Structural Fire Engineering: Learning Module 1

Stress-Strain Curves at Elevated Temperatures

Supplemental Material

Overview

Evaluate the effects of temperature on the material properties of structural steel by analyzing stress-strain data.

Learning Objectives

- Determine the *Yield Stress* and calculate the *Young's Modulus* from a stress-strain curve of structural steel at elevated temperatures.
- Interpret and describe how the stress-strain curve of structural steel changes with increasing temperature. Specifically, how the shape and proportional limit change and how that relates back to the *Yield Stress* and *Young's Modulus*.
- Describe the two different testing methods used for tension coupons at elevated temperatures and explain how these two different testing methods impact the σ–ε results.
- Explain the importance of obtaining σ–ε data at elevated temperatures for structural fire engineering.

Students should already understand:

- How to determine the *Yield Stress* and calculate the *Young's Modulus* from stress-strain of structural steel at ambient temperatures obtained from data, measured through testing of tension coupons.
- The difference between engineering stress-strain curves and true stress-strain curves.

Additional Notes

Some materials-based classes are lab-based classes. If you would like to make this a lab-based class exercise, we recommend using the practice/homework problem as an in-class assignment.

Stress-Strain Curves at Elevated Temperatures

General Trends in Steel Properties with Increasing Temperature

As temperature increases:

- Young's Modulus, E, reduces
- Yield Stress, F_y, reduces
- Ultimate Stress, F_u, reduces (sometimes see increase in F_u at 200° to 300°C)
- Idealized bi-linear behavior at ambient temperature cannot be assumed above 300-400°C
- Initial portion of stress-strain curve becomes nonlinear at lower strain values (proportional limit reduces)
- Variability in properties increases

Testing Methodologies

Just as with ambient temperatures, at elevated temperatures there are standards referenced to provide uniformity between tests. ASTM E21 is the governing standard for testing tensile coupons at elevated temperature. This standard provides information with regards to rate of loading, size of the coupon, along with requirements for the testing apparatus (the furnace heating the coupon).

Transient testing

In a real building fire, structural members will be loaded prior to the fire starting. Therefore, large-scale fire experiments are typically conducted through transient testing, which means the structural system or members are loaded and then exposed to a fire scenario. However, there is no consensus on what loading levels to use or what fire scenario would represent all fire scenarios. Therefore, for the purpose of tension coupon testing, this method is not traditionally used.

Steady state testing

ASTM E21 testing methodology requires that a tension coupon is heated to a set temperature, and with the temperature remaining constant, the coupon is loaded to failure. This type of testing is called stead state testing. The results from these tests produce stress-strain curves and relationships at set temperatures that can be utilized for numerical simulations.

Calculating Material Properties

Figure 1 shows the stress-strain curve of A36 steel varying with temperature. While the plot shows that the mechanical properties of steel change with temperature, these curves also show that the shape of stress-strain relationship changes with temperature. This teaching module will review how to calculate material properties from stress-strain curves. At elevated temperatures there are different methodologies to do this. As the instructor, you have the options of reviewing these different methodologies or just introducing one of them.

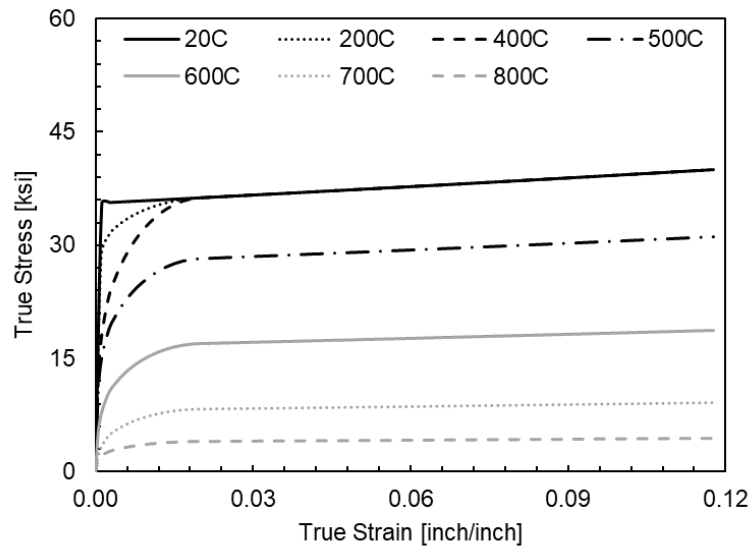


Figure 1: Calculated Stress-Strain curve of Structural Steel at Elevated Temperatures

Calculating Yield Stress

At ambient temperature, the *Yield Stress* is calculated by calculating the *Young's Modulus*, *E*, and drawing a line with the slope of *E* started at a strain of 0.2%. The intersection of the newly drawn line (shown in red in Figure 2) and the steel stress-strain curve is the *Yield Stress* (F_y). This process is shown in Figure 2, with the proportional limit as the transition on the curve from linear response to non-linear response. In addition, the strain associated with the *Yield Stress* is the *Yield Strain*. The region beyond the strain that is deemed the plastic region.

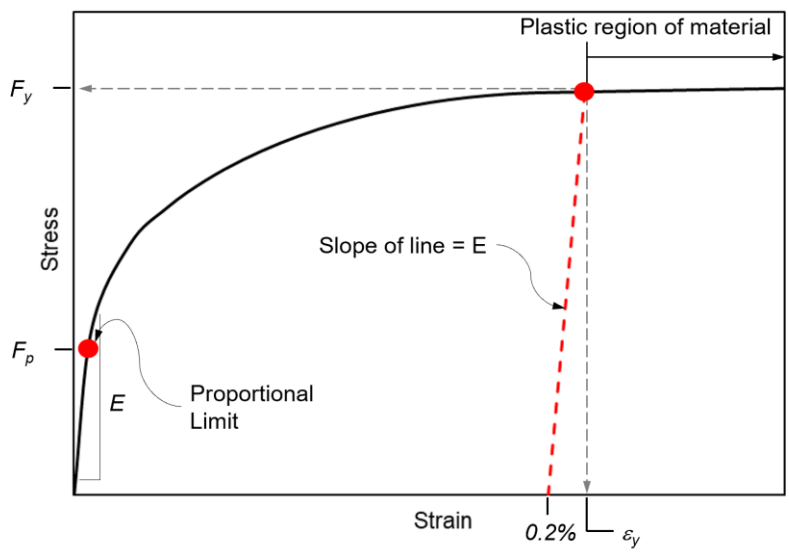


Figure 2: Calculating the *Yield Stress* from stress-strain curves

At elevated temperatures, there are a few methods of calculating the yield stress. ASTM E21 prescribes that the calculation of the yield stress at elevated temperatures is the same method

as at ambient temperature, at the 0.2% strain offset. However, Eurocode 3 and AISC *Specification* have both adopted using the 2% strain offset as the stress-strain curves at elevated temperatures (shown in Figure 1) are very nonlinear at lower strains. The purpose of this learning module is to introduce elevated temperatures to the students with regards to structural steel. Therefore, the PowerPoint slides do not show the different methods of calculating yield stress, and it is left up to the discretion of the instructor to bring up this topic.

Proportional limit

The proportional limit is the point on a stress-strain curve where the linear, elastic deformation region transitions into a non-linear, plastic deformation region. The transition point can be calculated by a specified percent change in slope. The proportional limit greatly influences the shape of the stress-strain curve as small strains. The elastic limit represents the greatest stress that can be applied to a material without causing permanent, or plastic, deformation, and this often occurs a greater strain than the proportional limit.

Material properties varying with temperatures

To quantify how the material properties (*Yield Stress, Young's Modulus, Proportional Limit*) are varying with temperature, the structural engineering community uses what is called a *retention factor*. As shown in Equation 1, the retention factor is the ratio of the value of a material property at an elevated temperature to the value of that material property at ambient temperature (20°C or 68°F).

$$Retention\ Factor = \frac{Value\ of\ a\ material\ property\ at\ elevated\ temperature}{Value\ of\ a\ material\ property\ at\ ambient\ temperature} \qquad \text{[Equation 1]}$$

The retention factors for *Yield Stress*, *Young's Modulus, and Proportional Limit* from the AISC *Specification* Appendix 4 are shown in Figure 3.

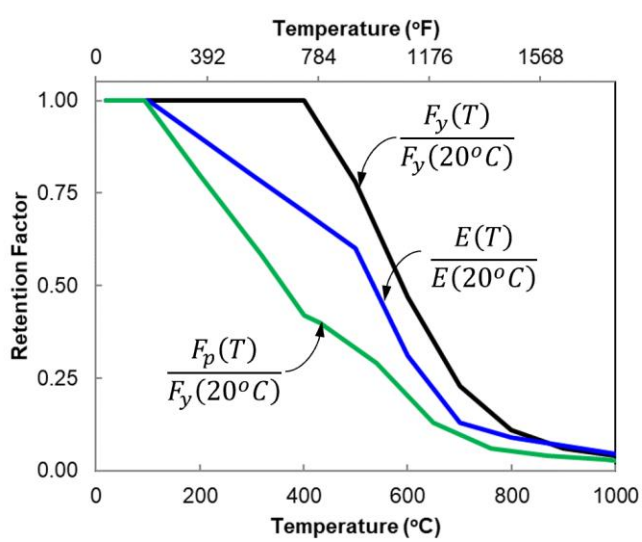


Figure 3: Retention factors for *Yield Stress* and *Young's Modulus* (data from AISC *Specification* Appendix 4)

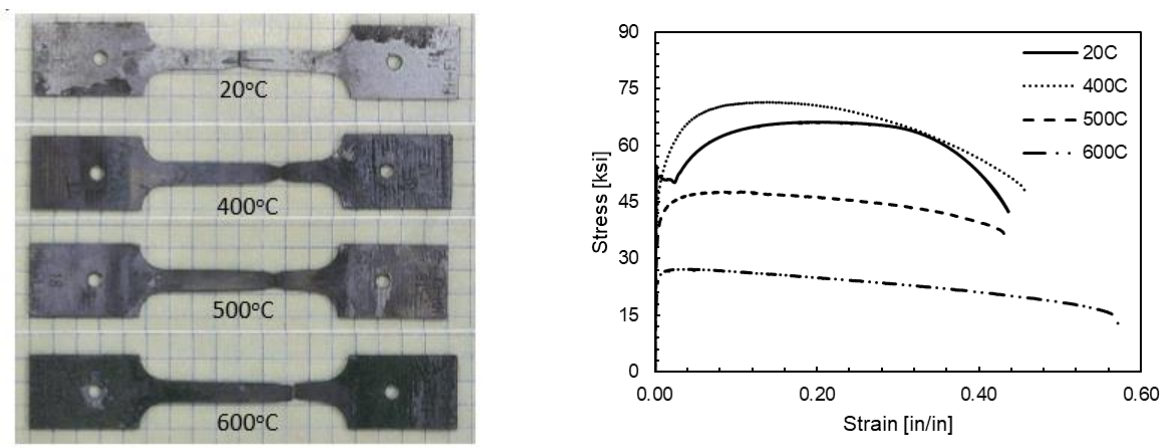
Figures 1 through 3 show that the material properties: (1) do not degrade with temperature in the same way, which leads to different retention factors for different material properties, and (2) do not degrade linearly.

- The proportional limit degrades faster with temperature than the *Yield Stress* or *Young's Modulus*: This means that the nonlinear portion of the stress-strain curve will occur at low temperatures. We see this in Figure 1 for the stress-strain curves at 20-200°C. The Young's Modulus and the Yield Stress are the same for these temperatures, but the rounded nonlinearity of the stress-strain curve at 200°C reflects the proportional limit.

- The *Young's Modulus* degrades faster with temperature than the *Yield Stress*: This behavior means that the slope of the elastic response is going to change faster at elevated temperatures than the yield stress. We see this in Figure 1 particularly in the stress-strain curves at 20 – 400°C, where the *Yield Stress* is not changing, but the slope of the elastic response is changing. We also see this as temperature continues to increase as the slope of the elastic response becomes smaller.

Failure of Steel Tensile Coupons at Elevated Temperatures

At elevated temperatures, the fracture strain of a steel tensile coupon differs with temperature. A picture of the tensile coupons tested at elevated temperatures can be seen in Figure 4. We can see from Figure 4b that the fracture strain (where the stress-strain curve stops) is not the same for all the specimens, and neither is the maximum measured stress.



(a) (b)

Figure 4: (a) Experimental coupons picture of the four specimens after the tensile test was conducted at 20°C, 400°C, 500°C, and 600°C (photo from Seif et. al., 2016) and (b) stress-strain curves of tested tensile coupons at 20°C, 400°C, 500°C, and 600°C

Additional Resources

AISC (2016), *Specification for Structural Steel Buildings* (Appendix 4), Standard ANSI/AISC 360-16, American Institute of Steel Construction, Inc., Chicago. IL. *(Available for free download at* aisc.org/Specification-for-Structural-Steel-Buildings-ANSIAISC-360-16-1*)*

ASTM E21-20 (2020), *Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials*, American Society for Testing and Materials, West Conshohocken, PA. (https://www.astm.org/Standards/E21)

Lee, J., Morovat, M.A., Hu, G., Engelhardt, M., and Taleff, E.M. (2020). "Experimental Investigation of Mechanical Properties of ASTM A992 Steel at Elevated Temperatures," *Engineering Journal*, American Institute of Steel Construction, Vol. 50, pp. 249-272. (*Available for free download for AISC Educator and Student Members at* aisc.org/Experimental-Investigation-of-Mechanical-Properties-of-ASTM-A992-Steel-at-Elevated-Temperatures)

Seif, M., et. al. (2016). *Temperature-Dependent Material Modeling for Structural Steels: Formulation and Application* (NIST Technical Note 1907). National Institute of Standards and Technology, Gaithersburg, MD. (*Available for download at:* nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1907.pdf)

"Stress-strain of steel at elevated temperatures" by Richard Walls, Stellenbosch University https://youtu.be/YCOjmybbGpI