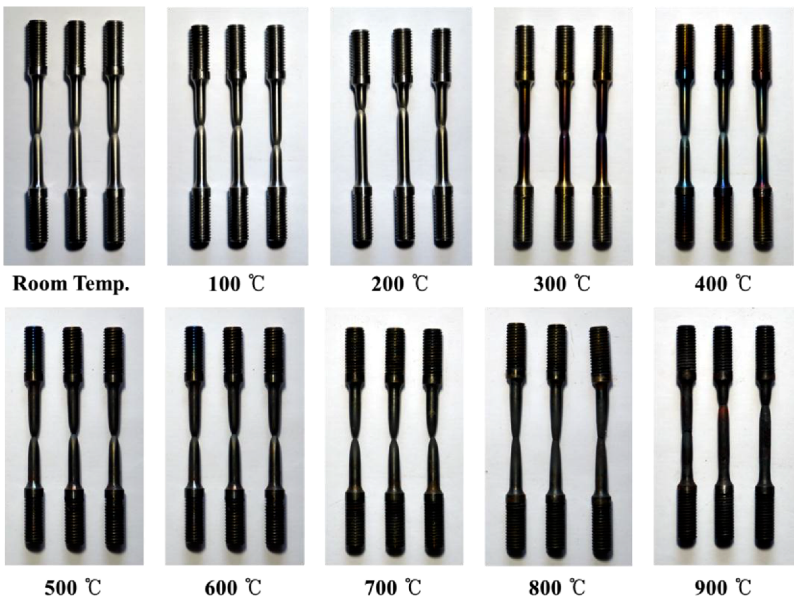


Figure 3. Photographs of specimens after high-temperature tension tests

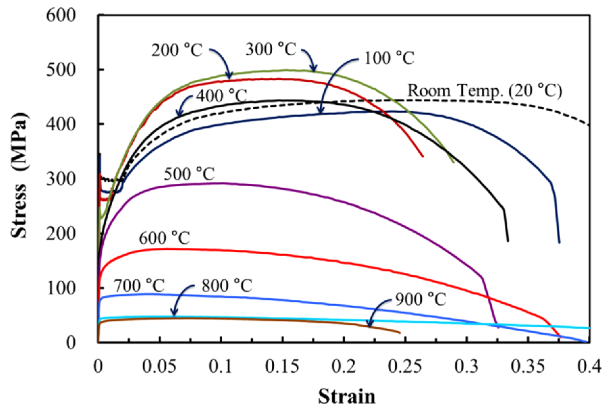


Figure 4. Stress-strain curves of SN400 at target temperatures

the yield strengths are gradually decreased; however, the ultimate strengths are higher than that at room temperature. Also, it is worth remarking that the yield plateau in a stress-strain curve becomes shorter and finally disappears over 400°C, and then the considerable degradation in strength occurred over 400°C.

The average test results of SN400 at elevated temperatures are summarized in Table 4. The proportional limit ($f_{p,T}$), yield strengths defined by strain levels of 0.2% offset ($f_{0.2,T}$), 0.5% ($f_{0.5,T}$), 1.5% ($f_{1.5,T}$), and 2.0% ($f_{2.0,T}$), ultimate tensile strength, elongation and elastic stiffness were obtained at each target temperature. It is clearly shown that, regardless of the definition of yield strain, yield strength abruptly decreased as temperature increased, in case that the temperature was over 400°C. Similar results were observed in ultimate tensile strength and elastic modulus at elevated temperatures.

5. Discussion: Comparison of Test Results With Design Guidelines

5.1. Thermal properties

Thermal properties, such as thermal conductivity, specific heat, and thermal expansion, measured from the SN400 tests are compared with those from design models (Eurocode 3, AISC specification, and ASCE manual; comparison of constitutive relationships for each design models can be found in Kodur *et al*., 2010). The measured properties of mild-strength steel SS400 and SM490 by Kwon (2002) are also included for comparison.

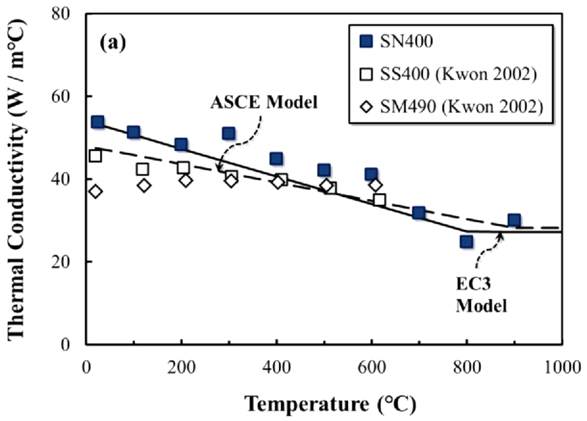
Figure 5 compares three high-temperature thermal properties, namely thermal conductivity, specific heat, and thermal strain, predicted by the design models with the measured properties of SN400, SS400, and SM490. As shown in Fig. 5(a), ASCE and Eurocode 3 offer the thermal conductivity models which decrease linearly until 900 and 800°C, respectively, and then converge into constant conductivity. Apparently, they are comparable to the test results of SN400, SS400 and SM490. In particular, ASCE model is well suited to SS400. SM490 has low thermal conductivity compared to the ASCE and Eurocode 3 models up to 400°C. The measured thermal conductivity of SN400 is higher than those of SS400 and SM490 especially up to 300°C. For SN400, Eurocode 3 provides more accurate predictions than ASCE, but it still underestimates thermal conductivity at 300°C and over, except for 800°C.

Figure 5(b) compares the measured specific heat values with the predictions by two different codes, Eurocode 3 and ASCE. Both models have sharp peaks at 725 and 735°C, respectively. The test results of SN400, SS400 and SM490 are comparable to the design models. Especially, the specific heat of SN400 agrees well with Eurocode 3 model, up to 900°C.

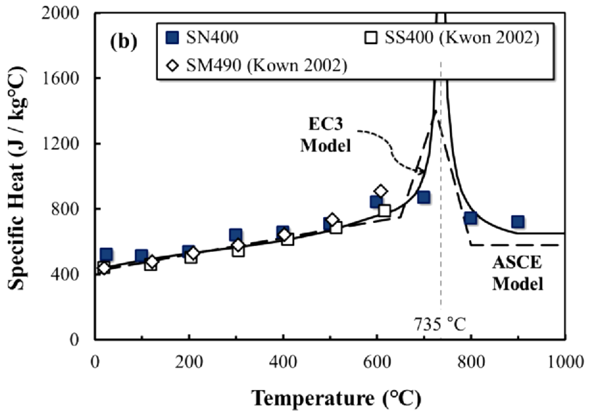
Figure 5(c) compares the measured thermal strain with that predicted by design models. Every design model provides a linearly increasing function of temperature up to 750°C. However, Eurocode 3 model has a transition range from 750 to 860°C, which reflects the phase change in steel within this temperature range. The test results of SN400, SS400 and SM490 agree with the design models up to 700°C. Over 750°C, Eurocode 3 model predicts

Table 4. Tensile coupon test results of SN400 at elevated temperatures (Average values of 3 specimens)

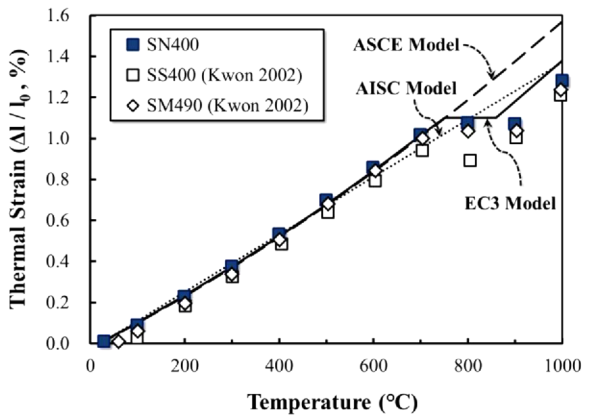
Temperature [°C]	Proportional limit	Yield strength				Ultimate tensile strength		Elongation [%]	Elastic stiffness [GPa]
	f_p [MPa]	$f_{0.2,T}$ [MPa]	$f_{0.5,T}$ [MPa]	$f_{1.5,T}$ [MPa]	$f_{2.0,T}$ [MPa]	ε_u	f_u [MPa]		
20	291	304	301	300	299	0.259	445	46	219
100	280	281	276	275	292	0.234	424	38	212
200	261	266	263	307	331	0.137	484	26	211
300	219	237	236	304	335	0.158	500	29	195
400	159	193	214	281	309	0.154	444	33	188
500	117	174	190	234	249	0.097	292	33	171
600	94	129	138	154	159	0.054	172	38	147
700	65	81	83	86	87	0.042	89	39	117
800	33	44	45	46	47	0.053	48	51	80
900	30	38	39	41	42	0.074	45	25	43



(a) Thermal conductivity



(b) Specific heat



(c) Thermal strain

Figure 5. Comparison of design models and test results: thermal properties.

more accurately than ASCE and AISC models. As a result, Eurocode 3 provides more accurate predictions for SN400 steel.

5.2. Mechanical properties

The mechanical performance of steel usually deteriorates at elevated temperatures. Reduction factors are utilized to consider the degradation of strength or stiffness. Those for SN400 were investigated in a series of high-temperature

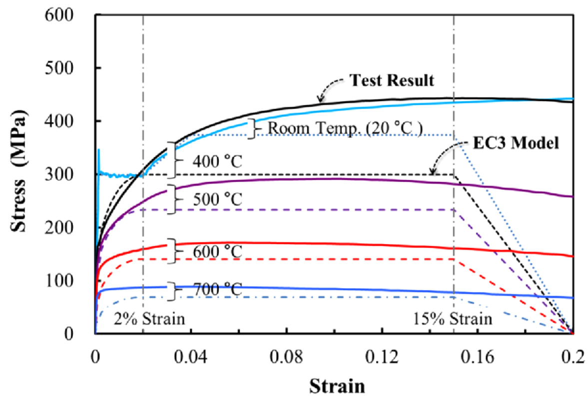


Figure 6. Comparison of Eurocode 3 and test results: stress-strain relationships.

tensile tests, and they were compared with various design models (Eurocode 3, AISC specification, and ASCE manual; comparison of constitutive relationships for each design models can be found in Kodur *et al*., 2010). In addition, those for SS400 and SM490 (Kwon, 2002) were included for comparison.

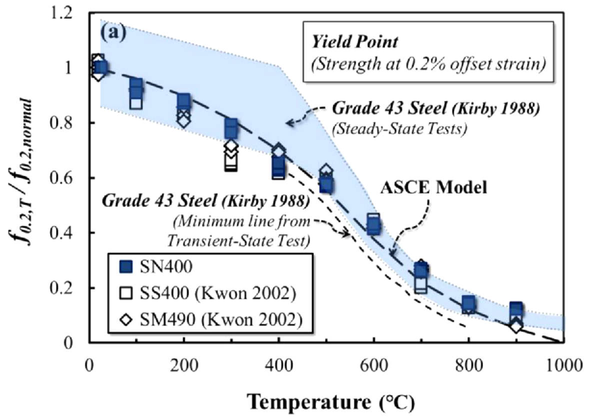
5.2.1. Stress-strain relationships

Eurocode 3 specifies constitutive relations that vary with temperature. Four different parts form up into the stress-strain curve at any elevated temperature: (1) a linear elastic part from zero strain to the proportional limit; (2) an elliptic transition from the proportional limit to the strain of 2.0%, whose strength corresponds to the effective yield strength ($f_{2.0,T}$); (3) a flat yield plateau from the strain of 2.0% to the limiting strain of 15%; and finally, (4) a linearly decreasing part heading to zero stress at the strain of 20%, which is the ultimate strain.

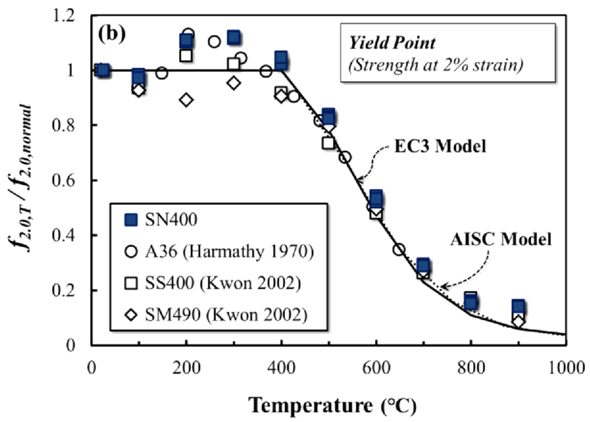
Figure 6 presents the comparison of the stress-strain curves obtained from steady-state tests of SN400 (solid line) and those predicted by Eurocode 3 (dotted line). It is noted that the curves from the test data are identical to those in Fig. 4. As shown in Fig. 6, the stress-strain curves predicted by Eurocode 3 are comparable to the test results up to the strain level of 2% when the temperature is 500°C or below. However, when the temperature is over 600°C or the strain exceeds 2%, there is a noticeable discrepancy in the shape of curves due to the following facts: (1) The effect of creep is implicitly included in the stress-strain model in Eurocode 3. In this model, strain hardening is not considered above 400°C, and the earlier nonlinear behavior is assumed above 600°C. (2) Also, SN400 shows significant strain hardening after yielding and excellent deformation capacity. However, Eurocode 3 model is generally suitable for the stress-strain curves of SN400, considering that the strain range of interest is below 2% in the building structure catching fire.

5.2.2. Yield strength and proportional limit

Figure 7 shows the reduction factors for yield strength



(a) Reduction factors for yield strength at 0.2% offset strain



(b) Reduction factors for yield strength at 2.0% strain

Figure 7. Comparison of design models and test results: reduction factors for yield strength.

of SN400, SS400 and SM490 at elevated temperatures. $f_{2.0,T}/f_{2.0,normal}$ (Fig. 7(a)) and $f_{2.0,T}/f_{2.0,normal}$ (Fig. 7(b)) are presented, where $f_{2.0,T}$ and $f_{2.0,T}$ are yield strengths corresponding to 0.2% offset and 2.0% strain levels at temperature T, respectively; and $f_{2.0,normal}$ and $f_{2.0,normal}$ are those at normal room temperature. Also, Fig. 7(a) includes the test results of mild-strength Grade 43 steel (equivalent to S275 steel, F_y=275 MPa) by Kirby and Preston (1988), and Fig. 7(b) includes the test result of A36 steel (F_y = 250MPa) by Harmathy and Stanzak (1970) at elevated temperatures. It is noted that the shaded area in Fig. 8(a) refers to the range of steady-state test results of Grade 43 steel. The reliability of each design model can be evaluated using the reduction factors. It is also valid for the properties discussed later.

Various codes and guidelines adopt yield strength as an important design parameter. However, the definitions of yield strength of steel at elevated temperatures are not identical. In this study, two different strain levels were adopted to define yield strength: 0.2% offset specified in ASCE manual, and 2.0% in Eurocode 3 and AISC specification. In the comparison of reduction factors for the yield strength ($f_{2.0,T}/f_{2.0,normal}$) at 0.2% offset strain

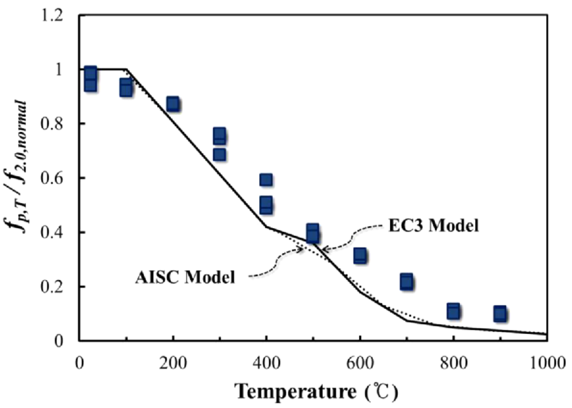


Figure 8. Comparison of design models and test results: reduction factors for the proportional limit.

obtained from the tests with those of ASCE model (Fig. 7(a)), it is indicated that the prediction of ASCE model is generally suitable for SN400, but not for SS400 and SM490 between 100 to 300°C. It is worth mentioning that the prediction of ASCE model is not accurate for SN400 at 400°C, because the yield plateau in stress-strain relationship is disappeared. Fig. 7(b) compares the reduction factors for yield strength at 2.0% strain ($f_{2.0,T}/f_{2.0,normal}$) obtained from the tests with those predicted by Eurocode 3 and AISC models. Apparently, both models provide similar predictions. The reduction factors by Eurocode 3 and AISC models are not conservative, especially for SM490 below 400°C. Similar to A36 and SS400, the yield strength of SN400 between 200 and 300°C is higher than that at room temperature. However, both models offer conservative predictions of reduction factors for the yield strength of SN400 at 2.0% strain, especially over 200°C.

Eurocode 3 and AISC models adopt the proportional limit to reflect viscoelastic behavior of steel at elevated temperatures (Kodur *et al*., 2010). Fig. 8 compares reduction factors for the proportional limit ($f_{p,T}/f_{2.0,normal}$, where $f_{p,T}$ is the stress at the proportional limit subjected to temperature T) of SN400, which were obtained from the tests and estimated by Eurocode 3 and AISC models. As shown in Fig. 8, both models provide conservative prediction for SN400 over 200°C.

5.2.3. Elastic modulus

The elastic modulus is one of the key properties of steel, since it affects buckling stress and instability of structures. The reduction factors for the elastic modulus, E_T/E_{normal}, of SN400, SS400 and SM490 obtained from steady and transient-state tests are compared with ASCE, Eurocode 3, and AISC model predictions in Fig. 9, where the elastic modulus was obtained from the stress-strain curve based on the tangent modulus of the initial elastic linear curve at the target temperature. Similar to the notations in the previous section, E_T and E_{normal} are elastic

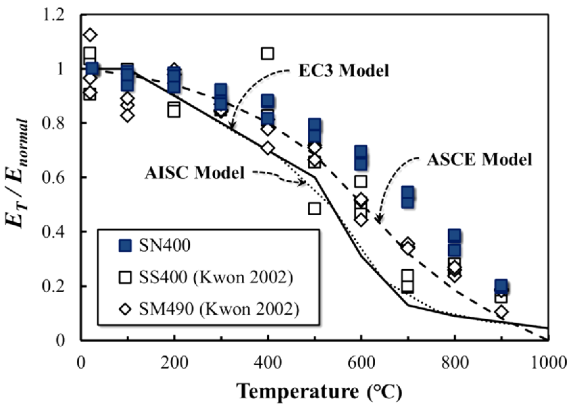


Figure 9. Comparison of design models and test results: reduction factors for the elastic modulus.

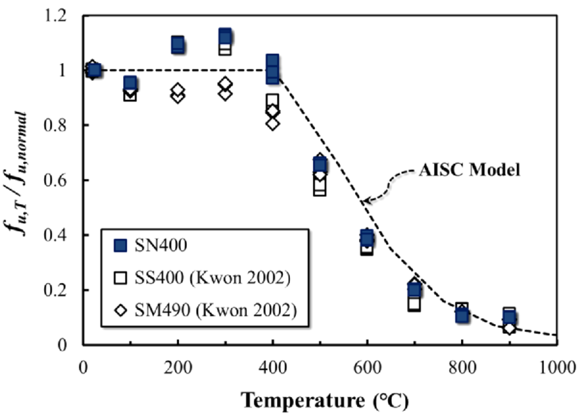


Figure 10. Comparison of AISC model and test results: reduction factors for ultimate tensile strength.

moduli at temperature T and normal room temperature, respectively. It is found that the elastic stiffness of SN400 is higher than those of SS400 and SM490 at elevated temperatures, and that the reduction factors predicted by ASCE model are reliable for SN400. Eurocode 3 and AISC models are lower than ASCE model between 200 and 900°C. Consequently, they predict conservatively in this range, except for SS400 at 200 and 500°C. In summary, Eurocode 3 and AISC models provide proper or conservative reduction factors for elastic moduli of SN400 at 200°C and over.

5.2.4. Ultimate tensile strength

The measured reduction factors for ultimate tensile strength, $f_{u,T} / f_{u,normal}$, of SN400, SS400 and SM490 are compared with AISC model predictions in Fig. 10, where $f_{u,T}$ and $f_{u,normal}$ are ultimate tensile strengths at temperature T and normal room temperature, respectively. It is noted that ASCE and Eurocode 3 are not included, since either of them does not provide a model for ultimate tensile strength. As discussed in 4.3, the ultimate tensile strength of SN400 between 200 and 300°C is higher than that at room temperature, and it is also observed in the ultimate tensile strengths of SS400. However, the estimated reduction factors by AISC model are higher than those from test results between 500 and 800°C. The reduction factors for SM490 at elevated temperatures are less than those of AISC model. Therefore, AISC model does not provide conservative predictions of the ultimate tensile strength of SM490.

6. Conclusions

An experimental study on the thermal and mechanical properties of SN400 at elevated temperatures was presented in this paper. For thermal properties, thermal conductivity and specific heat of SN400 were determined in the temperature range from 20 to 900°C. Also, the thermal expansion tests were conducted to measure expansion characteristics of SN400. For mechanical properties, steady-state tension coupon tests were executed in the temperature range from 20 to 900°C. The proportional limit, yield strength, elastic modulus, and ultimate tensile strength were determined from the stress-strain curve at each target temperature.

The thermal and mechanical properties obtained from the tests were compared with other test results of mild-strength steel, and with design guidelines such as Eurocode 3, AISC specification, and ASCE manual. The following remarks are made on the comparison:

(1) The reduction factors for the measured specific heat and thermal strain at elevated temperatures are comparable to those predicted by the current design models.

(2) However, there is a slight discrepancy between the thermal conductivity measured in the tests and those predicted by the design models.

(3) Regarding the mechanical properties, the stress-strain model provided by Eurocode 3 agree well with the test results of SN400 up to 2% strain level and it gives conservative prediction of stress-strain relationships at elevated temperatures.

(4) The yield strength predicted by ASCE model was adequate for SN400. In ASCE model provides the yield strength predictions based on the 0.2% offset strain. The yield strengths at 2.0% strain predicted by Eurocode 3 and AISC models are also reasonable within the entire temperature range.

(5) The proportional limits provided by Eurocode 3 and AISC models are conservative over 200°C.

(6) The elastic moduli predicted by the design models are generally suitable for SN400, but none of them is conservative at 100°C.

(7) In addition, AISC offers realistic predictions of reduction factors for the ultimate tensile strength of SN400 within the entire temperature range.

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References

American Institution of Steel Construction (AISC) (2010). Specification for structural steel buildings. Chicago.

American Society of Civil Engineers (ASCE) (1992). Structural fire protection. ASCE committee on fire protection, Manual No. 78, ASCE, Reston, VA.

Bentz, D. P. and Prasad, K. R. (2007). Thermal performance of fire resistive materials I. Characterization with respect to thermal performance models. Rep. No. NISTIR 7401, NIST, Gaithersburg, MD.

Chen, J., Young, B., and Uy, B. (2006). "Behavior of high strength structural steel at elevated temperatures." *Journal of Structural Engineering*, ASCE, 132, pp. 1948-1954.

European Committee for Standardization (CEN) (2005). Eurocode 3: Design of steel structures, Part 1.2: Structural fire design. Brussels.

Harmathy, T. Z. and Stanzak, W. W. (1970). "Elevated-temperature tensile and creep properties of some structural and prestressing steels." *ASTM Special Technical Publication*, 464, pp. 186-208.

International Organization for Standardization (ISO) (2011). Metallic materials-tensile testing-Part 2: Method of test at elevated temperature. ISO 6892-2, Geneva.

Japanese Standard (2012). Rolled steels for building structure (JIS G 3136). Japanese Industrial Standard Committee.

Kirby, B. R. and Preston, P. R. (1988). "High temperature properties of hot-rolled structural steels for use in fire engineering design studies." *Fire Safety Journal*, 13, pp. 27-37.

Kodur, V., Dwaikat, M., and Fike, R. (2010). "High-temperature properties of steel for fire resistance modeling of structures." *Journal of Materials in Civil Engineering*, ASCE, 22, pp. 423-434.

Korean Standard (2016a). Rolled steels for general structure (KS D 3503). Korean Agency for Technology and Standards.

Korean Standard (2016b). Rolled steels for welded structure (KS D 3515). Korean Agency for Technology and Standards.

Korean Standard (2016c). Rolled steels for building structure (KS D 3861). Korean Agency for Technology and Standards.

Kwon, I. K. (2002). Experimental study on the fire resistant performance of structural steels. Doctoral dissertation, Hanyang Univ. (in Korean).

Outinen, J. (1999). Mechanical properties of structural steels at elevated temperatures. Licentiate thesis, Helsinki University of Technology, Finland.

Sakumoto, Y., Yamaguchi, T., Ohashi, M. and Saito, H. (1992). "High-temperature properties of fire-resistant steel for buildings." *Journal of Structural Engineering*, ASCE, 118, pp. 391-407.

Sidey, M. P. and Teague, D. P. (1988). *Elevated temperature data for structural grades of galvanized steel*. British Steel (Welsh Laboratories) Report, UK.

Twilt, L. (1988). "Strength and deformation properties of steel at elevated temperatures." *Fire Safety Journal*, 13, pp. 9-15.

Wang, Y., Burgess, I., Wald, F., and Gillie, M. (2012). *Performance-based fire engineering of structures*. CRC Press.