



# Performance-Based Design of Structural Steel for Fire Conditions

A CALCULATION METHODOLOGY

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# Performance-Based Design of Structural Steel for Fire Conditions

## A Calculation Methodology

Prepared by the  
Special Design Issues—Fire Protection Committee of the  
Structural Engineering Institute of the  
American Society of Civil Engineers

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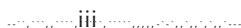
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# FOREWORD

Currently the designers of buildings in North America rely on the results of standard fire tests to ensure that building structures meet the fire resistance rating (FRR) requirements prescribed by national building codes. Under this approach there is generally no requirement to engineer a solution to the required structural fire safety of a building (i.e., a designer need merely demonstrate compliance with the solutions prescribed in the national building codes). In other areas of building design such as mechanical and structural, designers are permitted to rely on “good engineering practices.” With the development of performance-based building codes throughout North America, it is important that the design community has the tools necessary to take advantage of these new codes, which should enable the fire protection design of structural systems based on “good engineering practices.” In Europe, New Zealand, and Australia, performance-based requirements have been in place for several years. The benefit provided by these codes is to enable designers to create buildings that meet the implied safety standards of the historical prescriptive codes, which might otherwise prove to be a difficult task without a performance-based framework in place. Advanced research and development has resulted in the development of engineering tools that provide a real understanding of the structural response to fire. This allows a robust approach to designing structures to withstand fire.

In order to provide structural engineers with these tools, a method is being proposed here that will facilitate the design of structural steel for fire conditions using a performance-based approach. This approach is simplistic in nature and only considers a two-dimensional thermal response of structural steel to the fire. There are models available for the determination of the three-dimensional thermostructural response to fire that have been used in other areas of the world for many years. However, building designers and Authorities Having Jurisdiction in these areas

have had more time to become familiar with the use of performance-based designs. It is felt that the use of a method that predicts performance on the basis of limiting temperature alone will be conservative. Attempts to predict the likelihood of failure through more complicated mechanical interactions could produce more exact results but may complicate the process at this initial stage in the transformation to a performance-based regime in North America. In time, these matters may be incorporated into the framework of this approach as they become more accepted.

The mathematical models presented here are not new and some date back to the 1960s; however, they do offer a simple engineering approach to building structural fire safety. These approaches have been shown in the past to correlate well to experimental data. The method proposed here allows the designer to predict the time–temperature relationship expected in a compartment fire with a reasonable level of conservatism. Based on the compartment fire time–temperature relationship, the time for structural steel to reach the critical temperature can be calculated for comparison to the FRRs prescribed in the building codes. This, in turn, can be used to determine the required level of protection so that the time taken to reach the critical temperature is greater than the prescribed FRR. Also, a method is presented here that will allow the user to predict the expected maximum suspended ceiling temperature, to verify that the ceiling will remain intact for the duration of the fire. Finally, a method is presented here to calculate the required FRR for non-load-bearing partitions that form part of a fire-rated partition.

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Simpson Gumpertz & Heger

# CHAPTER 1

## DESIGN MANUAL

This chapter summarizes the calculation methodology proposed for the design of structural steel for fire conditions using a performance-based approach. It should be noted, however, that this chapter only summarizes the final equations to be used in a step-by-step manner. For a full derivation of the methodology, Chapters 2 through 7 and the appendices, which provide significant detail into the development of the methodology, should be reviewed. Nomenclature for all terms is at the end of this chapter.

### 1.1 SELECTION OF COMPARTMENTS OR AREAS TO DESIGN

For a proposed or existing building, the structural and fire protection engineers must collaborate to develop a list of possible locations where the start of a fire could lead to significant impact on the structural integrity of the building. To do this, the structural engineer must describe the structural system design approach to identify particular structural components that may be critical to the building's stability. At the same time the fire protection engineer must, with an understanding of the expected occupancy, determine the areas where fuel loads and the probability of flashover may be high.

It is unlikely that the area with the most critical structural nature will be the same as the area with the highest potential fire risk. Therefore, multiple compartments should be analyzed with a view to predict the range of fire scenarios that might reasonably be expected at any point throughout the building, thereby developing a range of possible structural fire scenarios. By doing this the designers can be assured that when the analysis is complete, the structural system has been adequately designed for probable and realistic fire scenarios.

1.2 DETERMINATION OF COMPARTMENT FUEL LOADS

Once various compartments within a proposed plan have been selected, the expected fuel load for each compartment has to be determined. This can be accomplished by estimating the mass of various fuel loads within the compartments using Table 1-1.

The totals in this table account for moveable fuel loads such as furniture and bookshelves; fixed fuel loads such as doors and window frames if combustible; and protected fuel loads such as wood framing in walls. For noncombustible construction the fuel load will likely be limited to the furnishings in the room. Care must be taken to separately account for the

TABLE 1-1. Estimating Compartment Fuel Load

| Description                                | Cellulosic (kg) | Petrochemical (kg) |
|--------------------------------------------|-----------------|--------------------|
| <b>Building Fuels</b>                      |                 |                    |
| <i>Structural Fuels</i>                    |                 |                    |
| Non-load-bearing                           |                 |                    |
| Interior finish and trim                   |                 |                    |
| <i>Service Fuels</i>                       |                 |                    |
| Stored fuel sources                        |                 |                    |
| Other                                      |                 |                    |
| <i>Nonstructural Fuels</i>                 |                 |                    |
| Non-load-bearing                           |                 |                    |
| Interior finish and trim                   |                 |                    |
| <b>Contents Fuels</b>                      |                 |                    |
| <i>Furnishings</i>                         |                 |                    |
| Furniture                                  |                 |                    |
| Decorations                                |                 |                    |
| Carpet                                     |                 |                    |
| Other                                      |                 |                    |
| <i>Occupant-Related Goods</i>              |                 |                    |
| Paper in filing cabinets                   |                 |                    |
| Other                                      |                 |                    |
| Subtotal (kg)                              |                 |                    |
| <b>Conversion to Wood (kg)<sup>a</sup></b> |                 |                    |
| Wood equivalent energy content             |                 |                    |
| (MJ) (based on 18.0 MJ/kg)                 |                 |                    |
| <b>Fuel Load (MJ)</b>                      |                 |                    |

<sup>a</sup>The mass of petrochemical-based materials is adjusted by a factor of 4.  
Source: Fitzgerald 1999.

fuel content of noncellulosic materials such as plastic containers, binders, etc.

Once the mass of the contents in the room is totaled, it is converted to an energy value based on 18 MJ/kg for cellulosic products, keeping in mind that the plastic-based materials are to be adjusted by a factor of 4 (Fitzgerald 1999) prior to adding the mass to the cellulosic-based materials to account for the higher heat energy content of these materials. This total fuel load is then divided by either the compartment floor area or total surface area to yield a per-unit area depending upon the inputs required for the model. Care should be taken to ensure the fuel load (MJ/m<sup>2</sup>) is calculated correctly for the model chosen.

The fuel load calculated in this table should be considered as an average fuel load to be expected for the occupancy. It is important to convert this average value to a more conservative value to be used for design purposes. Based on a normal statistical distribution, the average fuel load can be converted to a 90th-percentile value using the following equation:

$$L_{fd} = \frac{1.58}{A_f} \sum M_i H_{ui}$$

In this case,  $H_{ui} = 18 \text{ MJ/kg}$ .

The user may wish to use a factor of 2 instead of 1.58 to account for the expected peak values to provide a more conservative analysis.

### 1.3 PREDICTED COMPARTMENT FIRE TIME-TEMPERATURE RELATIONSHIP

In the early 1990s the Eurocodes proposed design equations for predicting the time-temperature relationship of structural steel exposed to fire conditions. They have been modified many times; for example, the European Convention for Constructional Steel (ECCS) Model Code on Fire Engineering (ECCS 2001) was prepared by ECCS—Technical Committee 3 to act as a follow-up to the Eurocodes. The ECCS document provided improvements to the approaches identified in the Eurocodes to reflect the improved understanding from research that has taken place since the introduction of the original Eurocodes.

Now, based on experimentation performed by A. H. Buchanan (Buchanan 2001), we are proposing that the ECCS 2001 equations be modified and used for the calculation methodology in this Manual (to be referenced herein as the Modified Eurocodes). The revised time-temperature equations are thus as follows:

$$T_t = 20 + 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*})$$

where

$$t^* = t \times \Gamma$$

$$\Gamma = \frac{(F_v/0.04)^2}{(b/1,900)^2}$$

$$F_v = A_h H_h^{1/2}$$

The decay rates are:

$$T_t = T_{\max} - 625(t^* - t_{\max}^* \cdot x) \text{ for } t_{\max}^* \leq 0.5$$

$$T_t = T_{\max} - 250(3 - t_{\max}^*)(t^* - t_{\max}^* \cdot x) \text{ for } 0.5 \leq t_{\max}^* \leq 2.0$$

$$T_t = T_{\max} - 250(t^* - t_{\max}^* \cdot x) \text{ for } t_{\max}^* \geq 2.0$$

using the following for the decay phase of the fire:

$$t^* = t \times \Gamma$$

$$\Gamma = \frac{\sqrt{(F_v/0.04)}}{\sqrt{(b/1900)}}$$

where  $\Gamma$  = is defined differently in the decay phase.

$$t_{\max}^* = (0.2 \times 10^{-3} \cdot (L_{t,d}/F_v)) \cdot \Gamma \text{ and}$$

$$x = 1.0 \text{ if } t_{\max} > t_{\lim}, \text{ or } x = t_{\lim} \cdot \Gamma / t_{\max}^* \text{ if } t_{\max} = t_{\lim}$$

where

$$t_{\lim} = 25 \text{ min for a slow-growth fire}$$

$$t_{\lim} = 20 \text{ min for a medium-growth fire}$$

$$t_{\lim} = 15 \text{ min for a fast-growth fire}$$

This model is applicable for the following conditions:

- Fire compartment floor areas are  $< 500 \text{ m}^2$  ( $5,380 \text{ ft}^2$ );
- Openings are only present in the vertical plane;
- Limited to fire compartments with mainly cellulosic-type fire loads (approximately 90%);
- Thermal inertia:  $400 \leq b \leq 2,000 \text{ J/m}^2\text{s}^{1/2}\text{K}$ ;
- Opening factor:  $0.02 \leq F_v \leq 0.2$ ; and
- The compartment boundaries are constructed of one material.

Before these equations can be used, the compartment geometry must be defined, including:

1. Compartment dimensions;
2. Thermal inertia of bounding surfaces; and
3. Fuel load defined in MJ/m<sup>2</sup> total surface area of the compartment, which is given by:

$$L_{td} = L_{fd} \times A_f / A_t$$

## 1.4 PREDICTED STEEL TIME-TEMPERATURE RELATIONSHIP

Within each compartment to be analyzed, various structural components will need to be selected to include any or all of the following:

1. Exposed structural steel, in the form of either beams, columns, or trusses; and
2. Protected structural steel, such as columns protected by bulkheads.

These models represent simple one-dimensional analyses of the impact of the fire on the steel temperature and assume a uniform temperature distribution throughout. This is, in fact, a conservative approach in that it does not account for the actual temperature gradient that will exist in the steel.

Although not specifically addressed by the proposed methodology, methods for determining the temperature rise of structural steel protected by a suspended ceiling and steel studs protected by a wall assembly are available. The reader should review the appropriate sections of Chapter 6 and the related references for more information. It should be pointed out that these methods are not as well defined or backed up by experimental data and should be used only as a tool to gauge order of magnitude impacts from fire exposure.

Depending upon the type of element selected for analysis, different equations would be used as follows:

*Unprotected Steel* (Buchanan 2001):

$$T_s = \frac{F_s}{V_s \rho_s c_{ps}} \{h_c(T_t - T_s) + \sigma \epsilon (T_t^4 - T_s^4)\} \Delta t (^{\circ}\text{C})$$

where

$\frac{F_s}{V_s}$  = the steel section ratio as determined by Fig. 6-2 in Chapter 6.

$\rho_s$  = steel density of 7,850 kg/m<sup>3</sup>

$h_c$  = heat transfer coefficient, usually taken as a value between 20 W/m<sup>2</sup> °C to 25 W/m<sup>2</sup> °C.  
 $c_{ps}$  = specific heat of steel, which is a function of temperature as follows:

For  $20 \leq T_s < 600$  °C,

$$c_{ps} = 425 + (0.733T_s - 1.69 \times 10^{-3} T_s^2 + 2.22 \times 10^{-6} T_s^3) \text{ (J/kg K)}.$$

For  $600 \text{ °C} \leq T_s < 735 \text{ °C}$ ,

$$c_{ps} = 666 + 13,002/(738 - T_s) \text{ (J/kg K)}.$$

For  $735 \text{ °C} \leq T_s < 900 \text{ °C}$ ,

$$c_{ps} = 545 + 17,820/(T_s - 731) \text{ (J/kg K)}.$$

For  $900 \text{ °C} \leq T_s \leq 1,200 \text{ °C}$ ,

$$c_{ps} = 650 \text{ (J/kg K)}.$$

$\epsilon$  = emissivity, determined as in Table 1-2.

Refer to Section 6.5.1 in Chapter 6 for a full explanation of the related terms.

*Protected Steel* (Buchanan 2001):

$$T_s = \frac{F_s}{V_s} \frac{k_i}{d_i \rho_s c_{ps}} \left\{ \rho_s c_s / \left( \rho_s c_s + \frac{F}{V} (d_i \rho_i c_i) \right) \right\} (T_i - T_s) \Delta t (\text{°C})$$

TABLE 1-2.

| Type of Construction                                                                                             | Resultant Emissivity |
|------------------------------------------------------------------------------------------------------------------|----------------------|
| Column exposed to fire on all sides                                                                              | 0.7                  |
| Column outside building façade                                                                                   | 0.3                  |
| Floor girder with floor slab of concrete, only the underside of the bottom flange being directly exposed to fire | 0.5                  |
| Floor girder with floor slab on the top flange                                                                   |                      |
| Girder of I section for which the width–depth ratio is not less than 0.5                                         | 0.5–0.7              |
| Box girder and lattice girder                                                                                    | 0.7                  |

where subscript  $i$  denotes the values for the protecting insulation, the thickness for which the designer should be able to obtain from the architectural drawings. Refer to Section 6.5.2 in Chapter 6 for a full explanation of the related terms.

The time-temperature history developed from these equations should be compared with the established critical temperature for the type of steel being assessed (see Table 1-3). This will enable the user to establish a pass/fail criterion and therefore the level of protection required (i.e., if the temperature of the steel reaches the critical temperature based on a fire scenario, then protection of the steel will be required). The effectiveness of the thickness to reduce the temperature of the steel can be calculated, thereby allowing the designer to specify the required thickness.

The designer should keep in mind that these temperatures vary with applied load and do not account for the load distribution that is typically built into a building's structural frame. Therefore, the above temperatures can be considered as conservative approximations of the time when the start of failure might be expected.

## 1.5 WORKED EXAMPLE

The following description will demonstrate how the calculation methodology is applied to a real building application.

### 1.5.1 Building Description

- Five-story justice center consisting of both private and general offices, file storage areas, court rooms, libraries, and meeting rooms, with a floor area of  $\sim 2,300 \text{ m}^2$  ( $24,750 \text{ ft}^2$ );
- Noncombustible construction, steel-framed building containing column and beam primary supporting steel and open web steel joist construction supporting a composite floor/ceiling assembly consisting of metal lath and 100-mm (4-inch) poured concrete;

TABLE 1-3. Critical Temperatures for Various Types of Steel

| Steel              | Standard/Reference                                                 | Temperature        |
|--------------------|--------------------------------------------------------------------|--------------------|
| Structural steel   | ASTM E-119                                                         | 538°C              |
| Reinforcing steel  | ASTM E-119                                                         | 593°C              |
| Prestressing steel | ASTM E-119                                                         | 426°C              |
| Light-gauge steel  | European Committee for<br>Standardization (1993)<br>Gerlich et al. | 350°C<br><br>400°C |



- Exterior wall construction consisting of spandrel panels and fixed glazing;
- Interior wall construction consisting of steel stud framing and 13-mm (0.5-inch) gypsum wall board (GWB) on either side of the studs;
- Exit stair and other shaft walls of 150-mm- (6-inch)-thick poured concrete;
- Combination of suspended ceiling and GWB ceiling throughout;
- Fully sprinklered complete with fire alarm system that shuts down the air handling system upon alarm initiation at the fire alarm panel; and
- Mixture of wood and metal furnishings throughout. There are limited quantities of plastic furniture.

Figures 1-1 through 1-5 show the plans for each floor of the building.

1.5.2 Existing Building Code Requirements

The building code requirements contained in the (IBC 2003) will be used in this example as applicable. These requirements are summarized in Table 1-4.

1.5.3 Description of Structural System

There is no portion of the structural assembly that dominates in terms of significance to overall building structural integrity. All columns and beams are designed to support loads as specified by the prescriptive code for maximum expected combination of live and dead loads. As a

TABLE 1-4. Summary of Prescriptive Fire Resistance Ratings (FRRs) for a 5-Story Commercial Building

| Building Element                  | IBC (2003 Edition)<br>Required FRR | Reference (Use Group B,<br>Type IIA Construction) |
|-----------------------------------|------------------------------------|---------------------------------------------------|
| Floor/ceiling assembly            | 1 hr                               | Table 601                                         |
| Load-bearing walls                | 1 hr                               | Table 601                                         |
| Supporting structural<br>elements | 1 hr                               | Table 601                                         |
| Exit and other shafts             | 2 hr                               | Sections 707.4 and 1019.1                         |
| Corridors                         | 0 hr                               | Table 1016.1                                      |

Source: International Code Council (2003).

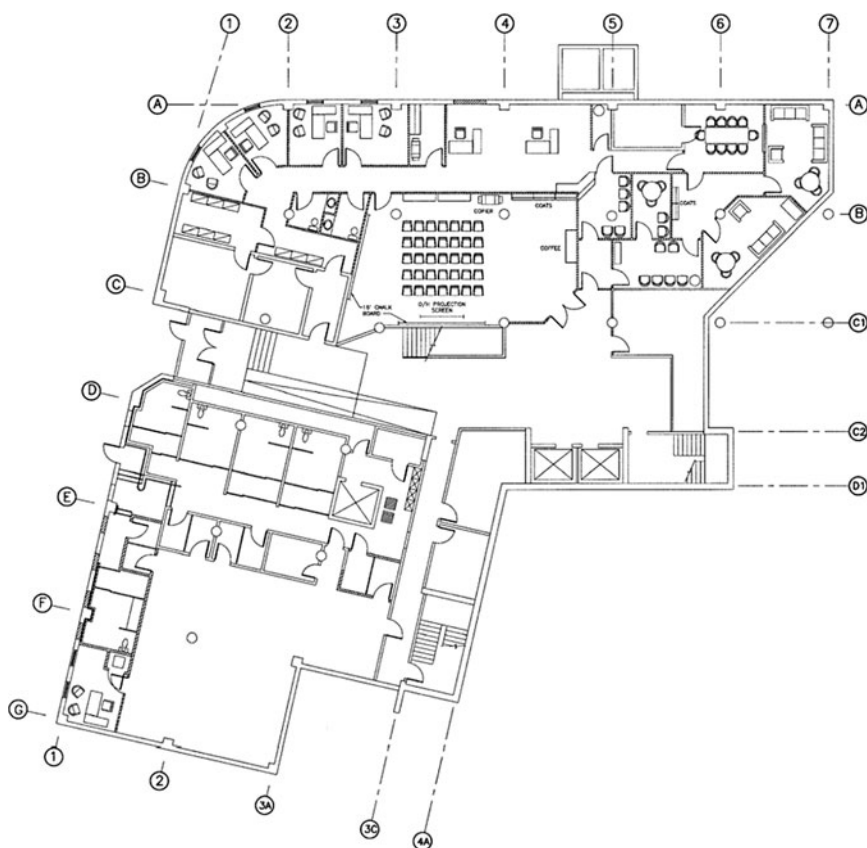


FIGURE 1-1. Work Example: Level 1 Floor Plan

result, the selection of the compartments to be analyzed is to be based on fuel load and geometry considerations that take into account the number of structural elements that may be present within a particular compartment.

### 1.5.4 Description of Compartments to be Analyzed

There are a large number of possible compartments from which to select. However, the intent is to select a number of compartments that reasonably represents the range of possible fire scenarios that might be expected within the building in order to determine the required fire resistance ratings (FRRs). Initially, this may pose to the designer some concern with the potential number of compartments to analyze. However,

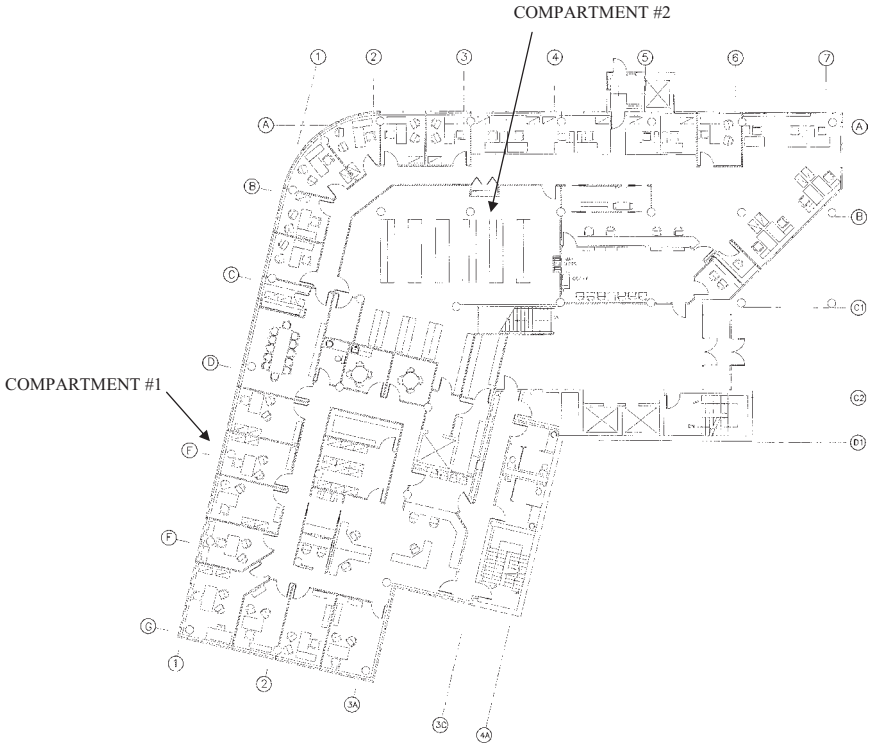


FIGURE 1-2. Work Example: Level 2 Floor Plan

with experience the designer will become better equipped to select an appropriate range of compartments, such as those containing the greatest number of columns.

**1.5.4.1 Compartment 1.** Typical private office as indicated on Fig. 1-2, consisting of:

- One wooden desk;
- Three fabric-covered upholstered chairs;
- Two wooden book/file storage units that have an open front;

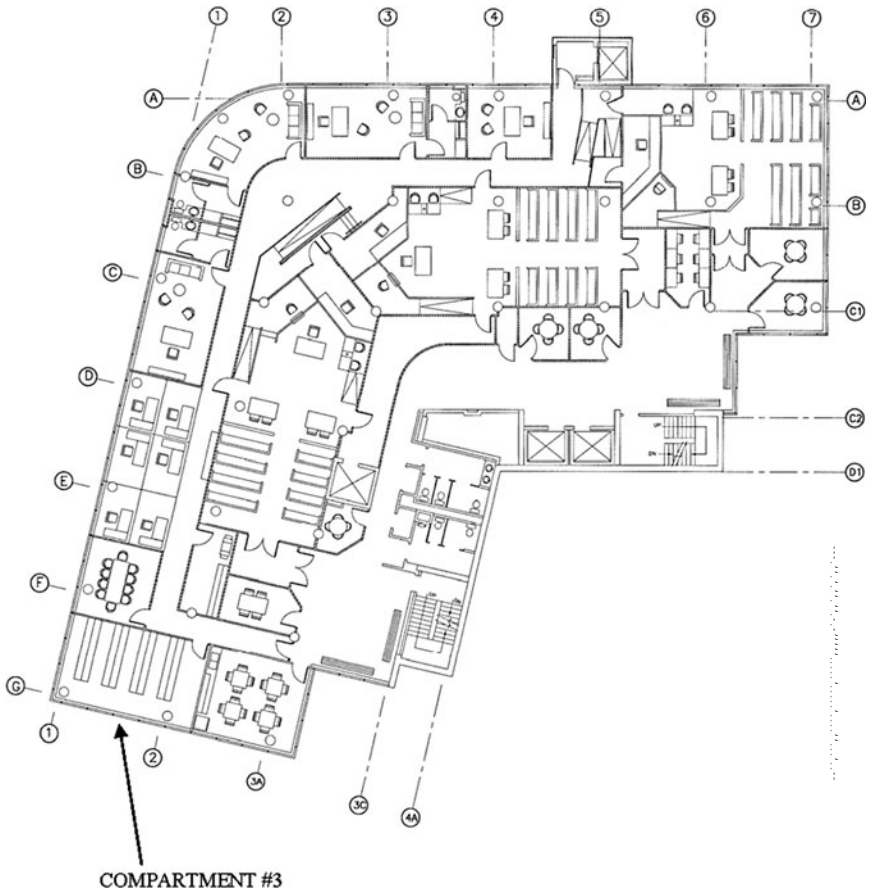


FIGURE 1-3. Work Example: Level 3 Floor Plan

- Miscellaneous plastic storage vessels such as wastebaskets, desktop file holders, etc.; and
- GWB steel stud walls and suspended acoustic tile ceiling.

**1.5.4.2 Compartment 2.** Large file storage area as indicated on Fig. 1-2 used for archived file storage, consisting of:

- Nine rows of back-to-back metal shelving units used for storage of paper files in bankers boxes, complete with lids; and
- GWB steel stud walls and suspended GWB ceiling.

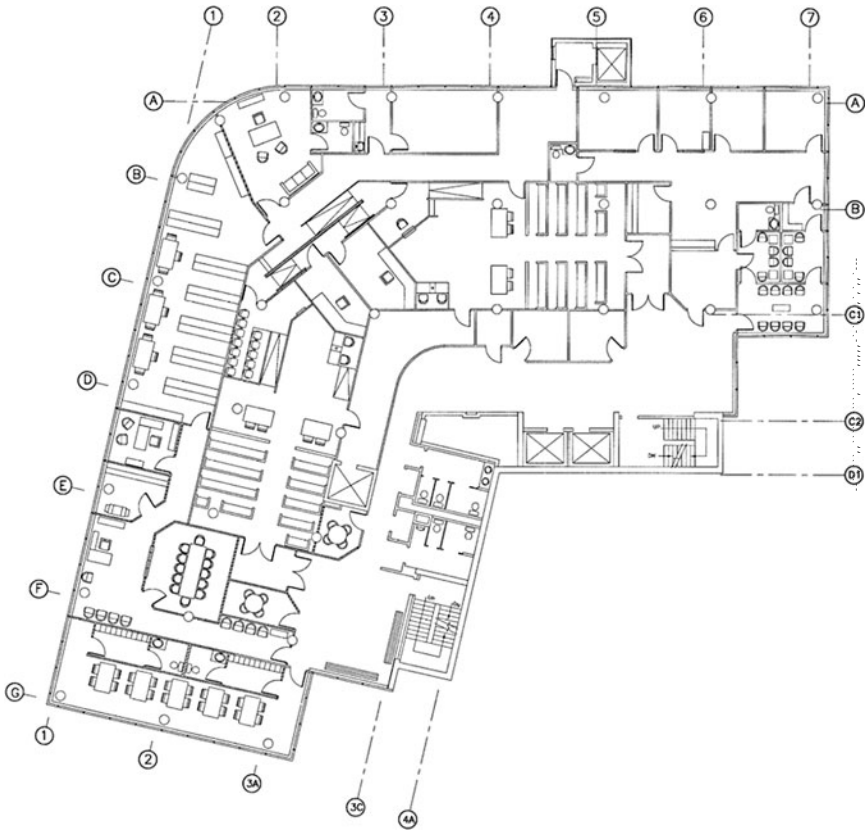


FIGURE 1-4. Work Example: Level 4 Floor Plan

**1.5.4.4 Compartment 3.** Small file storage area as indicated on Fig. 1-3 used for active file storage, consisting of:

- Four rows of back-to-back metal shelving units used for storage of paper files in bankers boxes, complete with lids; and
- GWB steel stud walls and suspended GWB ceiling.

**1.5.4.3 Compartment 4.** Small conference room as indicated on Fig. 1-5, consisting of:

- One large wooden conference table and 12 upholstered metal chairs; and
- GWB steel stud walls and suspended acoustic tile ceiling.

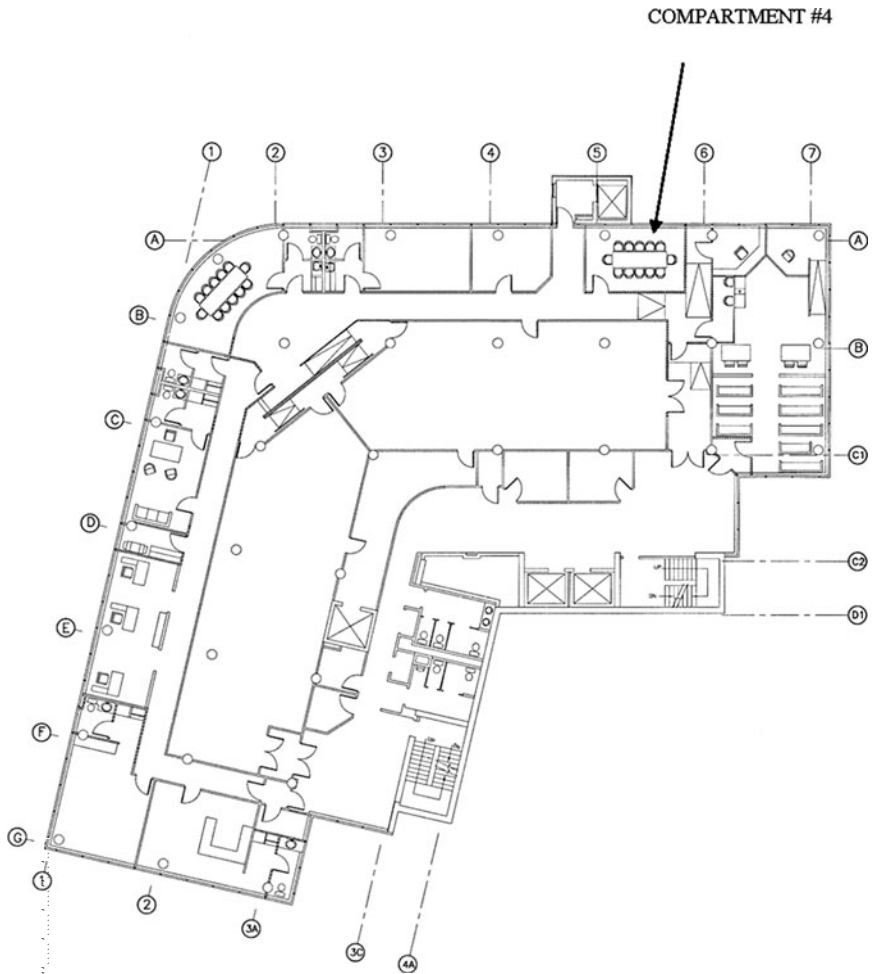


FIGURE 1-5. Work Example: Level 5 Floor Plan

A summary of the above information is provided in Table 1-5.

### 1.5.5 Fuel Load of Compartments to be Analyzed

Using Table 1-1, estimates of the compartment fuel loads are calculated and summarized in Table 1-6. The fuel loads in this table are representative of the existing conditions and should only be taken as average values. To use these values for design purposes, the 90% fractile should be used. For further explanation of the development of the 90% fractile value, refer to

TABLE 1-5. Summary of Geometric Variables for Compartments 1 through 4 of the Worked Example

| Variable                                  | Compartment |       |       |      |
|-------------------------------------------|-------------|-------|-------|------|
|                                           | 1           | 2     | 3     | 4    |
| Room width (m)                            | 3           | 12.2  | 8.3   | 5.5  |
| Room length (m)                           | 4.9         | 9.8   | 4.9   | 3.7  |
| Room height (m)                           | 2.8         | 3     | 3     | 2.7  |
| Room floor area (m <sup>2</sup> )         | 14.7        | 119.6 | 40.7  | 20.4 |
| Room total surface area (m <sup>2</sup> ) | 73.6        | 371.2 | 160.6 | 90.5 |
| Vent height (m)                           | 2.1         | 2.1   | 2.1   | 2.1  |
| Vent width (m)                            | 0.9         | 0.9   | 0.9   | 0.9  |
| Vent area (m <sup>2</sup> )               | 1.9         | 5.7   | 1.9   | 1.9  |
| Number of ventilation openings            | 1           | 3     | 1     | 1    |

Appendix B (CIB W14 Workshop 1986). Table 1-7 summarizes the fuel load per unit floor and surface area for the fuel load data summarized in Table 1-6 and compares this data to design values suggested (CIB W14 Workshop 1986) in Appendix B.

To be conservative, the referenced fuel load data will be used for the calculations after conversion to a value per total compartment surface area value.

### 1.5.6 Impact of Fire on Structural Columns

With reference to Figs. 1-1 through 1-5, there are protected columns within each compartment, as indicated by the small circles shown on the floor plans. For the purposes of the example, the following will be assumed:

- The columns are W310 × 33 sections assuming fire exposure on all four sides of the column;
- The thermal inertia of the bounding surfaces for the compartment will be assumed to be 1,100 W/m °C for a combination of lightweight concrete construction;
- The density of steel will be 7,850 kg/m<sup>3</sup>; and
- The critical steel temperature will be 538 °C.

Using the geometric information from Table 1-5, the referenced compartment fuel load from Table 1-7 is adjusted to a per-unit total surface area value. The above information, the compartment time–temperature

TABLE 1-6. Summary of Compartments 1 through 4 Fuel Loads

| Fuel                                                    | Compartment 1   |                 | Compartment 2   |              | Compartment 3   |              | Compartment 4   |                 |
|---------------------------------------------------------|-----------------|-----------------|-----------------|--------------|-----------------|--------------|-----------------|-----------------|
|                                                         | Cellulosic (kg) | Plastic (kg)    | Cellulosic (kg) | Plastic (kg) | Cellulosic (kg) | Plastic (kg) | Cellulosic (kg) | Plastic (kg)    |
| <i>Structural</i>                                       | —               | —               | —               | —            | —               | —            | —               | —               |
| <i>Service</i>                                          | —               | —               | —               | —            | —               | —            | —               | —               |
| <i>Nonstructural</i>                                    |                 |                 |                 |              |                 |              |                 |                 |
| Non-load-bearing                                        | —               | —               | —               | —            | —               | —            | —               | —               |
| Finish and trim                                         | —               | —               | —               | —            | —               | —            | —               | —               |
| <i>Furnishings</i>                                      |                 |                 |                 |              |                 |              |                 |                 |
| Furniture                                               | 300             | 30 <sup>a</sup> | —               | —            | —               | —            | 363             | 36 <sup>a</sup> |
| Decorations                                             | 12              | 2               | —               | —            | —               | —            | 12              | 2               |
| Other                                                   | —               | —               | 3,636           | —            | 1,818           | —            | —               | —               |
| <i>Occupant goods</i>                                   | 25              | 10              | —               | —            | —               | —            | —               | —               |
| Subtotal (kg)                                           | 337             | 42              | 3,636           | —            | 1,818           | —            | 375             | 38              |
| Conversion to wood (kg) (factor of 4 for plastic)       | 337             | 168             | 3,636           | —            | 1,818           | —            | 375             | 152             |
| Wood equivalent energy content (MJ) (based on 18 MJ/kg) | 6,066           | 3,024           | 65,454          | —            | 32,727          | —            | 6,750           | 2,736           |
| <b>Fuel Load (MJ)</b>                                   | 9,090           |                 | 65,454          |              | 32,727          |              | 9,486           |                 |

<sup>a</sup>Assumed that plastics make up 10% of the weight of the furniture.

TABLE 1-7. Compartment Fuel Load per Unit Area (MJ/m<sup>2</sup>)

|                                                     | Compartment        |                    |                    |                    |
|-----------------------------------------------------|--------------------|--------------------|--------------------|--------------------|
|                                                     | 1                  | 2                  | 3                  | 4                  |
| Fuel load (MJ)                                      | 9,090              | 65,454             | 32,727             | 9,486              |
| Fuel load/floor area (MJ/m <sup>2</sup> )           | 618                | 547                | 804                | 465                |
| Fuel load/total surface area (MJ/m <sup>2</sup> )   | 123                | 176                | 204                | 104                |
| Reference fuel load/floor area (MJ/m <sup>2</sup> ) | 1,264 <sup>a</sup> | 3,160 <sup>b</sup> | 3,160 <sup>b</sup> | 1,240 <sup>c</sup> |

<sup>a</sup>Taken from Table B-12 for Business Office and adjusted by a factor of 1.58.  
<sup>b</sup>Taken from Table B-12 for Libraries and adjusted by a factor of 1.58.  
<sup>c</sup>Taken from Table B-6 for U.S. Government for Conference Rooms and adjusted by a factor of 1.58.

curves using the Modified Eurocode equations, and the related steel time–temperature curve equations for insulated steel were used to determine the required protection to maintain the steel temperature below 538 °C for the prescribed FRR from Table 1-4. Table 1-8 summarizes the calculated protection required to achieve a 1-hour FRR compared with the prescribed protection required in the IBC (i.e., the protection required to ensure that the steel temperature is not increased to a value above the critical temperature before 60 min from the start of the fire). Table 1-9 summarizes the protection level that will be required to ensure that the critical temperature of the steel is not exceeded.

The results of Table 1-8 predict protection levels that are essentially equivalent to those prescribed by the IBC. However, to achieve a protection level that will ensure that the critical temperature of the steel is not exceeded requires more protection than that prescribed by the IBC. At first glance it may appear that nothing has been gained from undertaking this analysis, in that a reduction in required FRRs has not been achieved. However, this analysis has enhanced the performance of the structural integrity of the building by demonstrating that the required protection is actually greater than that which would normally be required under the prescriptive codes. Notwithstanding this fact, the methodology has provided a means to rationally determine FRRs based on a real fire scenario and does not take into consideration the thermomechanical properties of the steel exposed to fire, thus leading to conservative results.

TABLE 1-8. Summary of Steel Column Protection Requirements, Calculated vs. Prescribed

| Description of Protection       | Thickness of Protection Required |               |               |               | Requirements for<br>1 hr FRR (IBC 2003) |
|---------------------------------|----------------------------------|---------------|---------------|---------------|-----------------------------------------|
|                                 | Compartment 1                    | Compartment 2 | Compartment 3 | Compartment 4 |                                         |
| Mineral wool slabs <sup>a</sup> | 50 mm                            | 44 mm         | 38 mm         | 50 mm         | — <sup>b</sup>                          |
| 12.7 mm gypsum                  | 3 layers                         | 2 layers      | 2 layers      | 3 layers      | 2 layers <sup>c</sup>                   |
| Concrete                        | 25 mm                            | 25 mm         | 13 mm         | 25 mm         | 25 mm <sup>c</sup>                      |

<sup>a</sup>Mineral wool slabs would be required to be protected by some form of barrier such as metal cladding or GWB, which has not been accounted for in the calculations.

<sup>b</sup>Data not available in IBC (2003).

<sup>c</sup>IBC (2003) Table 720.1(1).

TABLE 1-9. Summary of Steel Column Protection Requirements, Calculated vs. Prescribed to Ensure the Critical Temperature Is Not Exceeded

| Description of Protection       | Thickness of Protection Required |                |                |               | Requirements for<br>1 hr FRR (IBC 2003) |
|---------------------------------|----------------------------------|----------------|----------------|---------------|-----------------------------------------|
|                                 | Compartment 1                    | Compartment 2  | Compartment 3  | Compartment 4 |                                         |
| Mineral wool slabs <sup>a</sup> | 75 mm                            | — <sup>b</sup> | — <sup>b</sup> | 100 mm        | — <sup>c</sup>                          |
| 12.7 mm gypsum                  | 4 layers                         | — <sup>b</sup> | — <sup>b</sup> | 5 layers      | 2 layers <sup>d</sup>                   |
| Concrete                        | 32 mm                            | — <sup>b</sup> | — <sup>b</sup> | 38 mm         | 25 mm <sup>d</sup>                      |

<sup>a</sup>Mineral wool slabs would be required to be protected by some form of barrier such as metal cladding or gypsum, which has not been accounted for in the calculations.

<sup>b</sup>Could not provide a practical level of protection that would ensure the critical temperature of 538 °C was not exceeded.

<sup>c</sup>Data not available in IBC (2003).

<sup>d</sup>IBC (2003) Table 720.1(1).

## Nomenclature

| Alphabetic<br>Symbols | Description                                                                                                                                                     | Units                                       |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|
| $A_i$                 | Internal surface area per unit length of insulation                                                                                                             | $\text{m}^2/\text{m}$                       |
| $A_f$                 | Compartment floor area                                                                                                                                          | $\text{m}^2$                                |
| $A_h$                 | Area of horizontal compartment vent openings                                                                                                                    | $\text{m}^2$                                |
| $A_t$                 | Area of total surface area of compartment                                                                                                                       | $\text{m}^2$                                |
| $A_v$                 | Area of vertical compartment vent openings                                                                                                                      | $\text{m}^2$                                |
| $A_{vi}$              | Area of compartment vent opening $i$                                                                                                                            | $\text{m}^2$                                |
| $A_w$                 | Compartment width                                                                                                                                               | $\text{m}$                                  |
| $b$                   | $\sqrt{k\rho c}$ thermal inertia                                                                                                                                | $\text{J}/\text{m}^2\text{s}^{1/2}\text{K}$ |
| $c_{ps}$              | Specific heat of steel                                                                                                                                          | $\text{J}/\text{kg}^\circ\text{C}$          |
| $c_p$                 | Specific heat                                                                                                                                                   | $\text{J}/\text{kg}^\circ\text{C}$          |
| $C$                   | Constant based on whether a light or heavy building construction material has been used for the compartment boundaries:<br>$C = 0$ for heavy; $C = 1$ for light | —                                           |
| $d_i$                 | Thickness of insulating material                                                                                                                                | $\text{m}$                                  |
| $F_d$                 | Factor for the distribution characteristics of the fuel loads                                                                                                   | —                                           |
| $F_s$                 | Surface area of steel exposed to the fire per unit length                                                                                                       | $\text{m}^2/\text{m}$                       |
| $F_v$                 | Ventilation factor                                                                                                                                              | $\text{m}^{1/2}$                            |
| $g$                   | Gravitational constant                                                                                                                                          | $\text{m}/\text{s}^2$                       |
| $h_c$                 | Convective heat transfer coefficient                                                                                                                            | $\text{W}/\text{m}^2\text{K}$               |
| $h_c''$               | Combustion enthalpy                                                                                                                                             | $\text{kcal}/\text{kg}$                     |
| $H'$                  | Normalized heat load for a real fire                                                                                                                            | $\text{s}^{1/2}\text{K}$                    |
| $H''$                 | Normalized heat load for the standard fire test                                                                                                                 | $\text{s}^{1/2}\text{K}$                    |
| $H_A$                 | Total area of all compartment openings                                                                                                                          | $\text{m}^2$                                |
| $H_c$                 | Height of compartment                                                                                                                                           | $\text{m}$                                  |
| $H_H$                 | Calculated mean opening height for all compartment openings                                                                                                     | $\text{m}$                                  |
| $H_i$                 | Height of compartment vent $i$                                                                                                                                  | $\text{m}$                                  |
| $H_v$                 | Compartment vent height                                                                                                                                         | $\text{m}$                                  |
| $H_{ui}$              | Lower calorific value of the combustible material                                                                                                               | $\text{MJ}/\text{kg}$                       |
| $H_w$                 | Compartment vent width                                                                                                                                          | $\text{m}$                                  |
| $k$                   | Thermal conductivity                                                                                                                                            | $\text{W}/\text{mK}$                        |



Nomenclature *Continued*

| Alphabetic<br>Symbols | Description                                                                                             | Units             |
|-----------------------|---------------------------------------------------------------------------------------------------------|-------------------|
| $k_b$                 | Factor applied to account for the insulation properties of the compartment enclosure                    | —                 |
| $k_i$                 | Thermal conductivity of thickness being analyzed                                                        | W/mK              |
| $k_{fs}$              | Thermal conductivity of the floor slab                                                                  | W/mK              |
| $K_d$                 | Factor applied to the mean fuel load to obtain the 80th or 90th percentile values to be used for design | —                 |
| $L$                   | Mass of fuel load per unit floor area                                                                   | kg/m <sup>2</sup> |
| $L_{fk}$              | Average calorific fuel load per unit floor area                                                         | MJ/m <sup>2</sup> |
| $L_{tk}$              | Average calorific fuel load per unit total surface area                                                 | MJ/m <sup>2</sup> |
| $L_{fd}$              | Design calorific fuel load per unit floor area                                                          | MJ/m <sup>2</sup> |
| $L_{td}$              | Design calorific fuel load per unit total surface area                                                  | MJ/m <sup>2</sup> |
| $\dot{m}$             | Burning rate                                                                                            | kg/hr             |
| $\dot{m}_{air}$       | Mass flow rate of air into the compartment                                                              | kg/hr             |
| $\dot{m}_f$           | Mass flow rate of hot gases                                                                             | kg/hr             |
| $\dot{m}_p$           | Mass flow rate of combustion gases                                                                      | kg/hr             |
| $m_i$                 | Combustion factor                                                                                       | —                 |
| $M_i$                 | Mass of product of combustion $i$                                                                       | kg                |
| $q$                   | Heat per unit length                                                                                    | J/m               |
| $q''$                 | Heat flux                                                                                               | W/m <sup>2</sup>  |
| $q''_c$               | Convective heat flux                                                                                    | W/m <sup>2</sup>  |
| $q''_r$               | Radiative heat flux                                                                                     | W/m <sup>2</sup>  |
| $\dot{q}_C$           | Rate of heat release due to combustion                                                                  | W                 |
| $\dot{q}_L$           | Rate of convective heat loss due to outflow of hot gases                                                | W                 |
| $\dot{q}_W$           | Rate of heat loss through compartment boundaries                                                        | W                 |
| $\dot{q}_R$           | Rate of heat loss by radiation through compartment openings                                             | W                 |
| $\dot{q}_B$           | Rate of heat storage in the gas volume                                                                  | W                 |
| $t$                   | Time                                                                                                    | hr                |
| $t_e$                 | Equivalent time for identical fire severity as standard fire test                                       | hr                |
| $\Delta t$            | Time step                                                                                               | hr                |
| $T_0$                 | Ambient temperature                                                                                     | °C                |

Nomenclature *Continued*

| Alphabetic Symbols | Description                                                     | Units                 |
|--------------------|-----------------------------------------------------------------|-----------------------|
| $T_1$              | Temperature as a function of combustion gas temperature $T_t$   | $^{\circ}\text{C}$    |
| $T_{co}$           | Temperature of the plenum side of the floor slab                | $^{\circ}\text{C}$    |
| $T_{ci}$           | Temperature of the plenum side of the suspended ceiling         | $^{\circ}\text{C}$    |
| $T_{fs}$           | Temperature of the floor slab                                   | $^{\circ}\text{C}$    |
| $T_{fi}$           | Temperature of the middle of the lowest strip of the floor slab | $^{\circ}\text{C}$    |
| $T_i$              | Temperature of internal surface $i$                             | $^{\circ}\text{C}$    |
| $T_{\max}$         | Maximum compartment temperature                                 | $^{\circ}\text{C}$    |
| $T_t$              | Compartment temperature at time $t$                             | $^{\circ}\text{C}$    |
| $T_s$              | Steel temperature at time $t$                                   | $^{\circ}\text{C}$    |
| $T_{\tau}$         | Temperature at time $\tau$ (start of compartment fire decay)    | hr                    |
| $T_w$              | Wall surface temperature                                        | $^{\circ}\text{C}$    |
| $\Delta T$         | Change in temperature                                           | $^{\circ}\text{C}$    |
| $\Delta T_s$       | Change in steel temperature over time $\Delta t$                | $^{\circ}\text{C}$    |
| $V_s$              | Volume per unit length of the steel section                     | $\text{m}^3/\text{m}$ |
| $\Delta x_1$       | Thickness of layer being assessed                               | m                     |

| Greek Symbols |                                                                                                               | Units                         |
|---------------|---------------------------------------------------------------------------------------------------------------|-------------------------------|
| $\alpha$      | Convective heat transfer coefficient                                                                          | $\text{W}/\text{m}^2\text{C}$ |
| $\alpha_1$    | Surface coefficient of heat transfer in the boundary layer between the combustion gases and suspended ceiling | $\text{W}/\text{m}^2\text{C}$ |
| $\alpha_2$    | Surface coefficient of heat transfer in the boundary layer between the suspended ceiling and floor slab       | $\text{W}/\text{m}^2\text{C}$ |
| $\alpha_i$    | Heat transfer coefficient of the inner surface exposed to fire                                                | $\text{W}/\text{m}^2\text{C}$ |
| $\epsilon$    | Emissivity                                                                                                    | —                             |
| $\epsilon_w$  | Emissivity of the compartment walls                                                                           | —                             |
| $\epsilon_r$  | Resultant emissivity based on combining emissivity of fire gases and steel                                    | —                             |
| $\epsilon_i$  | Emissivity of the $i$ th inner compartment surface                                                            | —                             |
| $\epsilon_f$  | Emissivity of the gases in the compartment                                                                    | —                             |



Nomenclature *Continued*

| Greek Symbols |                                                                                                           | Units                     |
|---------------|-----------------------------------------------------------------------------------------------------------|---------------------------|
| $\rho$        | Density                                                                                                   | $\text{kg/m}^3$           |
| $\rho_a$      | Air density                                                                                               | $\text{kg/m}^3$           |
| $\rho_s$      | Steel density                                                                                             | $\text{kg/m}^3$           |
| $\sigma$      | Steffan-Boltzman constant                                                                                 | $\text{kW/m}^2\text{K}^4$ |
| $\gamma_{q1}$ | Factor of consequence of structural failure based on type of fire compartment and overall building height | —                         |
| $\gamma_{q2}$ | Factor to account for probability of occurrence of a fire based on fires reported to fire service         | —                         |
| $\gamma_n$    | Factor to account for the influence of sprinklers                                                         | —                         |
| $\Gamma$      | Fictitious time                                                                                           | hr                        |
| $\tau$        | Duration of burning period of fire                                                                        | hr                        |
| $\Phi$        | Ventilation parameter                                                                                     | $\text{kg/s}$             |

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## CHAPTER 2

# CURRENT APPROACH TO STRUCTURAL FIRE SAFETY

Under the current prescriptive code regime there is generally no requirement to undertake an engineering approach to structural fire safety, since the required fire resistance ratings (FRRs) are prescribed and the FRRs of materials and assemblies are determined through standard tests. However, there is growing criticism that these standard tests may not be relevant based on current construction practices and materials, and that they do not accurately reflect a real compartment fire scenario given the difference in the time–temperature curves between standard vs. real fires. This document proposes a method that can be used to determine required FRRs based on a realistic engineering approach. This method is a comparative one that allows an understanding of relative performance of structural elements and assemblies. It is not intended to capture real structural fire responses in that it does not allow for the actual thermomechanical responses of structural steel to real fire conditions. However, in doing so, this proposed method provides for a conservative assessment of the expected performance.

Current building code requirements for determining the fire resistance of structural systems are based on the reaction of specimens to a standard fire exposure, such as defined by test standards ASTM E119 (ASTM 1998), ISO 834 (ISO 1999), and NFPA 251 (NFPA 2006). These standards have been the fundamental basis for determining FRRs in building code applications since the 1920s. Although these standards have resulted in a reasonable level of safety (given the lack of frequent building failures), there is nevertheless a growing body of evidence which suggests that the entire testing procedure used by these standards is not realistic. Unfortunately, the time–temperature curves used by the standards do not compare well to the time–temperature curve of a real compartment fire.

The result is that building construction may be needlessly costly. The rate of rise of the compartment fire temperatures, as well as their duration, are key, with a short-hot fire causing the most significant structural fire response due to the greater gradients that can occur in the structural elements. Therefore, when designing structures for fire the key issue is to ensure that both of these factors are addressed. Some of the criticisms are:

- The standards are based on a specified time-temperature exposure that is constantly increasing, whereas the time-temperature relationship of a real fire has defined components consisting of growth, fully developed, and decay periods. Figure 2-1 indicates the typical difference between the test curve and a more realistic curve (Boring, Spence, and Wells 1981).
- Load-bearing structural members are tested at a load corresponding to the maximum permissible stress of the member being tested. This is significant since the load-bearing structural members in a building are not typically designed to carry a load at the maximum permissible stress, nor is the building load distributed evenly throughout the structural members (Pettersson and Wittenveen 1980).
- Only a single component of the overall building structural system is tested. By only performing a single-element test, it is not possible

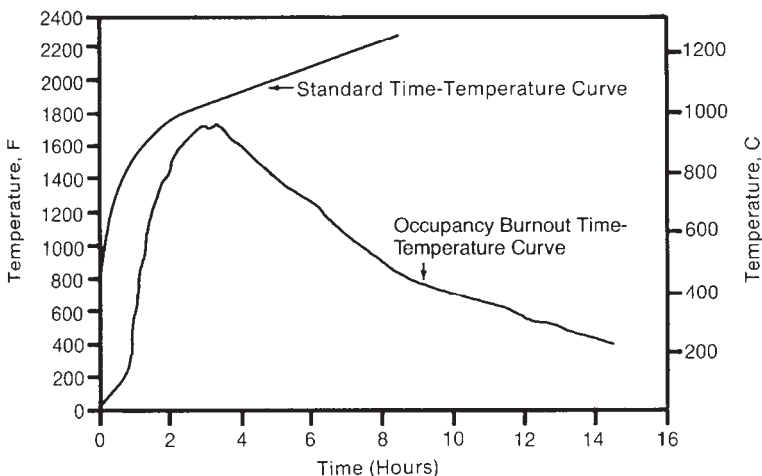


FIGURE 2-1. Standard vs. Realistic Compartment Fire Time-Temperature Curve

Source: Parkinson and Kodur 2006.

to account for the load distribution that will likely occur throughout the remainder of the supporting assembly when a single member of the system fails (SCI 2000). This is also true of the method proposed here. However, the method proposed here allows for a more realistic consideration of the time–temperature profile of the compartment fire.

- The FRR of the structural member is defined by the length of time it can withstand the standard fire exposure while satisfying specific performance criteria. The success of the test is in part a function of the gas temperature within the furnace. The gas temperature is a function of the convective heat from the heat source and radiant heat from the furnace walls. Radiant energy is the dominant component of the total heat release rate incident upon the structural member, and since the magnitude of the radiant flux is proportional to the temperature to the fourth power, the impact of the radiation component can be significant. The type of furnace wall construction directly impacts the magnitude of the radiant energy. Therefore, if the wall construction from one furnace to another varies, then the impact of radiation may also vary (Drysdale 1985). The importance is that large deflections in fire can relieve thermal stresses and, as such, enhance structural response in real fires.

It should be pointed out that these examples, which identify the weakness of the current test standards, do not reflect a comprehensive critique of the standards.

It is also worth noting that ASTM E119 (ASTM 1998) states the following:

*This standard should be used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions and should not be used to describe or appraise the fire-hazard or fire-risk of materials, products, or assemblies under actual fire conditions. However, results of the test may be used as elements of a fire-hazard assessment or a fire-risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard or fire risk of a particular end use.*

## 2.1 HISTORY OF THE STANDARD TEST METHODS

In 1908 the American Society for Testing Materials (now ASTM International) published a draft standard test method based on the need to develop a common approach to evaluating the fire safety of building construction materials. In 1918 a time–temperature curve was established as part of an ASTM standard based on the maximum temperatures

experienced in real fires at the time. The curve was not based on the response of building components to a real fire but, rather, on what the authors have described as a worst-case time-temperature relationship to be expected during a fire.

This curve has remained essentially unchanged and has been adopted by numerous countries around the world with only minor variations. Figure 2-2 shows a comparison between the time-temperature curves of the standards of various countries.

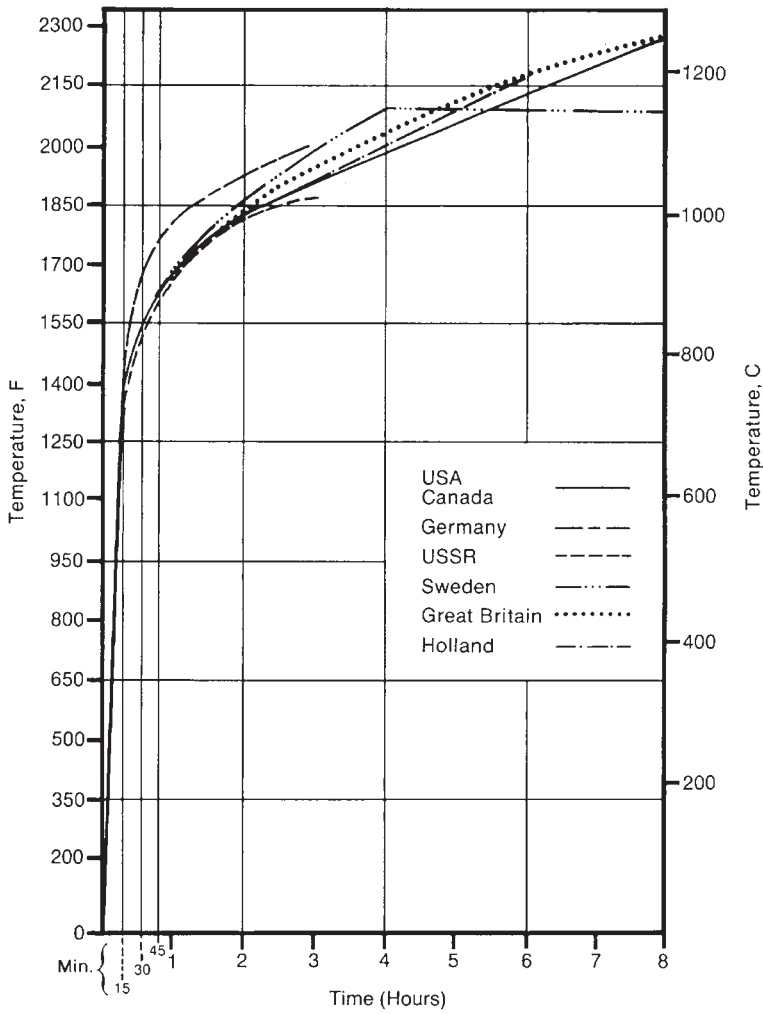


FIGURE 2-2. Standard Test Curves for Various Countries  
Source: Parkinson and Kodur 2006.

For ASTM E119 (ASTM 1998) the standard time–temperature curve may be represented by the following equation:

$$T_t = T_0 + 345 \log(0.133t + 1) \quad (2-1)$$

This standard time–temperature curve allowed the construction industry to determine the FRR for a given structural member or assembly based on the time to failure in the furnace. The difficulty came when trying to relate this time to failure to the building code requirements. To address this, the “Fire Load Concept” was proposed by Ingberg in 1928. This concept proposed that the total heat release rate over the time required for a real fire to consume all combustible contents within a fire compartment could be considered the fire severity, with the fire severity being equal to the area under the real fire curve. This fire severity would vary depending upon the fire load within the fire compartment. For example, the fire severity in a typical office (area under the curve represented by a real fire in an office) would be expected to be less than the fire severity in an industrial plant with significant levels of storage (area under the curve represented by a real fire in a plant). It was proposed that the fire severity for a typical compartment fire could be related to the fire resistance determined by the standard fire test by equating the area under the real fire curve above a baseline temperature to the area under the standard fire curve (i.e., the point at which the area under the standard fire curve is equal to the area under the real fire curve would provide the equivalent fire resistance for the fire severity being considered). From this, the fire resistance required for a particular compartment could be determined if the compartment fire load was known. Figure 2-3 illustrates this concept.

To represent this relationship, Ingberg performed a number of tests and generated the data shown in Table 2-1.

In addition to other data, such as provisions for fire fighting, exiting requirements, and building size, Table 2-1 was used to form the minimum fire resistance requirements for the current prescriptive building codes.

The North American construction industry relies on the FRR as tested and catalogued by testing laboratories such as Underwriters Laboratories in the United States. The building codes, in turn, reference these standard tests for use when selecting building components required to meet a prescribed FRR. This places a significant amount of importance on the results of the test (i.e., the building codes stipulate that a designer merely needs to select a construction component from the catalogue that has a listed FRR that is equal to or greater than the required rating to ensure code compliance, with the assumption that code compliance ensures building fire safety). The significance of this reliance on the catalogued data is described in the following sections.

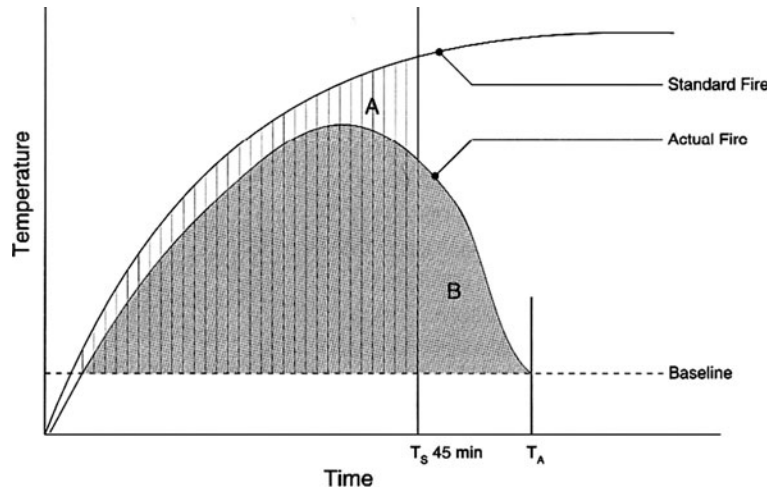


FIGURE 2-3. Ingberg's Fire Load Concept  
Source: Parkinson and Kodur 2006.

TABLE 2-1. Summary of Ingberg's Fuel Load vs. FRR

| Fire Load of Occupancy <sup>a</sup> |                    | Fuel Load <sup>b</sup> |                     | Fire Resistance <sup>c</sup> |
|-------------------------------------|--------------------|------------------------|---------------------|------------------------------|
| kg/m <sup>2</sup>                   | lb/ft <sup>2</sup> | MJ/m <sup>2</sup>      | BTU/ft <sup>2</sup> | minutes                      |
| 24.4                                | 5                  | 456                    | 40,000              | 30                           |
| 48.8                                | 10                 | 912                    | 80,000              | 60                           |
| 73.2                                | 15                 | 1,368                  | 120,000             | 90                           |
| 97.6                                | 20                 | 1,824                  | 160,000             | 120                          |
| 146.5                               | 30                 | 2,736                  | 240,000             | 180                          |
| 195                                 | 40                 | 3,590                  | 320,000             | 270                          |

<sup>a</sup>Ratio of combustible fuel load per unit floor area.  
<sup>b</sup>Ratio of energy content of combustibles per unit area.  
<sup>c</sup>FRR required for structures exposed to fire in room with fire load shown.  
Source: Parkinson and Kodur (2006).

The information above provides a summary description of the basis for the approach currently prescribed in most building codes in North America. Further critical review of the practical problems associated with the standard tests is contained in Appendix A.

## CHAPTER 3

# THE PERFORMANCE-BASED DESIGN PHILOSOPHY

Currently, draft performance-based standards are either in use or are being written as first-generation documents. The general format of these documents is as follows:

1. A stated main objective identifying the broad design principle;
2. A stated sub-objective or functional objective which states specific design philosophies for a particular aspect of the building; and
3. A statement of performance requirements identifying specific design considerations.

Typically, the performance requirements related to fire safety are:

1. To ensure that a fire, once started, will not spread beyond the room of origin;
2. To ensure that occupants will be given early warning of a fire occurrence to enable rapid evacuation from the building;
3. To ensure that the structure will remain standing long enough to allow occupants to escape;
4. To ensure that the structure will remain standing long enough for emergency personnel to perform their duties; and
5. To ensure that the burning building will not fall down upon or ignite the neighboring properties.

Similarly, for structural safety the requirement is to reduce the probability of structural failure and to design the structure in a way that will ensure that the entire structural system will remain stable when a localized collapse occurs.

As stated in Chapter 1, the current prescriptive building codes specify the required fire resistance ratings (FRRs) for floor and wall assemblies and structural members based on occupancy, building height, and building construction. Typically, these start at a minimum 45-min FRR, followed by 1-hr, 1.5-hr, 2-hr, and 4-hr ratings. These ratings have a long history and have been developed based on consensus, experience, and past fire losses. As with the standard fire test, these ratings are potentially conservative since they are applied indiscriminately. For example, a two-story educational facility will require that structural members supporting the first floor be protected by a 1-hr FRR regardless of whether this rating is adequate based on actual fire load, risk, etc. To offer a justifiable alternative to this approach that will satisfy the objectives stated above, a performance-based design should be based on the following:

1. A fire scenario must be characterized by predicting fire load, fire size, fire severity, and fire duration, and a time–temperature relationship for the fire scenario must be calculated;
2. The fire must be modeled in a location that represents a worst-case design for the building (i.e., consideration must be given to both structural and fuel load to ensure that the modeled compartment is representative of the building). To do this, multiple compartments should be assessed as the worst-case fire location, which is not necessarily a structurally critical region in the building; and
3. The time–temperature relationship of the fire-exposed steel must be calculated and the thermal properties determined relative to the known failure criteria of the member under consideration. Time-to-failure values must be predicted based on this analysis.

The purpose of utilizing a performance-based design is to engineer a solution to a technical problem that stands on technical merit instead of depending upon past practice. Although it can be argued that “If it ain’t broke, don’t fix it,” it has also been demonstrated previously that reliance on the current prescriptive approach may result in unnecessarily costly buildings, and that a performance-based approach may yield an equivalent level of fire safety but at reduced cost. However, it is difficult to quantify the limitations of the current approach relative to their impact on overall building fire/structural safety given that no calculations are performed, other than to state that the approach is conservative in nature so as to ensure that a disaster will not happen in severe fire scenarios.

It may appear self-evident that to proceed on the basis of an engineering approach will yield more realistic results. However, there are several concerns relative to the performance-based approach:

1. In most jurisdictions, national codes are consensus-based documents that are continually updated to reflect an improved understanding of the impact of fire in buildings and the reality of current building construction practices. Inherent in these documents is an implied level of safety, albeit not necessarily based on sound analytical models. Although the existing prescriptive approach to the determination of FRRs can be criticized, it is difficult to argue that this approach has not served the public safety well, given the lack of frequent large loss fires in countries which adopt such codes. Therefore, the use of performance-based codes should ensure an “equivalent level” of safety. This approach will ensure that the public’s perception of the safety of the building environment is not eroded. It is thus important to be able to quantify this equivalency, which may not be possible in clear terms.
2. One of the benefits of performance-based designs as they concern building fire safety is that the approach provides the designer with the ability to evaluate the fire safety of buildings that would otherwise not lend themselves to assessment under the prescriptive code regime. However, one of the drawbacks is that performance-based codes may inadvertently result in a lowering of the minimum fire safety levels (Babrauskas 1998) that would not be permitted with the book-of-rules approach of the prescriptive code. This might be the result if the designer does not adequately allow for the expected fuel load.
3. The prescriptive code approach has redundancies, in that minimum fire safety measures are often prescribed exclusive of other measures. However, trade-offs are permitted in some cases, as with automatic sprinkler protection. Under the performance-based regime, these trade-offs could be eliminated as designers argue that they are not required. It could be argued that the operation of the sprinkler system would reduce the time–temperature curve to a point below which a structural member will fail, thereby minimizing the need for structural fire protection. Although the failure rate of sprinkler systems is low, it would be unreasonable to assume that they will never fail. Unfortunately, the rationalization for these trade-offs is not well-defined in the prescriptive codes, so that understanding the implications of the trade-offs is not always easy.
4. Development of the fire scenario can be difficult given the many possible combinations of events that may take place to result in a fire. Furthermore, human interference often directly affects the outcome of a fire. Such interference is often difficult, if not impossible, to predict or control.
5. Performance-based designs are based on fire dynamics, which is not a precise science. There is still experimentation required on which to base and refine the underlying physics (Babrauskas 1999). As a result,