UNIVERSITY PROGRAMS

Structural Fire Engineering: Learning Module 3

System-Level Behavior in a Fire

Supplemental Material

Overview

Evaluate the effects of a fire on a frame using the results of a finite element model of the fire behavior of a frame (in Abaqus) and a fire time-temperature curve or the steel time-temperature (*T-t*) response to a fire.

Learning Objectives

- Evaluate how different design fires impact the axial force demands in the beams and columns with varying compartment fires,
- Explain how system-level effects of a fire on a steel structure are different than individual member effects.

Students should already understand

- Temperature-dependent material properties of steel (Learning Module 1)
- Individual member behavior in fire (Learning Module 2a and 2b)

Lesson Plan

This lesson plan can be used for students with or without proficiency in finite element applications. However, students should have a basic understanding of finite element analysis.

If you would like to have students run the parametric fire mentioned in this learning module, the heat transfer results are provided in the spreadsheet (Parametric Fire-Heat Transfer Results.xlsx), along with the fire curve itself.

System-Level Behavior in a Fire

Restraint of heated column by cooler floors above and below

The cooler floors above and/or below a heated column can act as rotational restraints. These restraints decrease the temperature-dependent slenderness ratio. Typical gravity columns have pinned boundary conditions as shown in Figure 1a. These pinned boundary conditions allow for rotation at the column end as shown by the deformed column shape in Figure 1a. However, when considering a heated column with a cooler floor above and below, the rotation of the column ends is restrained by the cooler floors as shown in Figure 1b. This restraint will change the buckling shape of the column.

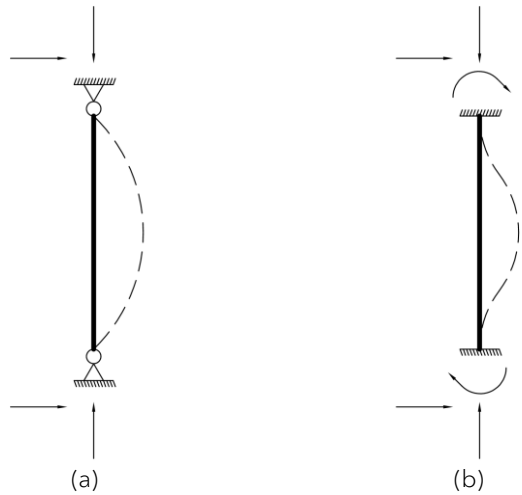

Figure 1: Deformed shape of a column (a) with pin-pin restraints and (b) with pin-pin restraints and cooler floors above and below the heated column

The dotted line depicts the deformed shape of the column, whereas the solid line is the undeformed shape. When the column has pin-pin restraints, the column ends are not restrained against rotation. When the column is heated, however, <u>and</u> has cooler floors above and below the heated column, the cooler floors prevent rotation at the ends of the column and act as rotational restraints making the column act as if it has fixed- fixed boundary conditions. This causes the deformation to start further away from the ends of the column. As the rest of this learning module will explain, the cooler floors can increase the nominal compression capacity compared to when the changing boundary conditions are not considered.

These cooler floors above and below are intended to be stories that do not have smoke infiltration or fires, thereby keeping these floors near ambient temperatures.

Compartment Fires

Two different compartment fires will be considered throughout this teaching module, shown in Figure 2. The first is the ASTM E119 fire (ASTM 2018) and the second is a fire developed from the parametric time-temperature curve in Eurocode (CEN 2002). The parametric fire curve was developed using the compartment properties in Table 1.

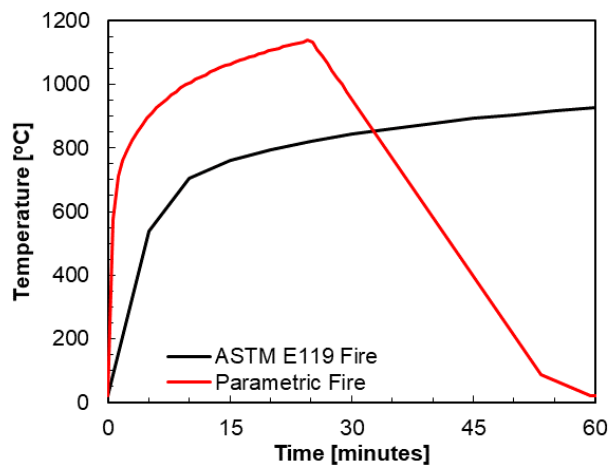

Figure 2: Compartment fires considered in analysis

Table 1: Properties of compartment for parametric time-temperature curve in Eurocode (CEN 2002)

Compartment Property	Value
Fire load density ($q_{t,d}$)	200 MJ/m^2
Material property of interior walls (b)	1166 J/m^{2}s$^{1/2}$K
Opening factor (F_v)	0.12 m$^{1/2}$

The heat transfer analysis was performed on the beam and columns for both compartment fires. Figure 3 shows that the beam is exposed to the compartment fire from three sides (every side except the top flange), and the column is exposed just on one side. Nodes 1-5 will reappear in the results of the heat transfer analysis that will be used as input into the structural analysis.

Figure 3: Heat transfer analysis with nodal designations for (a) beam and (b) column

Structural Fire Engineering Analysis Process

The analysis process for structural fire engineering consists of three steps, as shown in Figure 4.

1. Calculate or identify the compartment fires (Figure 2).
2. Perform a two-dimensional heat transfer analysis using the compartment fire and the thickness of fire protection on the members.
3. Use the nodal temperatures from the heat transfer analysis as temperature inputs in a structural analysis with temperature-dependent mechanical properties.

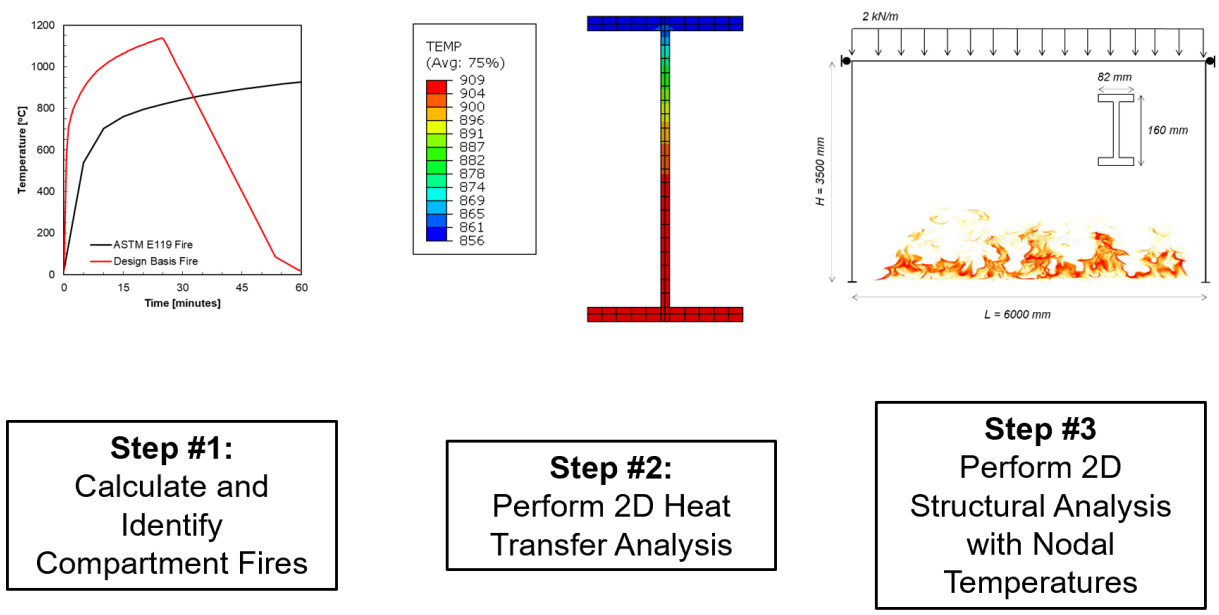

Figure 4: Analysis process for structural fire engineering

Heat Transfer Analysis of the Beam and Columns:

ASTM E119 Fire

The column and beam were subjected to the ASTM E119 fire, resulting in a thermal distribution through the beam and column shown in Figures 5a and 5b, respectively.

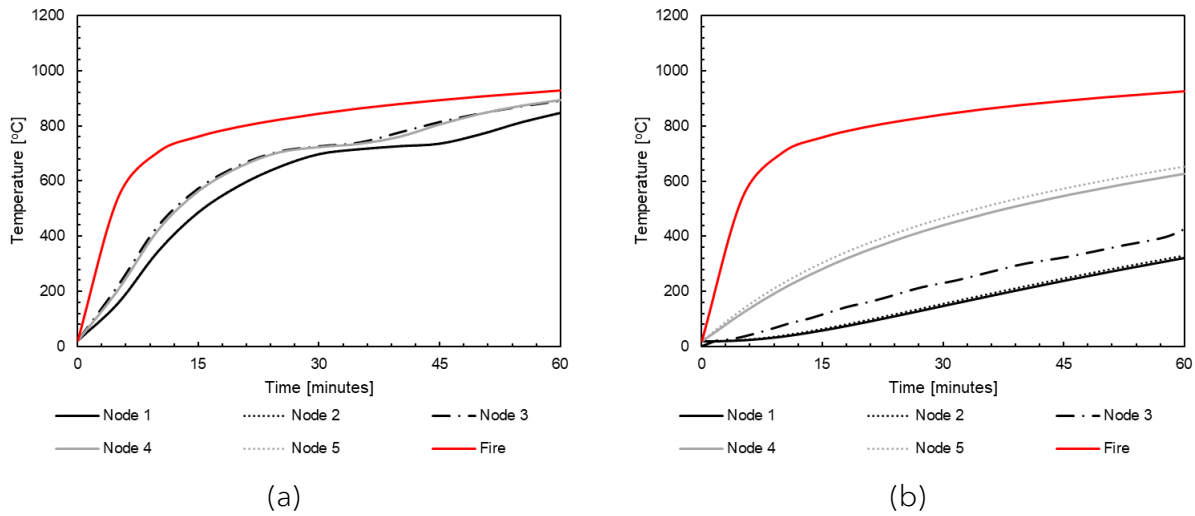

Figure 5: Thermal distribution through the cross section of (a) beam and (b) column when subjected to the ASTM E119 fire

The beam is exposed to the compartment fire from three sides (every side except the top flange), and the column is exposed from just one side, as shown in Figure 3. Node 5 is part of the flange fully exposed to the fire and Node 1 is part of the flange not fully exposed to the fire.

Figure 5a shows there is little thermal gradient through the cross section of the beam, and that the beam temperatures follow the general trend of the fire curve. We can see that there is a bit of a "bump" around 700°C for the steel temperatures due to the phase change of steel. In addition, we see that the temperature of the steel does not quite reach the temperature of the fire.

In contrast, Figure 5b shows there is a thermal gradient through the cross section of the column. We do not see a "bump" in the steel temperatures because they all remain under 700°C. The difference between the exposed flange and unexposed flange is 330°C after 1 hour of fire exposure. Like the beam temperatures, the column temperatures follow the trend of the fire.

Parametric Fire

The column and beam were subjected to the ASTM E119 fire, resulting in a thermal distribution through the beam and column as shown in Figures 6 and 6b, respectively.

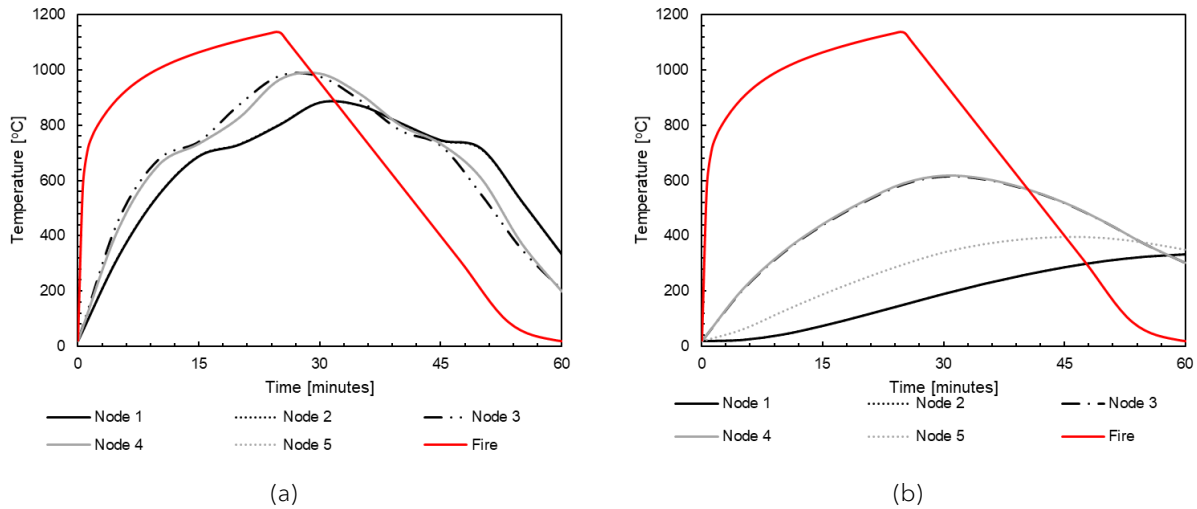

Figure 6: Thermal distribution through the cross section of (a) beam and (b) column when subjected to the parametric compartment fire

Figure 6a shows the resulting thermal distribution through the beam when the beam is exposed to the parametric compartment fire. Like the ASTM E119 heat transfer analysis, there is little differential between the bottom and top flange temperatures, as expected, because we are heating from three sides. We can see that there is a bit of a "bump" in steel temperatures around 700°C, during both the heating and the cooling portions, due to the phase change of steel. The beam temperatures also follow the trend of the fire. In addition, we see that the temperature of the steel does not quite reach the temperature of the fire in the heating portion. The gas temperatures increase and then decrease, and therefore, so do the temperatures of the steel. However, there is a delay in the temperature change of the gas and steel due to convective heat transfer.

Figure 6b shows the heat transfer analysis for the column exposed to the parametric fire from one side. There is a lot more differential between the two flanges of the column, as expected, because we are heating from one side. This follows the same trend as the ASTM E119 heat transfer analysis. We do not see a "bump" in the steel temperatures because they all remain under 700°C. We see a delay in the temperature change of the steel due to the trend of the gas temperature. We also see that the top flange continues to heat up even when the bottom flange is cooling down, resulting in a more uniform temperature distribution across the depth of the section at the end of 1 hour. The heat flow through the cross section does not stop because the gas temperature is decreasing. This is different from what we saw in the ASTM E119 heat transfer where we saw a large temperature distribution through the cross section at 1 hour.

Structural Analysis Results for the Frame: Beam Deflections

One method of measuring structural behavior is deflection. During a fire, there will be large beam deflections. This can be seen during both these compartment fires. Figures 7a and 7b show the beam deflections during the ASTM E119 and parametric fires, respectively.

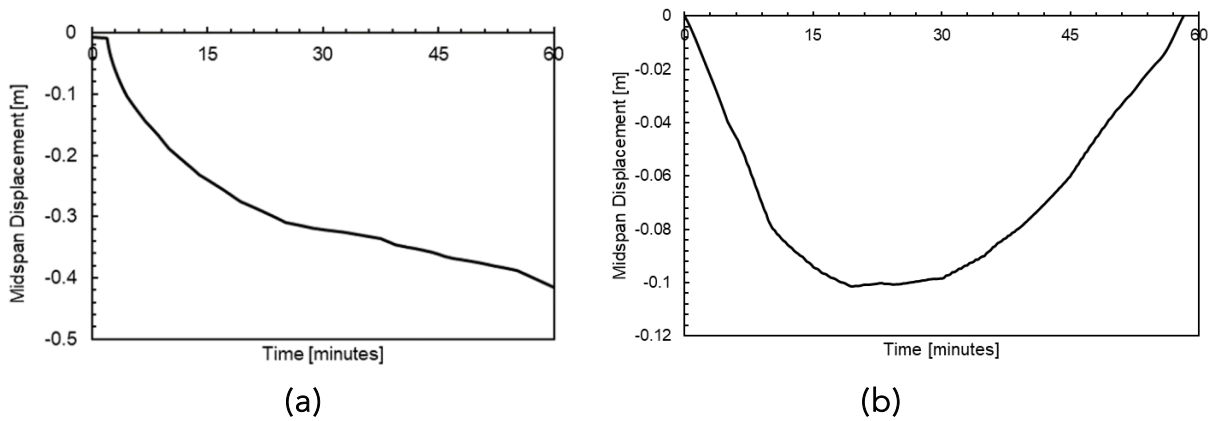

Figure 7: Midspan beam deflections during compartment fires (a) ASTM E119 and (b) parametric time-temperature fire

From the results of the ASTM E119 fire deflections (Figure 7a), we see that the deflections are continuously increasing, just as the fire curve was continuously increasing. The maximum beam bottom flange temperature is 893°C at 1 hour and this results in a displacement of 415 mm or 16 inches. This displacement is equal to the length of the beam divided by 14. To compare, the allowable dead load and live load deflection of a beam at ambient temperature is *L*/240 per the International Building Code (ICC 2018). We see with increasing time, there is increasing deflection, but the deflection is not linear.

From the results of the parametric fire (Figure 7b), we see that the deflection is significantly less and that it increases and decreases, recovering all the deflection and therefore behaving elastically. The maximum beam bottom flange temperature is about 986°C at 30 minutes, and this results in a displacement of 101 mm or 4 inches. This displacement is equal to the length of the beam divided by 50. To compare, the allowable dead load and live load deflection of a beam at ambient temperature is *L*/240 per the International Building Code (ICC 2018). We see that the displacement increases until about 20 minutes, and then begins to decrease.

Discussion Questions

Q1. Why is the midspan deflection of the beam subjected to the ASTM E119 fire not linear?

Answer:
The deflection is going to be dependent upon the stiffness of the beam (*E*), which changes as a function of temperature. Not only does this material property not change linearly as a function of temperature, but the temperature of the steel is not changing linearly with time (Figure 5a). Therefore, these two nonlinearities combine to result in nonlinear displacement. In addition, at this magnitude of deflection, there may be plastic behavior of the steel beam, which would cause additional nonlinear behavior.

Q2. How does the thermal distribution or gradient through the cross section of the steel beam influence the deflections shown in Figure 7b (parametric fire)?

Answer:
When the thermal gradient through the cross section begins to equalize, the beam will actually start deflecting upwards. Therefore, the increasing and decreasing temperature of the bottom flange contributes to the increasing and decreasing deflection in addition to the thermal gradient. Figure 8a shows a W-section at ambient temperature.

The geometric neutral axis is at the same location as the plastic neutral axis, in the middle. As the beam begins to heat up, each finite element of the beam section will have a different temperature (Figure 8b). Therefore, the plastic neutral axis and geometric neutral axis will not be the same. The plastic neutral axis will shift upward because the higher temperature steel has a lower stiffness and strength.

When the beam is heated such that there is a large thermal gradient through the cross section, the steel material at the bottom of the beam will soften and have less resistance to the tensile stress demands due to bending. This behavior will cause the beam to deflect just purely due to the heat.

During the cooling phase of the fire, the thermal gradient will begin to go away (Figure 8c). Heat transfer through the section will continue thereby heating the top portion of the beam; however, the gas temperature is decreasing, thereby decreasing the temperature of the bottom portion. The neutral axis will shift back towards the center of the beam and the beam will begin to deflect upwards towards the flange with the hotter temperatures (and thereby lower capacity to resist demands).

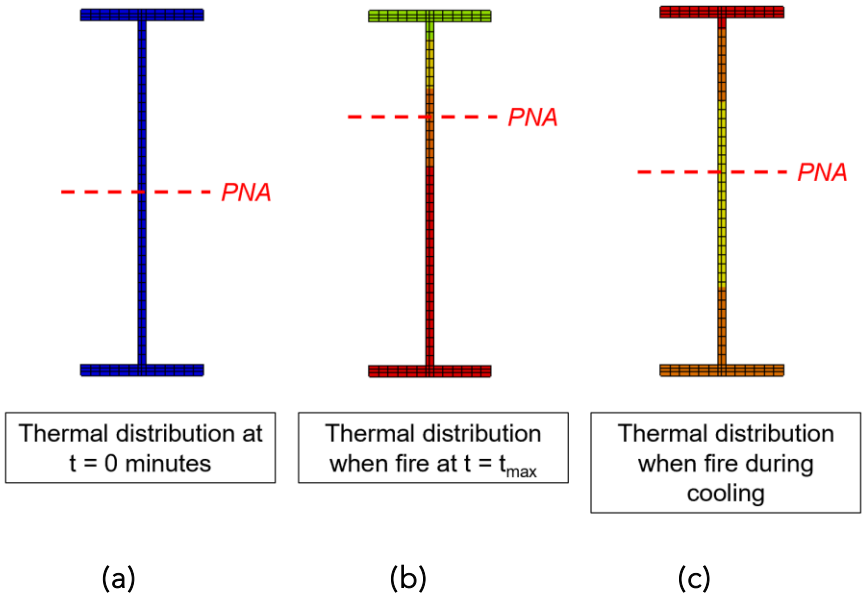

Figure 8: Changing location of plastic neutral axis (PNA) throughout a fire in a steel beam section (a) ambient temperature, (b) at maximum time of heating (t_{max}) of fire, and (c) during cooling

As the temperature-dependent material properties degrade with increasing temperature, the neutral axis will shift in the beam to accommodate for the unbalanced stiffness. The neutral axis will shift upwards as the bottom flange heats up and then shift downwards in the cross section as the top flange heats up and the bottom flange cools down. While there is not a large thermal gradient through this cross section, this thermal gradient can influence the structural behavior.

Structural Analysis Results for the Frame: Beam Forces

Note to instructor: This next portion of material can be presented as part of the teaching module or assigned for homework. Students can be given the finite element program output and asked the discussion questions.

As the frame heats up, the beam will want to expand; however, it cannot because in a real building the surrounding cooler structure is restraining the expansion. This is simulated with boundary conditions at the top nodes as shown here. This restraint will cause axial force in the beam.

At ambient temperature, we would expect no axial force in the beam due to this loading. However, during the fire we see axial force in the beam, and the force will vary throughout the fire. Figure 9 shows the axial forces that develop in the frame due to both fires.

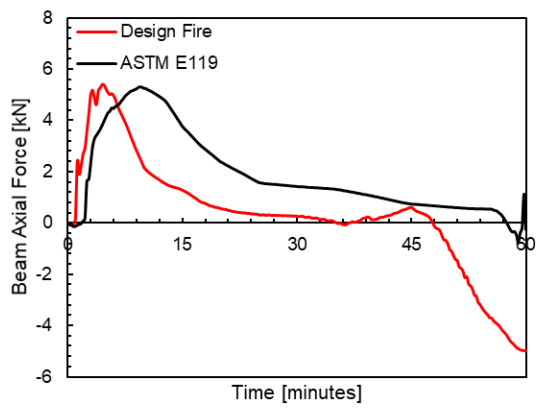

Figure 9: Axial forces in beam due to compartment fires

Discussion Question

Q3. How do these axial forces relate to the time-temperature fire curves?

Answer:

In the ASTM E119 fire, the fire is always increasing in temperature. Therefore, the beam should be expanding throughout the fire. The restraint from the building around it will therefore cause compression in the beam. We see this in the black line of the axial force plot where the axial force in the beam is always in compression.

For the design fire, we see that the beam is expanding (positive force means a compression reaction at the restraint and therefore compression in the beam) until about 30 minutes at which the reaction changes to demonstrate that the beam is contracting (negative force means a tension reaction at the restraint). This makes sense when following the fire curve. This follows the trend of the fire itself and the bottom flange temperatures of the beam.

The following homework question is about performance-based fire design. A description of performance-based design and a homework activity for the students can be found below.

References

ASTM E119-20 (2020), *Standard Test Methods for Fire Tests of Building Construction and Materials*, American Society for Testing and Materials, West Conshohocken, PA. (https://www.astm.org/Standards/E119.htm)

Buchanan, A.H. and Abu, A.K. (2017). *Structural Design for Fire Safety*, 2nd Ed., John Wiley & Sons.

CEN (2002). *Eurocode 1: Actions on structures*, Part 1-2: General actions - Actions on structures exposed to fire, European Committee For Standardization: Geneva, Switzerland.

ICC (2018). *International Building Code*, International Code Council: Falls Church, VA.