Constitutive Model of ASTM A992 Steel at Elevated Temperature for Application in Nuclear Power Plants

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1. Introduction

It is essential to know the mechanical properties of steel structures subjected to thermal loads, such as fire or unexpected temperature extremities. One of the key elements is the constitutive model at elevated temperature to evaluate the behavior of steel structures engaging thermal loads. This paper provides the constitution model induced from the enormous experimental testing carried out by the authors for ASTM A992 steel. ASTM A992 is the most common grade of high strength steel used for building structures in the U.S. and considered to be applied in Korean nuclear power plant in an immediate future.

2. Methods and Model

This paper presents the results of tension tests of A992 steel at elevated temperatures. From this test data, the stress-strain curve at elevated temperature was developed using the best-fitting curve method. In addition, two temperature-dependent models for stress-strain behavior were developed: a detailed model for use in advanced analysis and a simplified model.

2.1 Tension Test Results

An extensive experimental testing was performed by the authors from room temperature per ASTM E8 to elevated temperature per ASTM E21 up to 1,000°C in an increment of 100°C[1,2]. Test specimens were taken from the web of W30x99 sections of ASTM A992 steel. Fig.1 shows the initial part of stress-strain curves obtained from experimental tests [3].

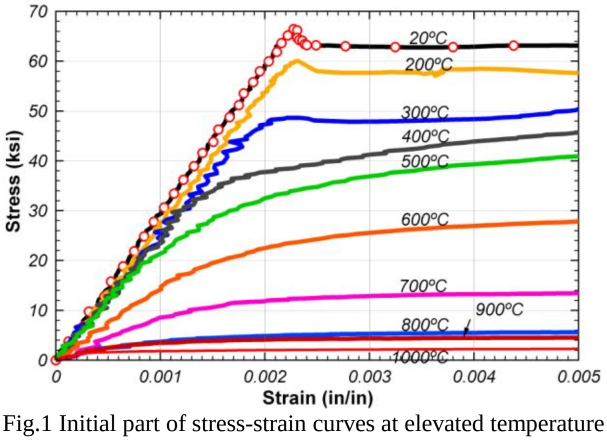


Fig.1 Initial part of stress-strain curves at elevated temperature

2.2 Normalized Stress-Strain Curves

Most of the literature on high-elevated temperature of structural steel reported the yield stress and tensile strength with the limited initial part of stress-strain curves according to the technical report of National Institute of Standards and Technology[4]. It is important to note that a full stress strain curve is hard to achieve because of some strain data loss during the resetting period of extensometer. The authors developed the technology for generating the full stress-strain curves with compensating the lost data during an extensometer resetting period [3].

In order to establish the constitutive model at elevated temperature, it's critical to find the pattern of the stress-strain curves. The normalized full stress-strain curves were obtained from the extensive experimental tests by using a retention stress and strain factor. Fig.2 shows the normalized full stress-strain curves at elevated temperatures.

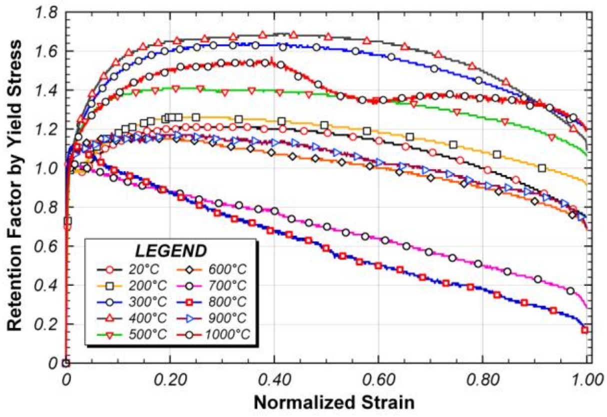


Fig.2 Normalized stress-strain curves at elevated temperature

2.3 Detailed Constitutive Model

The detailed constitutive model developed for the use of more accurate structural analysis: closest simulation with the stress-strain curves at each temperature level while using a best-fitting curve process.

The detailed constitutive model for elevated temperature has been developed by using a strain with four different zones. The constants and parameters are obtained from the best-fitting curve of experimental testing results at elevated temperatures. The schematic diagram and detailed constitutive model are shown on Fig.3 and Table I respectively.

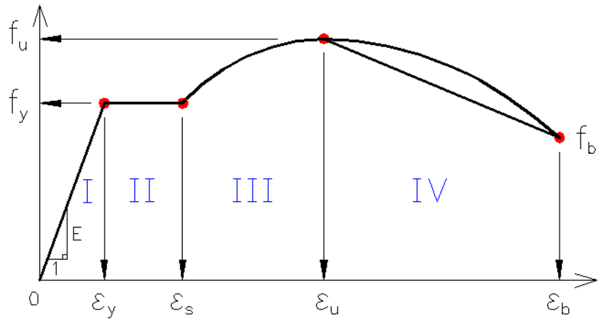


Fig. 3 Schematic diagram of detailed constitutive model

Table I: Detailed Constitutive Model

Zone	Strain	Stress	Temperature
I	$\varepsilon \leq \varepsilon_y$	$E\,\varepsilon$	20 ~ 1,000°C
II	$\varepsilon_y \leq \varepsilon \leq \varepsilon_s$	f_y	20 ~ 300°C $\varepsilon_s = \varepsilon_y$ for T ≥ 400°C
III	$\varepsilon_s \leq \varepsilon \leq \varepsilon_u$	$f_y + c\left[1 - \left(\frac{\varepsilon - \varepsilon_s - a}{a}\right)^2\right]^{1/2}$	20 ~ 1,000°C
IV	$\varepsilon_u \leq \varepsilon \leq \varepsilon_b$	$f_b + d\left[1 - \left(\frac{\varepsilon - \varepsilon_u}{c}\right)^2\right]^{1/2}$	20 ~ 1,000°C (except 700 and 800°C)
		$f_u + \frac{d}{b}(\varepsilon - \varepsilon_u)$	700 ~ 800°C only
Parameters		$a = \varepsilon_u - \varepsilon_s$, $b = \varepsilon_b - \varepsilon_u$, $c = f_u - f_y$, $d = f_u - f_b$	

2.4 Simplified Constitutive Model

A simple constitutive model in this study provides the use in design field or quick evaluation of the steel structure subjected to thermal loads. In practical reasons, there is no meaning for the constitutive model after reaching the tensile strength. Therefore, the suggested simplified model has limited the strain up to maximum 15% of total strain.

The schematic diagram of simplified constitutive model is shown on Fig. 4 and Table II respectively. The yield strain was assumed the extension of proportional limit at yield stress determined by 0.2% offset method in Fig. 2.

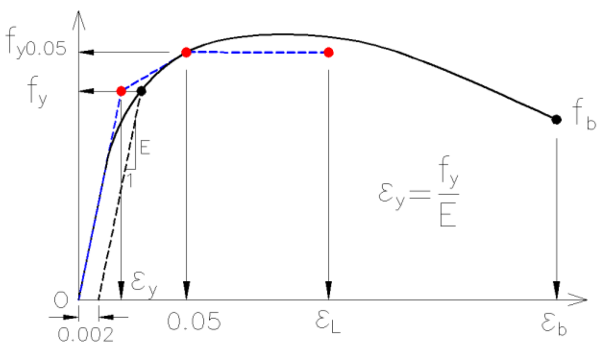


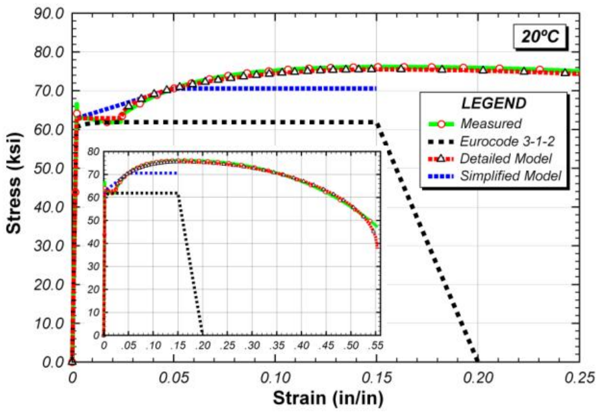
Fig. 4 Schematic diagram of simplified constitutive model

Table II: Parameters of Simplified Constitutive Model

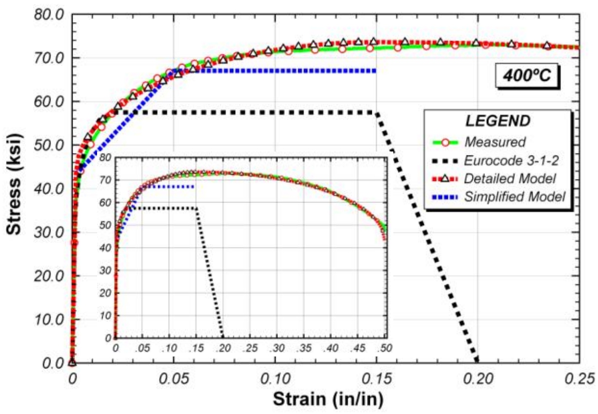
Temp (°C)	Parameter			
	E (ksi)	f_y (ksi)	$f_{y0.05}$ (ksi)	ε_L
20	29,600	62.9	70.6	0.15
200	26,900	58.4	69.2	0.15
300	24,900	48.4	72.3	0.15
400	24,500	43.3	67.1	0.15
500	22,800	38.5	53.0	0.15
600	14,500	26.9	30.8	0.15
700	8,100	12.0	12.0	0.10
800	5,200	5.3	5.3	0.10
900	4,800	4.3	4.8	0.15
1000	5,300	2.1	3.0	0.15

3. Model Verification

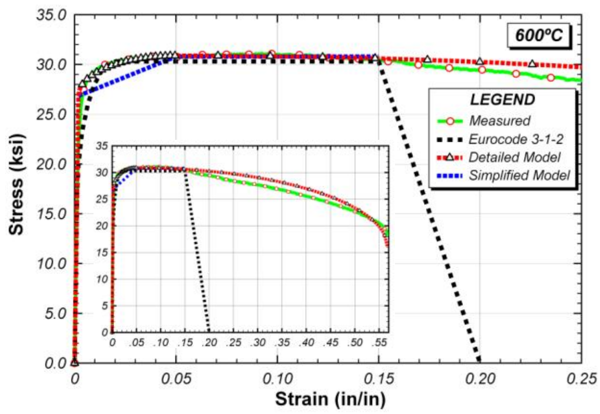
The suggested models as detailed model and simplified model was verified using the comparison of measured experimental data and Eurocode model; the only existing codified model that provides for steel stress-strain behavior at elevated temperatures [5]. Fig 5 shows the model comparison for typical turning point temperatures; 20°C, 400°C, 600°C, 700°C, and 1,000°C with initial part of stress-strain curves embedded in full range of strain curves.



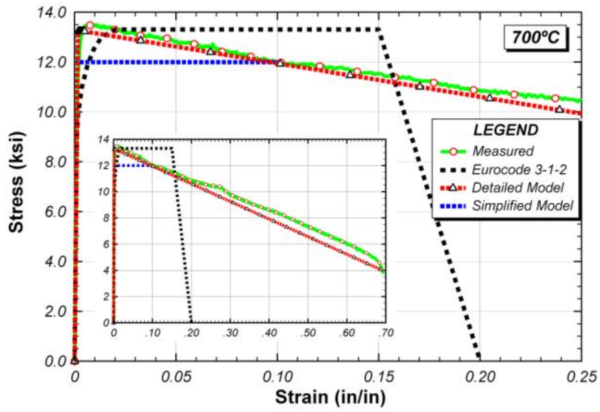
(a) Constitutive Model Verification at 20°C



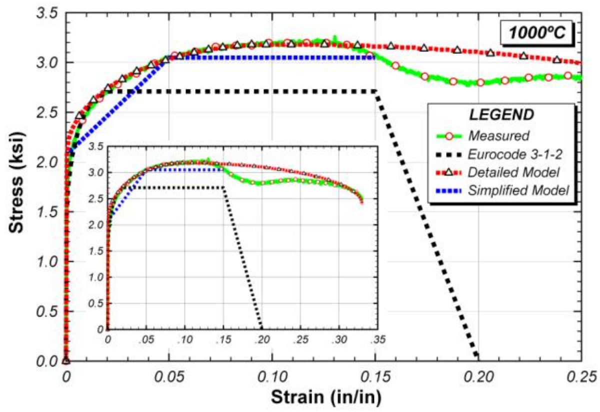
(b) Constitutive Model Verification at 400°C



(c) Constitutive Model Verification at 600°C



(d) Constitutive Model Verification at 700°C



(e) Constitutive Model Verification at 1,000°C

Fig. 5 Verification of constitutive model of ASTM A992 steel

5. Discussions

A material behavior of steel at elevated temperature is dramatically different at room temperature because of the metallurgical characteristics including the phase diagram behavior, the grain boundary change, and the crystal structure effect along with possible minor effects. Fig. 1 and Fig. 2 proved the general behavior of high strength steel at elevated temperatures because of the reasons mentioned previously.

There rarely is a constitutive model available for high strength steel such as ASTM A992 steel at elevated temperature. Most of the reports related to elevated temperature have targeted to find out the mechanical properties of low carbon mild steel such as yield stress, tensile strength, elastic modulus and failure elongation using initial part of stress-strain curves. This study has been focused on developing the constitutive model of relatively high strength steel as A992 (F_y=50~65ksi) for application in structural fire engineering and thermal related structural analysis field.

Testing indicated that most mechanical properties of steel (elastic modulus, yield stress, proportional limit, and tensile strength) decrease dramatically with increasing temperature up to the highest temperature tested, 1,000℃[6]. The elongation was fairly constant at lower temperature, with a slight rise at 700℃ and then a sharp maximum at 800℃ before returning to lower values up to 1,000℃. This phenomenon at low carbon steel such as A992 is directly related to the combined region of ferrite (α-Fe) and austenite (γ-Fe) above the eutectoid at phase diagram[7]. The tensile strength dropped to two-thirds of its room temperature value by 500℃, to one-third by 600℃, and to a fifth by 700℃. Above 800℃, the tensile strength was less than 5% of its room temperature value. Fig. 1 proves the above mentions.

In general, the detailed model has perfectly matched from room temperature up to 1000°C because of using the best-fitting curve approach method for specific material. Otherwise EC 3[5] has relatively good agreement at ellipse part from proportional limit to maximum stress at 600°C shown in Fig.5(c). EC 3 model has considerably deviated with the measured stress-strain curves for all other temperatures and has over estimated the strength at 700~800°C after yielding. One of the most possible deviate reasons is a different type of steel because of the microstructure and metallurgy characteristic differences [7].

It is important to recognize the difficulty to build up a simple single equation from the constitutive model of structural steel at elevated temperatures because of metallurgical characteristics, microstructures, chemical compositions and size differences. Therefore, the OL4 project, a nuclear power plant expected to build in Finland, strongly wants to use their own material code based on their thermal testing experience. This might have a potential impact on our design practice, cost and schedule if KHNP signed up with this potential blind project.

4. Conclusions

This paper provides two constitutive models for high strength steel of ASTM A992 steel at elevated temperature to use in steel structures or steel building subjected to fire loads and thermal loads.

One is the detailed full constitutive model and it has good agreements for every temperatures from room temperature to 1,000°C with increments of 100°C because it was developed using a best-fitting approach method with separated special zones; elastic, plastic plateau, strain-hardening and strain-softening regions. The curve-fitting results were helpful to derive the constitutive models of the stress-strain curves at room and elevated temperatures.

The first of these models was developed for academia, and very closely fit the observed test data throughout the strain-hardening and softening zones. The second model was developed as a design model. Despite its simplicity (assumed bilinear stress-strain behavior), it captures the observed stress-strain behavior better than the Eurocode 3-1-2 provisions, most notably in terms of its predicted strain softening behavior and ultimate strains.

A margin of safety is incorporated into the design model for both stress and strain. It may useful to use these constitutive models in analysis and design the steel structure subjected to thermal loads on nuclear power plant.

REFERENCES

[1] ASTM E8, Standard Test Methods for Tension Tests of Metallic Materials, American Society for Testing and Materials, West Conshohocken, PA, 2010.

[2] ASTM E21, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials, American Society for Testing and Materials, West Conshohocken, PA, 2009.

[3] J. Lee, Elevated Temperature Properties of Steel for Structural Fire Engineering Analysis, Ph.D. Dissertation, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 2012.

[4] W. Luecke, A.W. Banovic, and J.D. McColskey, High-temperature Tensile Constitutive Data and Models for Structural Steels in Fire, Technical Report Note 1714, The National Institute of Standards and Technology, Nov. 2011.

[5] Eurocode (1993). Eurocode 3 - Design of Steel Structures Part 1-2: General rules - Structural Fire Design, CEN: 74.

[6] J. Lee, M. A. Morovat, G. Hu, M. D. Engelhardt, E. M. Taleff, Experimental Investigation of Mechanical Properties of ASTM A992 Steel at Elevated Temperatures, Engineering Journal, American Institute of Steel Construction, Vol.50, No.4, p.249-272, Fourth Quarter 2013, Oct. 1st 2013.

[7] W. D. Callister Jr., Material Science and Engineering (An Introduction), John Wiley & Sons. Inc., 7th Ed., p.290-298, 2007.